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Why Study Earth System Science?

Perceiving Earth as a system begins when we first feel warmth from sunshine or get wet standing in the rain. Understanding Earth as a system – Earth System Science – requires a quantitative exploration of the connections among all parts (atmosphere, hydrosphere, lithosphere, and biosphere) of the system. The measurements of the GLOBE Program provide students with the means to begin this exploration for themselves.

The processes comprising the global environment are interconnected. Many of the major environmental issues of our time have driven scientists to study how these connections operate on a global basis – to understand the Earth as a system.

Studies of the stratospheric ozone layer involve questions about the processes which create and destroy ozone. Scientists have learned that ozone, a chemical primarily found in a layer centered about 25 km above Earth's surface, is connected to biological activity happening below Earth's surface. Different chemicals, present in the air in trace amounts, control the abundance of ozone in the atmosphere. The sources of these trace constituents include microorganisms in the soil and water, land plants, and even some animals.

Scientists studying climate changes are also interested in the connections between the different Earth processes. Some of the trace gases in the atmosphere make it more difficult for heat (infrared radiation) to escape from the Earth's surface to space. The amounts of these greenhouse gases found in the atmosphere are tied to the physical, chemical, and biological processes taking place in soil and water and on land. They are also influenced by the circulation of the oceans and atmosphere. To predict the future course of the climate we need to understand this detailed fabric of connections.

Ecologists study the way in which the living and non-living components of an ecosystem interact. Individual organisms and species compete and co-operate with one another. In some cases, interdependence is so strong that different plants and animals cannot reproduce or even exist without each other. There is a web of life with extensive recycling of nutrients, and each organism plays a role. If one component of the ecosystem is changed the effects ripple through the system.

Scientists do not know all the Earth system connections yet, but they keep working to gain a more complete understanding. GLOBE students can help through data collection and student research. GLOBE students and scientists working together will improve our understanding of the Earth system. As students conduct the full range of GLOBE measurements (perhaps spread over several school years in multiple grades), they should gain a perception that the environment is the result of an interplay among many processes that take place locally, regionally, and globally on time scales ranging from seconds to centuries. This is a key GLOBE lesson. The learning activities in this chapter help students learn this as they study annual variations in environmental parameters (the *Seasons and Phenology* section) and examine the connections among the various phenomena measured in GLOBE on local, regional, and global spatial scales (the *Exploring the Connections* section).

In addition to learning activities, there are phenology protocols within the *Seasons and Phenology* section. Phenology is the study of living organisms' response to seasonal changes in their environment. Change in the period between green-up and senescence, often synonymous with the growing season, may be an indication of global climate change. Broad-area estimates of the lengths of growing seasons are primarily based on satellite data. However, remote sensing estimates from satellites are not exact because the actual behavior of the plants must be inferred from the collective appearance of their foliage. GLOBE student observations, the only global network of ground-based plant phenology observations, will help scientists validate their estimates of global greenness values that they derive using satellite data. Monitoring the length of the growing season is important for society so that it can better adapt to variations in the length of the growing season and to other impacts of climate change, which may affect food production, economic growth, and human health.

The Big Picture

The planet we call Earth is made up of five 'spheres', the atmosphere, hydrosphere, lithosphere, cryosphere, and biosphere, connected to each other in a complex web of processes. See Figure EA-I-1. The atmosphere consists of the gases and particles suspended in the air. The oceans, inland water bodies, ground water, and ice sheets (cryosphere), comprise the hydrosphere. The lithosphere refers to the solid earth; the core, mantle, crust, and soil layers (pedosphere). The places on Earth where organisms live are collectively known as the biosphere. Instead of focusing on the individual parts of the Earth, Earth system scientists use chemistry, biology, and physics to study the cycles that connect these spheres with each other and with the energy from the sun, which ultimately drives almost all of these processes.

The major cycles that connect the different parts of the Earth are the energy cycle (see Figure EA-I-2), the water cycle (hydrologic cycle, see Figure EA-I-3), and the cycles of important individual elements (e.g., carbon, nitrogen, see Figure EA-I-4). Each cycle is made up of *reservoirs,* places where energy, water, and elements are stored for a period of time (e.g., chemical energy, sea ice, oceans, carbon dioxide), *fluxes,* the movement of matter from one reservoir to another (e.g., precipitation, transpiration, ocean currents, wind, river flow) and processes that change the form of energy, water, and elements (e.g., photosynthesis, condensation, fire). Every GLOBE measurement is designed to help Earth System scientists in their goal of determining the sizes of Earth's reservoirs and the rate of fluxes into and out of these reservoirs.

Energy from the sun flows through the environment, heating the atmosphere, the oceans, and the land surface, and fueling most of the biosphere. See Figure EA-I-2. Differences in the amount of energy absorbed in different places set the atmosphere and oceans in motion and help determine their overall temperature and chemical structure. These motions, such as wind patterns and ocean currents redistribute energy throughout the environment. Eventually the energy that began as sunshine (short-wave radiation) leaves the planet as Earth shine (light reflected by the atmosphere and surface back into space) and infrared radiation (heat, also called long wave radiation) emitted by all parts of the planet which reaches the top of the atmosphere. This flow of energy from the sun, through the environment, and back into space is a major connection in the Earth system; it defines Earth's climate.

Water and chemical elements are cycled through the environment. Water melts, evaporates, condenses, and freezes, and is moved from place to place in the atmosphere, the oceans, across the land surface, and through soil and rocks. See Figure EA-I-3. Each of the chemical elements undergoes chemical reactions, but the total amount of each on Earth remains essentially fixed. In this way, the environment consists of a set of cycles for water, carbon, nitrogen, phosphorous, etc. Since the cycles of the elements involve life, chemicals, and the solid Earth, they are collectively known as *biogeochemical cycles.* Figure EA-I-4 shows one of these, the carbon cycle.

Figure EA-I-1: Schematic Diagram of the Earth System from the Center of the Earth to 480 km up into the Atmosphere

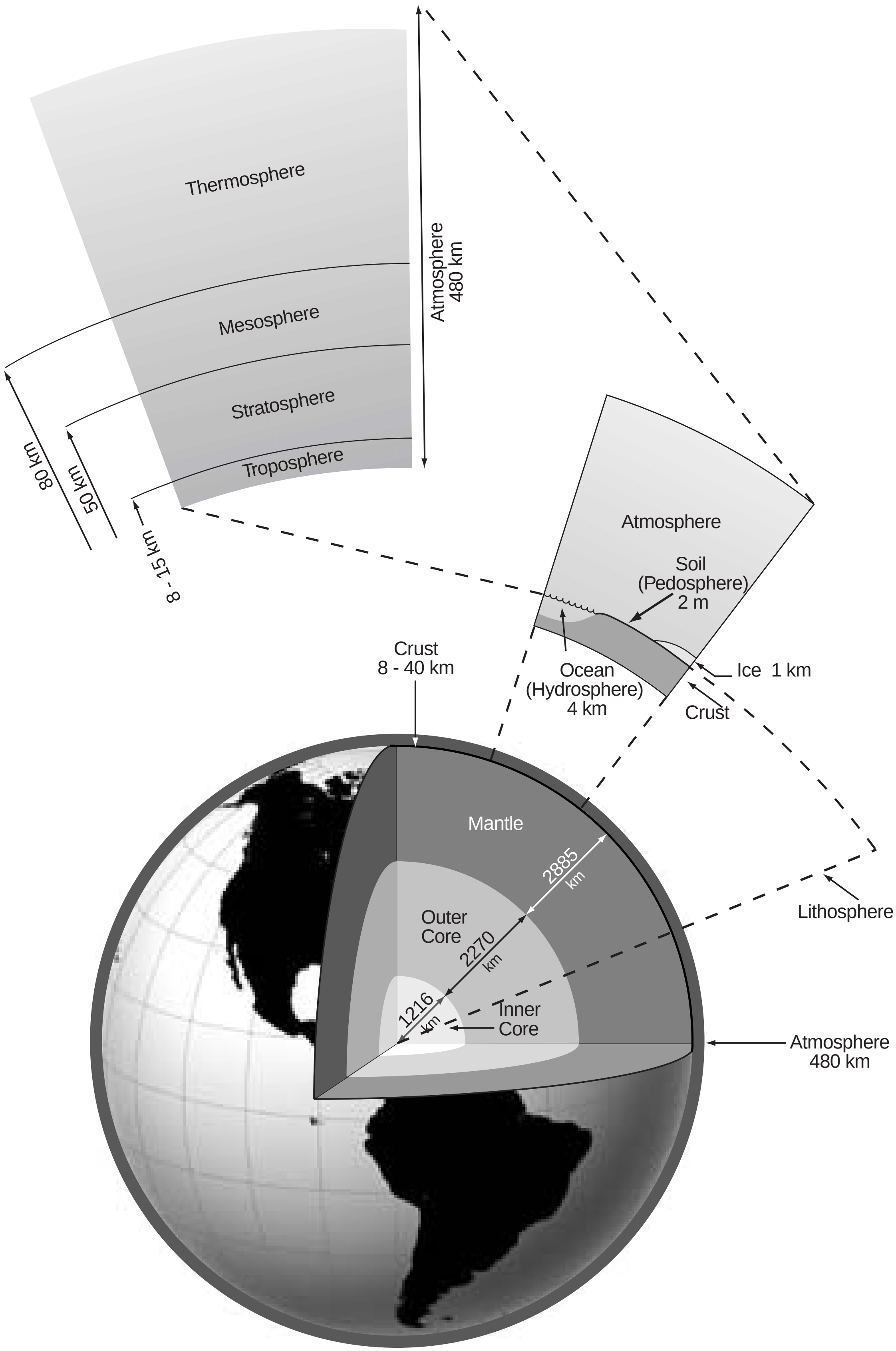


Figure EA-I-2: Schematic Diagram of the Earth's Energy Budget

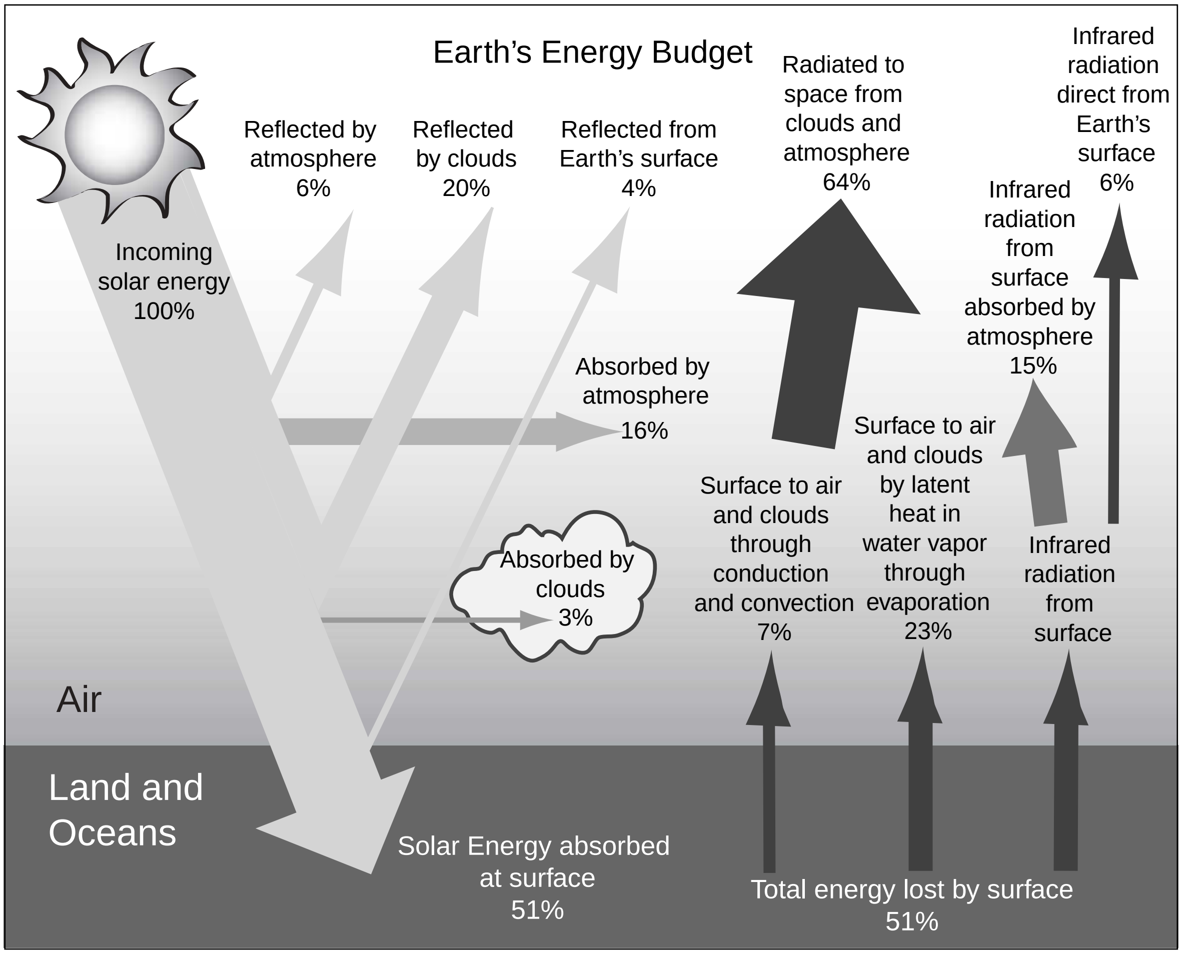


Figure EA-I-3: The Hydrologic Cycle

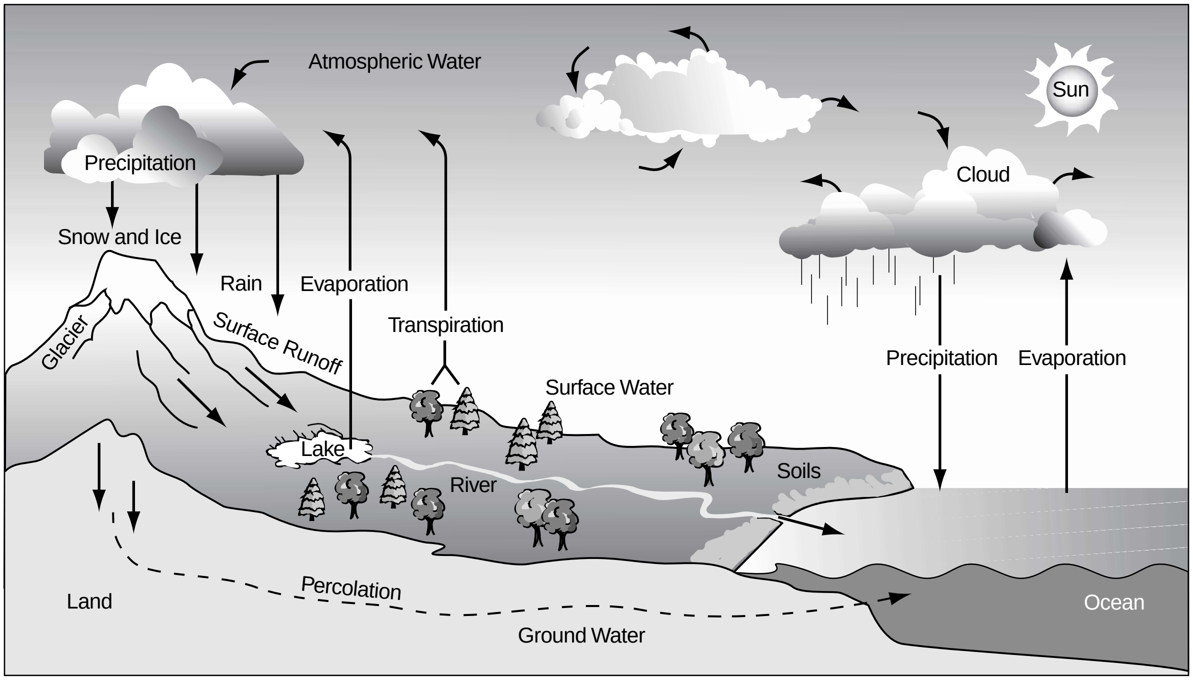
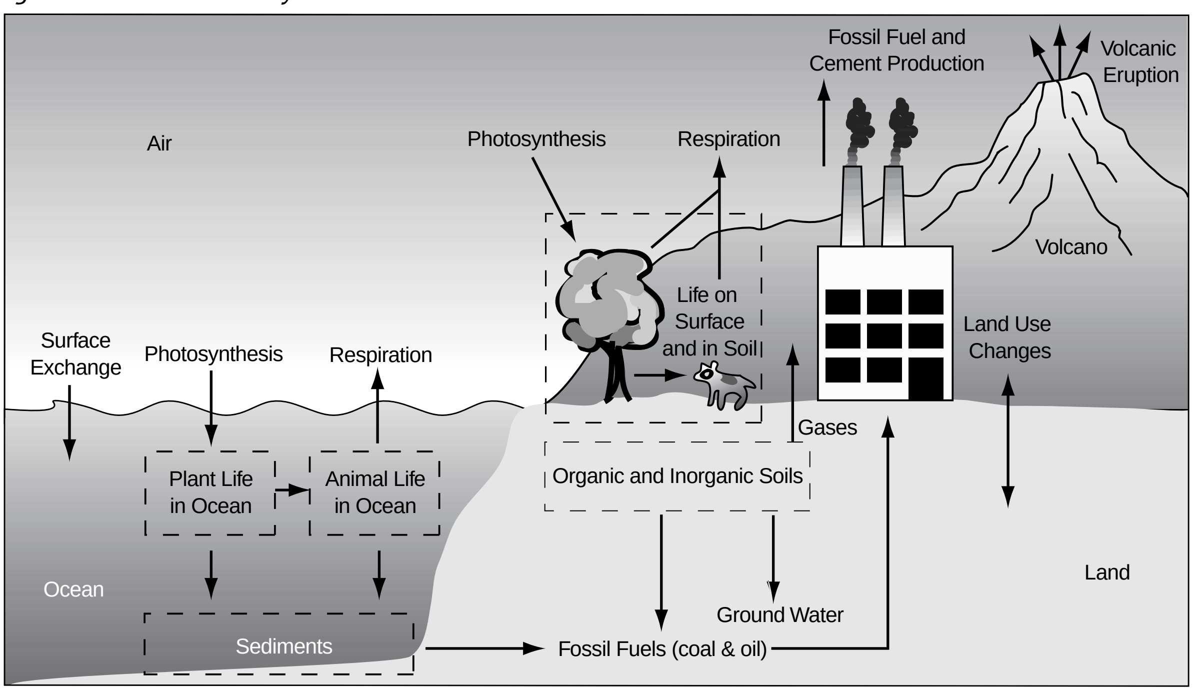


Figure EA-I-4: The Carbon Cycle



Components of the Earth System

The GLOBE program has students take measurements of many parts of the Earth's systems. The table below indicates where the GLOBE investigations lie with the components of the Earth system.

Components of the Earth System	GLOBE Investigations
Atmosphere (Air)	Atmosphere Investigation
Oceans and Fresh water bodies	Hydrology Investigation
Cryosphere (ice)	Atmosphere Investigation (solid precipitation) Hydrology Investigation (frozen water sites)
Soil	Soil Investigation
Terrestrial (land) vegetation	Land Cover Investigation Earth as a System Phenology Investigation

Cycles of the Earth System

In the environment, energy can be in the form of radiation (solar or short-wave radiation and infrared or long-wave radiation), sensible heat (thermal energy), latent heat (heat released when water goes from the gas to the liquid or solid state), kinetic energy (energy of motion including winds, tides, and ocean currents), potential energy (stored energy), and chemical energy (energy absorbed or released during chemical reactions). Scientists want to know, model and predict the amount of energy in all of its forms in each component of the Earth system, how it is exchanged among the components, and how it is moved from place to place within each of the components.

The energy cycle is intertwined with the hydrologic cycle. Some of the energy in the sunlight reaching Earth's surface causes evaporation from surface water and soils. The atmosphere transports the resulting water vapor until it condenses in clouds, releasing the latent energy that evaporated the water. Water droplets and ice particles in clouds grow in size until they form precipitation, falling to the surface as rain, snow, sleet, or hail. Once the precipitation falls, the water can remain frozen on the surface to melt at a later time, evaporate again into the atmosphere, fill spaces in the soil, be taken up by plants, be consumed by animals, leach through the soil into groundwater, run off the land surface into rivers, streams, lakes and ultimately into the oceans or become part of a surface water body. Snow and ice reflect more sunlight back to space than ocean water or most other types of land cover, so the amount of snow or ice covering Earth's surface affects the energy cycle.

Together, the combined energy and hydrologic cycles affect the biogeochemical cycles. In the atmosphere, chemical reactions driven by sunlight create and destroy a rich mixture of chemicals including ozone. Some of these chemicals combine with water to form aerosols –liquid and solid particles suspended in the air. Atmospheric chemicals and aerosols become incorporated in water droplets and ice crystals and are carried from the atmosphere to the surface by precipitation. Microorganisms in the soil and surface waters, plants, and animals all take in chemicals from the air and water around them and release other chemicals into the atmosphere, fresh water bodies, and oceans. Winds enhance evaporation of water from the surface and blow fine grain particles into the air where they are suspended as aerosols. Agricultural and industrial activities also input and remove energy, water, gases, and particles from surface waters, soil, rocks, and air. The quantity and distribution of gases such as water vapor, carbon dioxide, nitrous oxide (N_2O), and methane in the atmosphere determine how infrared radiation is absorbed and transmitted between Earth's surface and space. This in turn affects the temperature at the surface and throughout the atmosphere. There are many other ways in which the energy, water, and biogeochemical cycles interact and influence our environment, far more than can be described here.

How GLOBE Measurements Contribute to Earth System Studies

GLOBE measurements of the temperature of air, water bodies, and soil help track the energy cycle. GLOBE students also measure cloud cover, cloud type, aerosols, water transparency, and land cover. Each of these observations helps scientists determine what happens to the solar radiation (sunlight) and the thermal infrared radiation originating on Earth (heat). How much sunlight is reflected or absorbed by clouds or Earth's surface? How much out-going infrared radiation is absorbed by the atmosphere and how much is re-radiated back downward?

GLOBE measurements of liquid and solid precipitation, relative humidity, soil moisture, land cover, and canopy and ground cover and the identification of the dominant and codominant species of trees help track the hydrologic cycle. Knowing the characteristics of the top meter of soil and its infiltration properties enables scientists to calculate how water will pass into and through the soil; soil bulk density and particle density determine how much water can be stored in the soil. Measurements of the surface temperature of a water body and of soil moisture and temperature enable estimation of evaporation rates. How much rain falls on Earth? Is the hydrologic cycle becoming more intense? Are the various fluxes in the hydrologic cycle increasing?

GLOBE observations contribute to the study of the biogeochemical cycles. Measurements of the pH of precipitation, soil horizons, and surface waters are fundamental because pH influences how different chemical elements interact with water flowing through the environment. Lowering pH can mobilize different chemicals from the surfaces of rocks and soil particles. Living plants are a significant reservoir in the carbon cycle. Measurements of the mass of dried grasses and the circumference and height of trees enable estimation of how much carbon is stored in the living biomass of a forest or grassland. As carbon is added to the atmosphere, how much is taken out by terrestrial vegetation?

Open versus Closed Systems

If you look at Earth from outer space, the Earth is an *almost closed system*. A closed system is one in which no matter enters or leaves. (An *isolated system* is one in which no matter or energy enters or leaves.) Other than the transfer of some gases and particles entering Earth's atmosphere, the components remain on Earth without new additions. When studying Earth as a whole, you usually do not need to consider the effects of inputs and outputs to the Earth system except for the energy from the sun.

Smaller systems can be nested within larger systems. For instance, you can study a watershed — the land area which all drains into a common water body. Watersheds come in a variety of sizes with smaller ones combining to form larger ones. For example, you could study the entire area which drains into the Arctic Ocean, or focus only on the MacKenzie River basin in Canada, or on just the Liard River, a tributary of the MacKenzie. Where you define the boundaries of your system, as a watershed, depends on the questions being asked. These concepts will be developed more in *Exploring the Connections*.

Any system within the Earth system, such as a watershed, is considered an *open syste*m. Water and chemicals as well as energy enter and leave the boundaries of the system. Still, the components of this open system may be more closely connected to one another than they are to exchanges between the system and its surroundings. The inputs and outputs may be important for understanding the dynamics of the system you are studying.

Scales of Space and Time

All the processes of the Earth system occur on specific space and time scales. Some occur on a scale so small that our eyes cannot see them, while other phenomena cover an entire continent or the whole planet. The time scales for different phenomena vary tremendously as well. Some atmospheric chemical reactions happen in fractions of a second. The formation of soil with its interplay of physical, chemical, and biological characteristics happens locally over many years (generally at a rate of 1 cm of depth per century). Major weather systems including hurricanes usually develop and dissipate on time scales of one to two weeks and cover hundreds of kilometers.

Parts of the various cycles of the Earth system can be measured and understood locally on relatively short time scales, seconds to days; in other cases, one must try to characterize the whole globe for decades to test theories, understand processes, and gain overall knowledge. Let's consider one example of each situation:

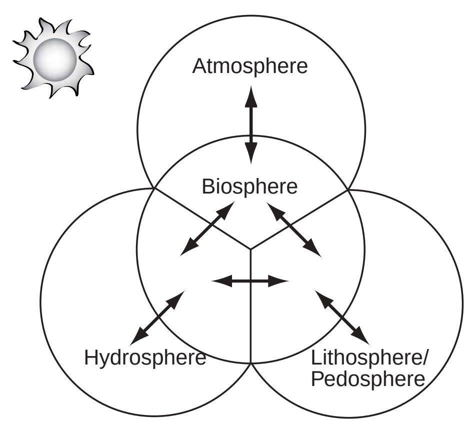
1. **The balance in the amount and flow of water in a small watershed.**
   We can sample the input of water to the surface by measuring precipitation at one or more sites (the more sites, the better the estimate will be). The evaporation of water can be calculated from temperature measurements of the surface soil and water and knowledge of the surface soil moisture and particle size distribution or texture. The transpiration of water by trees and other plants can be estimated by mapping the land cover, measuring canopy and ground cover at a number of sites, and identifying the dominant species of trees in the forests and woodlands. Measurements of soil moisture and the levels of streams, lakes, and rivers tell how much water is stored in the watershed (discounting aquifers or other major underground water bodies). The level of the stream or river through which water flows out of the watershed is an indication of how fast this flow is. The inputs and outputs must balance with the change in the amount of water stored. Most of the needed measurements are included in the GLOBE protocols and the others can often be obtained from other sources or measured with help from local scientists.
2. **Understanding the El Niño/Southern Oscillation (ENSO)**
   The warm episodes of the ENSO occur at irregular intervals of two to seven years. Changes develop across the entire equatorial Pacific basin and effects have been observed developing as much as six months later throughout the temperate zones of both hemispheres. Small remnant phenomena from warm events have been observed by satellites as much as ten years later. To thoroughly characterize this phenomenon and its effects we must take data for many years on a global scale and look for connections, causes, and consequences. Predictions based on an overall understanding of the ENSO can be examined locally using data records covering many months including the data sets collected and reported as part of GLOBE. GLOBE student data of air temperature and precipitation can be compared with model predictions of ENSO effects to help determine the adequacy of our current understanding and modeling abilities.

Key Concepts

As discussed in the previous pages, when studying Earth as a system, there are a few key concepts to understand. These are:

- The Earth is a system made up of components.
- Energy, water, and the chemical elements are stored in various places and forms and are transported and transformed by various processes and cycles.
- Connections among phenomena can be traced through the energy, hydrologic and biogeochemical cycles.
- Phenomena happen on a range of time and spatial scales.

Four Major Components of the Earth System



Note: See *Diagramming Earth as a System* in *Exploring the Connections Introduction.*

The Earth as a System

The Seasonal Cycle

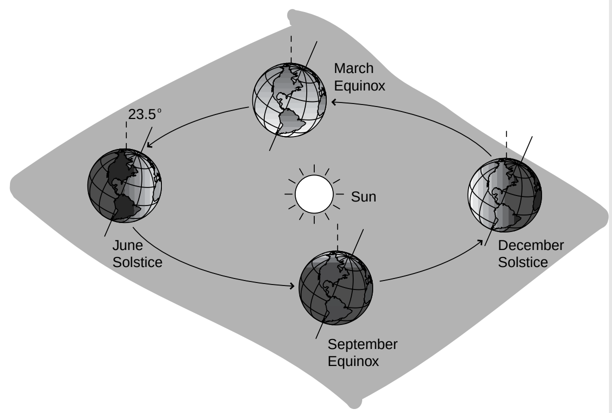
The Seasonal Picture: Why are there seasons?

Earth's seasons change in a regular fashion and bring a rhythm to our lives. Whether it is the arrival of winter snows, monsoon rains, or summer heat, our environment changes constantly, and these profound changes occur over relatively short time periods. That they recur in predictable ways helps make such huge, complex changes comprehensible. Many ancient civilizations observed that the Sun's position in the sky changed throughout the year and were able to construct calendars and make predictions based on their observations, which they used for agricultural and religious purposes.

All seasonal changes are driven by shifts in the intensity of sunlight reaching Earth's surface (*insolation*). More energy per unit area leads to higher temperatures, which results in more evaporation, which produces more rain, which starts plants growing. This sequence describes Spring for many mid-latitude climates. Since visible light is the main form of solar energy reaching Earth, day length is a reasonably accurate way to gauge the level of insolation and has long been used as a way to understand when one season ends and the next one begins. The first day of summer, (*summer solstice*) is the longest day of the year. Winter starts on the shortest day of the year, (*winter solstice*). The first days of spring and fall are when the day and night are of equal length — roughly 12 hours each. These days are named *vernal* and *autumnal equinoxes*.

The changing day length results from the Earth's axis of rotation being inclined 23.5° with respect to the plane of its orbit around the sun. Figure EA-I-5 shows the inclined Earth at different positions in its orbit. Notice how at the solstice positions, each pole is tilted either toward or away from the Sun. The pole inclined toward the Sun receives 24 hours of sunlight, and the one inclined away is in Earth's shadow and experiences 24 hours of darkness. At the equinox positions, Earth is inclined in a way so that each pole receives equal amounts of insolation. This discussion focuses on the poles because they experience the greatest extremes of insolation. Because of the inclination of Earth's axis, insolation levels at every point on Earth change constantly. We call the aggregate effects of these changing levels *seasons*.

Figure EA-I-5: Tilt of the Earth's Axis



The tilt in Earth's axis of rotation has an additional effect, which amplifies the length of day effect. At every latitude, the Earth's surface is at a different angle with respect to the incoming sunlight. Look at Figure EA-I-6. When the surface is perpendicular to the sunlight, the sun is straight overhead, and the amount of sunlight striking a fixed area is at its maximum. As the sun moves lower in the sky and the angle at which sunlight strikes the ground decreases, the intensity of sunlight striking the same area gets smaller. In the summer, the sun is closer to being straight overhead at local solar noon than in the winter except close to the equator. So, not only is the day longer in summer than in winter, but the sun delivers more energy to each unit of area of Earth's surface in the hemisphere where it is summer.

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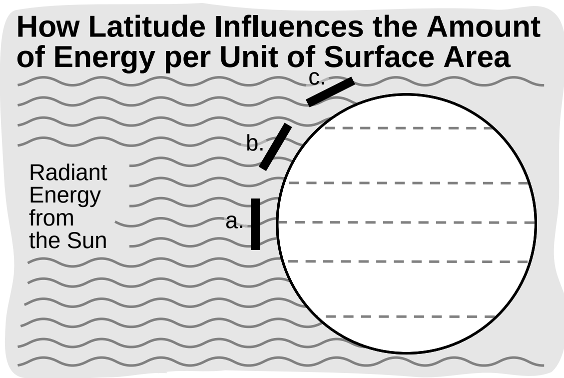
Figure EA-I-6: How Latitude Affects the Amount of Incoming Energy from the Sun

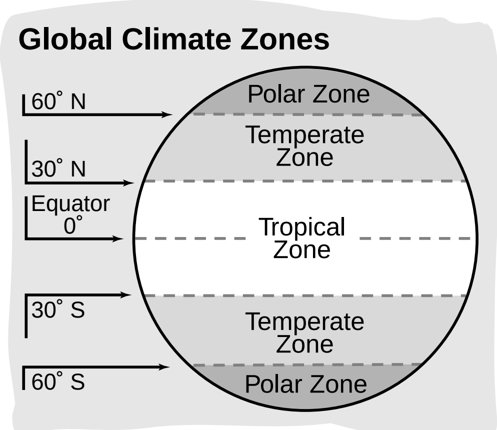


Factors Influencing Local Seasonal Patterns

Latitude

Figure EA-I-7 shows how insolation levels vary with latitude throughout the year. Because of this variation, latitude has a powerful influence in determining seasonal conditions and the annual patterns of environmental and climatic parameters such as precipitation and temperature. Because of the differences in the duration and directness of insolation, the world can be divided into the zones shown in Figure EA-I-8. The same season can be quite different in the Tropical, Temperate and Polar zones.

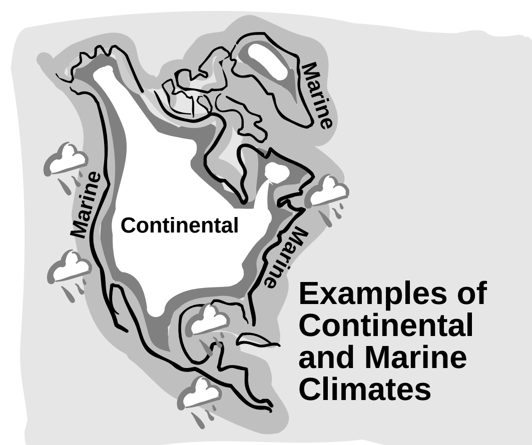
Figure EA-I-8: Approximate Global Climate Zones



Continental and Marine Climates

Climate also varies dramatically depending on the amount of water in the environment. When sunlight strikes the surface of water, four things keep the water surface from warming as much as the land surface. First, the specific heat or the energy it takes to heat one gram of water one K is 1 cal g^{-1} K^{-1} compared to 0.4 cal g^{-1} K^{-1} for soil. It therefore takes 2.5 times the energy to heat water by 1K than it takes to heat soil 1K. Second, some of the sunlight penetrates many meters into the water column. This spreads the incoming energy down into the water body and the surface is less warmed. Also, colder water from lower depths mixes to some extent with the surface water and moderates its temperature changes. Third, winds produce movement in the surface waters which causes a mixing of heat throughout the surface layer. Fourth, as surface water warms, evaporation increases. Evaporation cools the surface and so the temperature of the water surface responds less to solar heating than the land surface. Land which is near large bodies of water that do not freeze in winter has a marine climate. This features larger amounts of moisture and smaller temperature changes from summer to winter than a continental climate. The size of a continent affects both the temperature range and the amount of moisture in the interior – the larger the continent, the further away the ocean and the larger the difference between summer and winter.

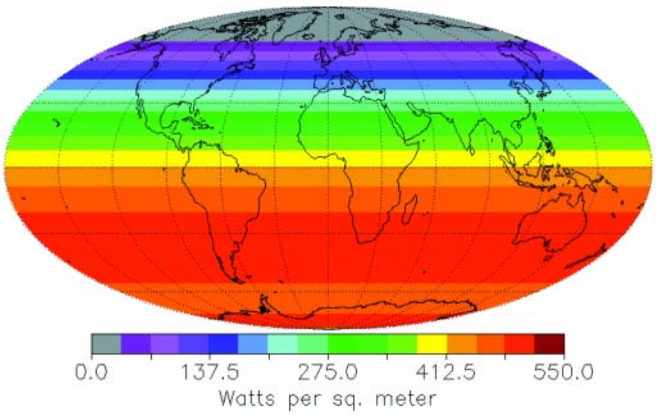
Figure EA-I-9: Continental and Marine Climates



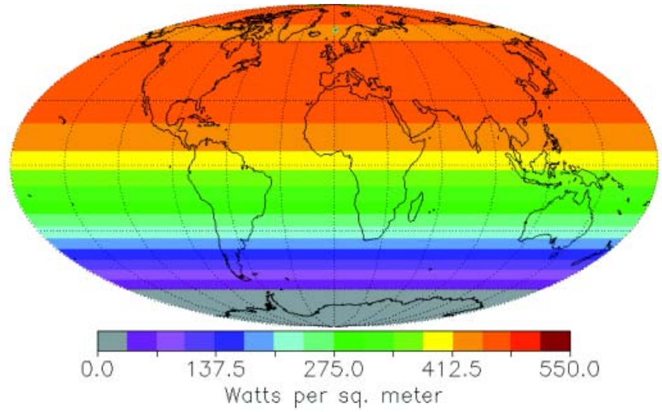
Wind Direction

The direction of the prevailing winds also affects local climate. If an area is downwind of the ocean (the west coasts of continents in mid-latitudes) the climate is strongly affected by the presence of the ocean as described above. If the winds are blowing from the interior of the continent, then they tend to be dry and to bring with them the larger contrasts in summer and winter tempera-

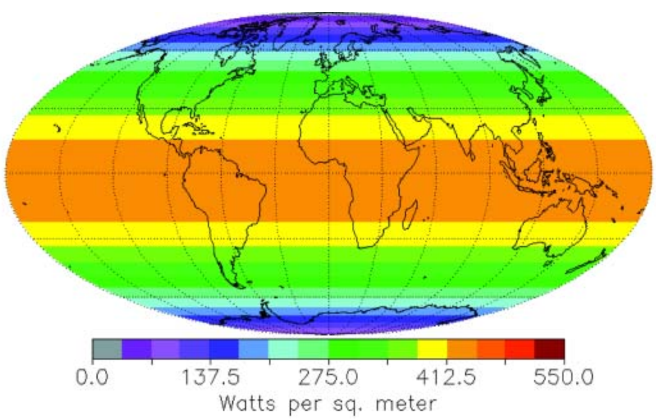
Figure EA-I-7: Incoming Solar Radiation Throughout the Year



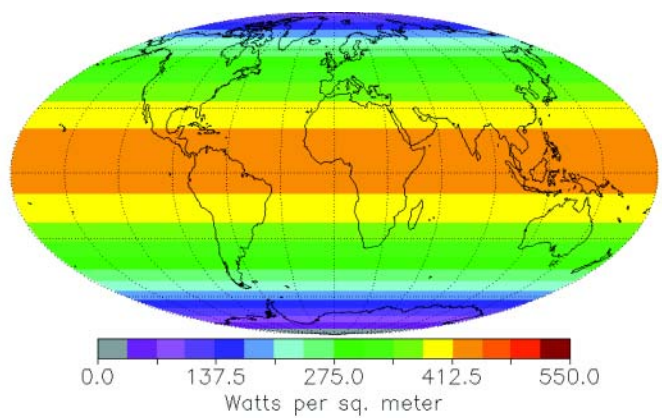
January Solar Radiation



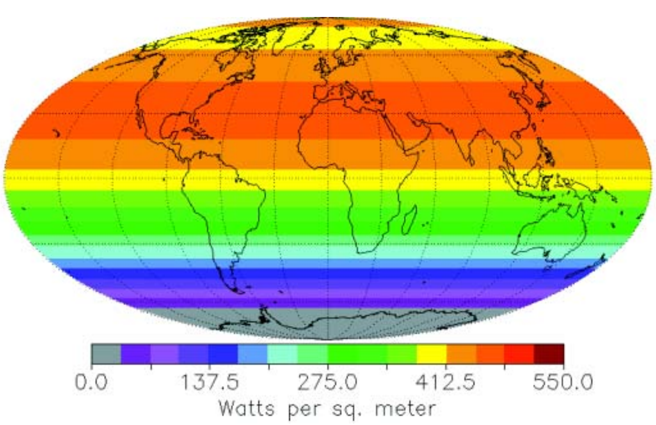
July Solar Radiation



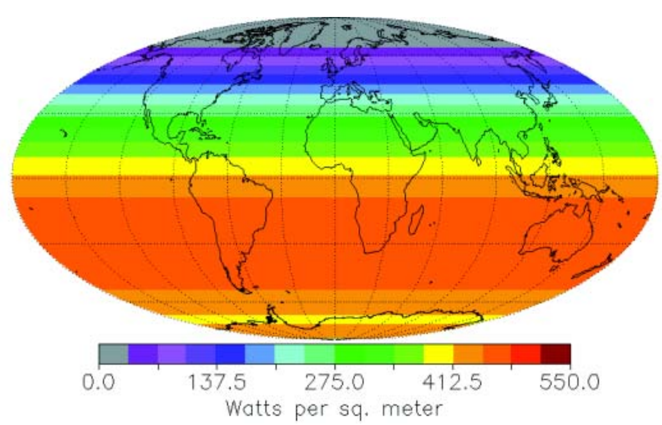
March Solar Radiation



September Solar Radiation

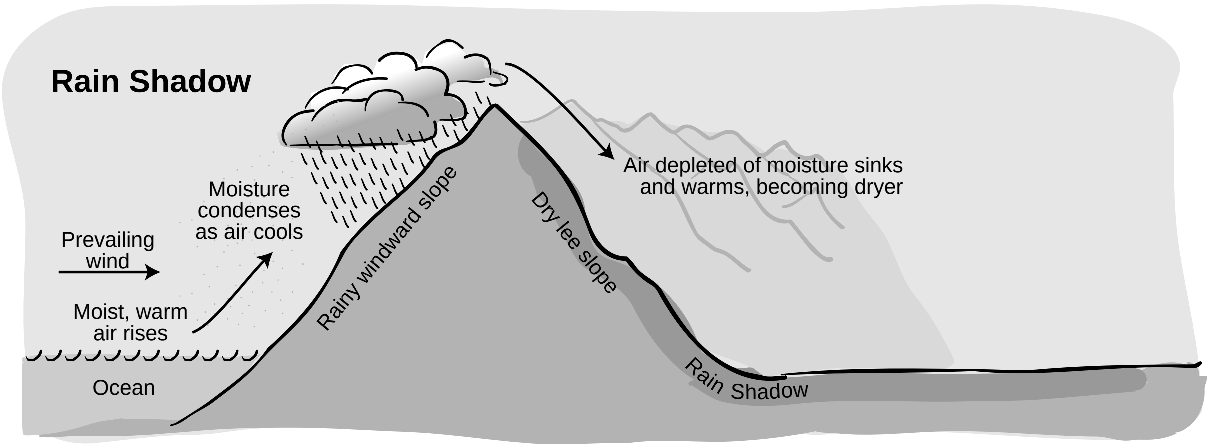


May Solar Radiation



November Solar Radiation

Figure EA-I-10: Mountain Producing a Rain Shadow Effect



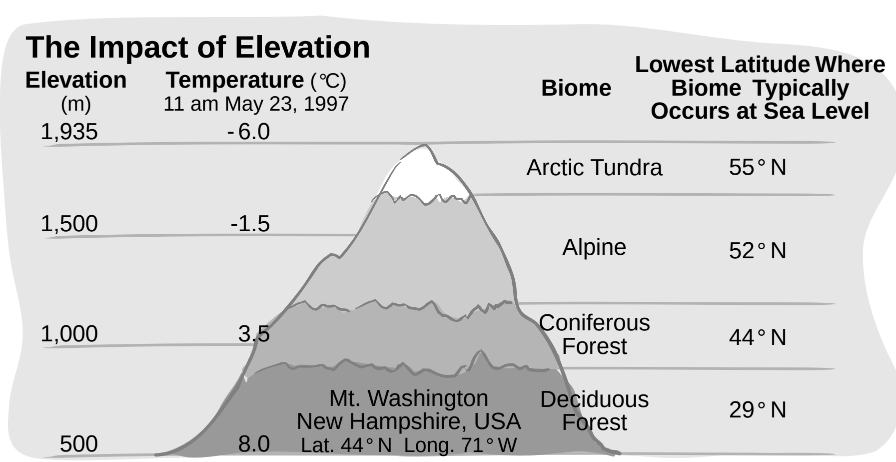
tures. Areas in the high latitude parts of the temperate zones and downwind of lakes receive large amounts of lake-effect snow while the lakes are unfrozen. Generally, prevailing winds connect the local climate with that upwind. Seasonal changes in prevailing wind direction can make seasonal contrasts greater or smaller.

Geographical Features

Geographical features have profound impacts on the climate of nearby regions. For example, mountains can cause moist air to rise and precipitate out almost all of its moisture. When dry air descends behind the mountain, it lacks enough moisture to provide much precipitation. The mountains create a rain shadow. See Figure EA-I-10. Many deserts are found in such rain shadows. In addition to arid land, typical desert regions lack the atmospheric moisture that acts as insulation between the Earth's surface and space (water is the major greenhouse gas on Earth). Consequently, desert areas easily radiate their heat energy out to space, and day and night temperature differences are considerable.

Elevation also influences seasonal patterns. Changes in elevation can affect the environment as much as changes in latitude. Average air temperature falls approximately 1˚ C for every 150 meter increase in elevation, and, in terms of growing season, every 300 m increase in elevation is roughly equivalent to moving poleward by 400-500 km (roughly four to five degrees of latitude). Mountain tops can be thought of as climatic is-

Figure EA-I-11: Impact of Elevation on Climate Zone



lands where, in the Northern Hemisphere, northern species extend their ranges southward on mountains where conditions resemble those of more northern latitudes. Plants growing on the top of New Hampshire's Mt. Washington (1,935 m) would feel right at home growing at sea level in the Arctic tundra, 2,400 km to the north in Canada. See Figure EA-I-11.

Students can study each of these effects by looking at GLOBE school data. A climatogram shows the monthly mean temperature and monthly total water equivalent of the precipitation for the whole year. Comparing these diagrams for schools in different areas (see Figure EA-I-12) makes these differences clear and prompts questions about the reasons for these differences.

Figure EA-I-12: Climatograms for Calcutta, India and Berkeley, California

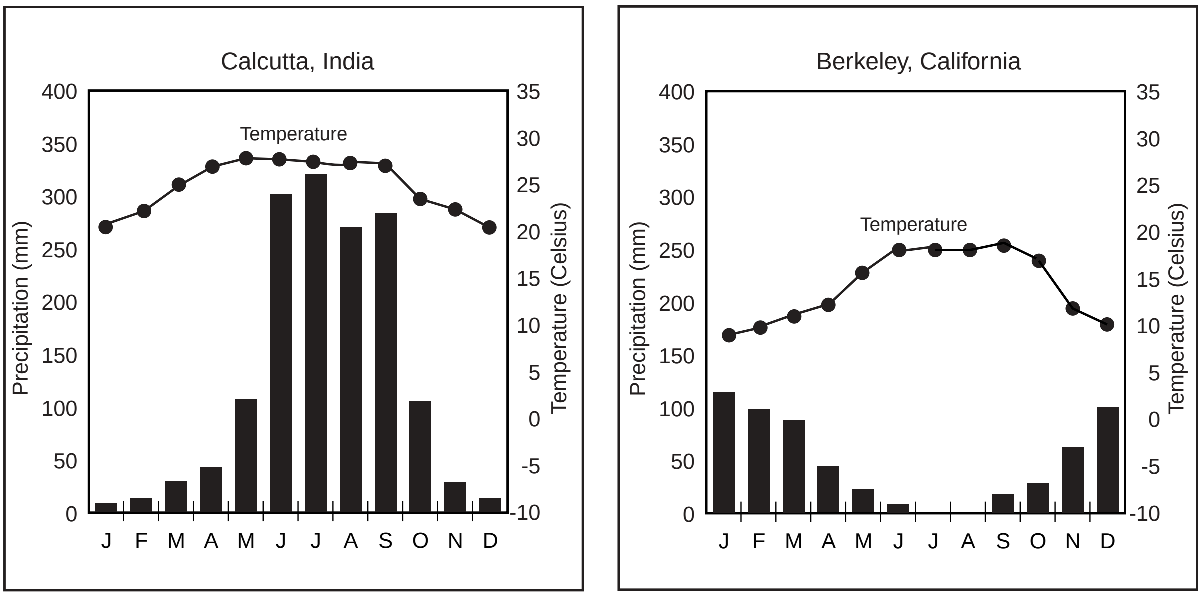
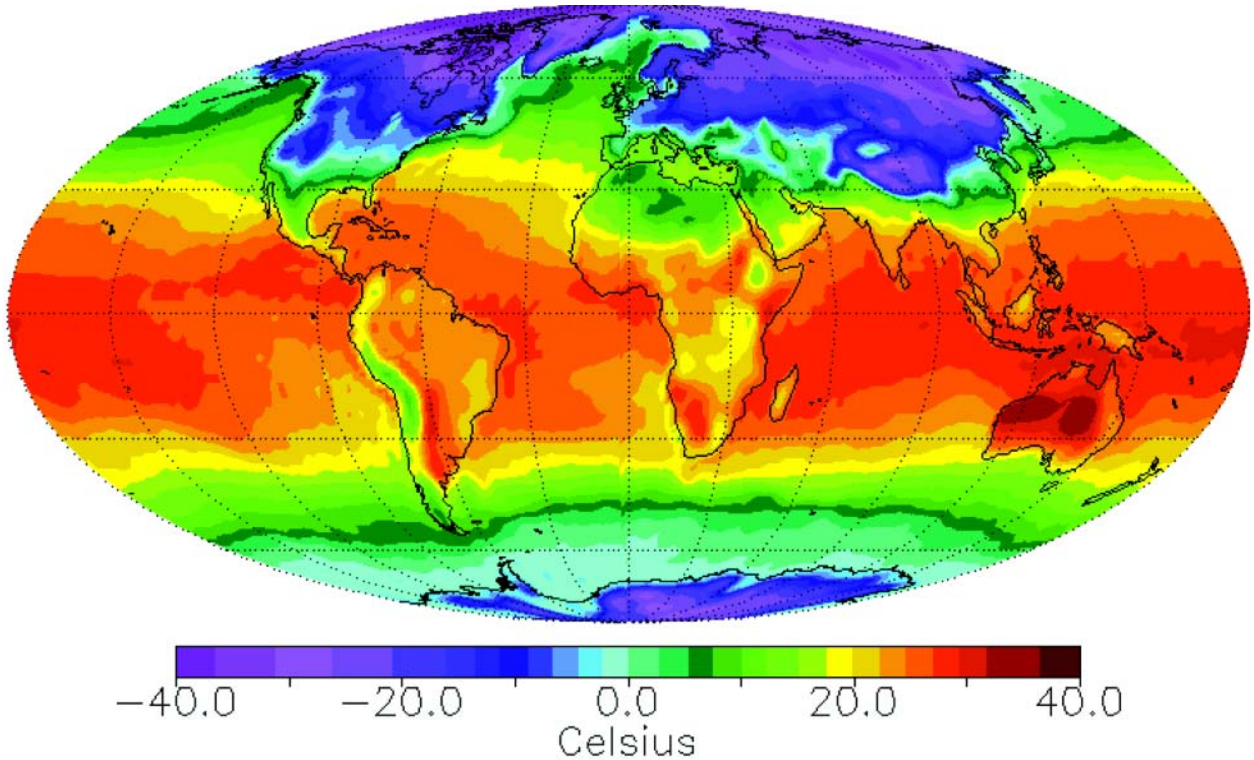
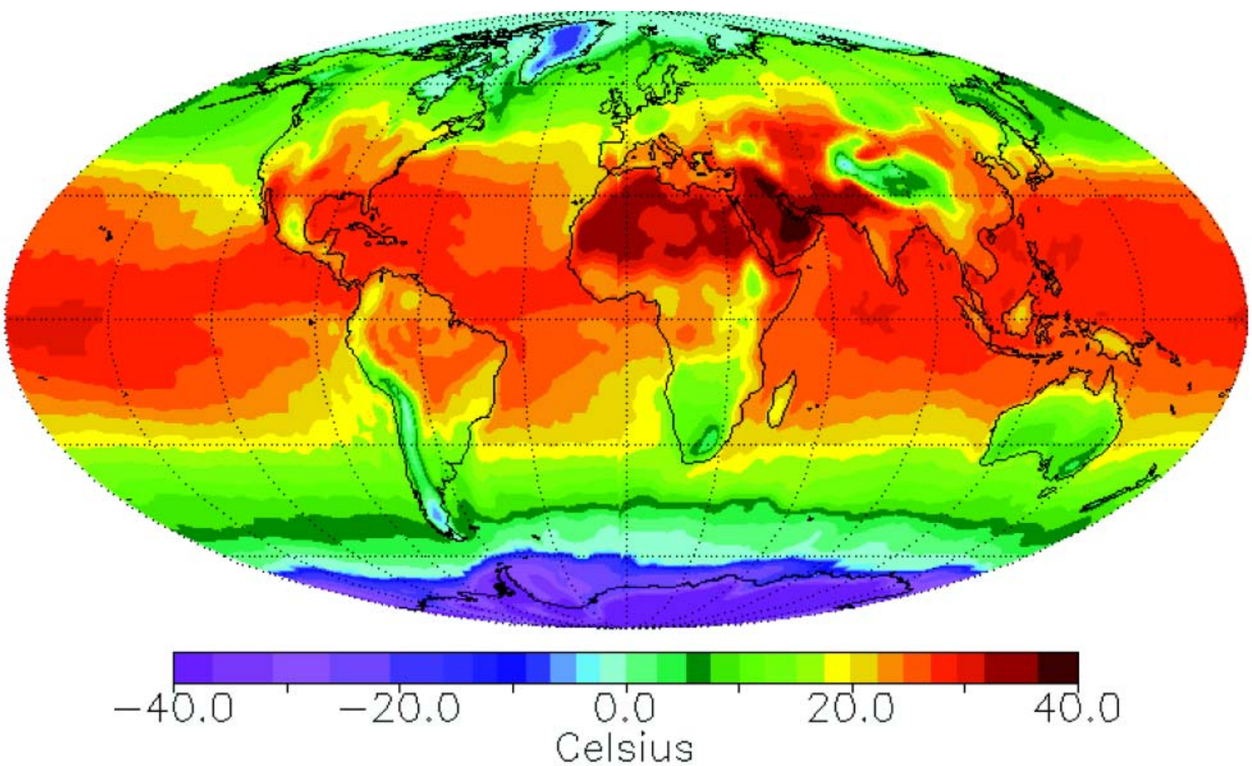


Figure EA-I-13: Global Surface Air Temperature in January and July, 1988.



January Air Temperature



July Air Temperature

The Earth System through the Seasonal Cycle

In GLOBE, the seasonal cycle plays a role in the timing of some measurements. Examining GLOBE data through the seasonal cycle can give you some understanding of how Earth works as a system. We can see this by examining some examples of how the seasonal cycle affects different components of the Earth system. The examples here may provide some background material to better understand and interpret GLOBE data. These examples indicate our current understanding and are based on previous studies. Many of the GLOBE data will reveal some of these seasonal patterns. As well, GLOBE data will expand and refine our understanding of seasonal patterns by examining many sites over a long period of time.

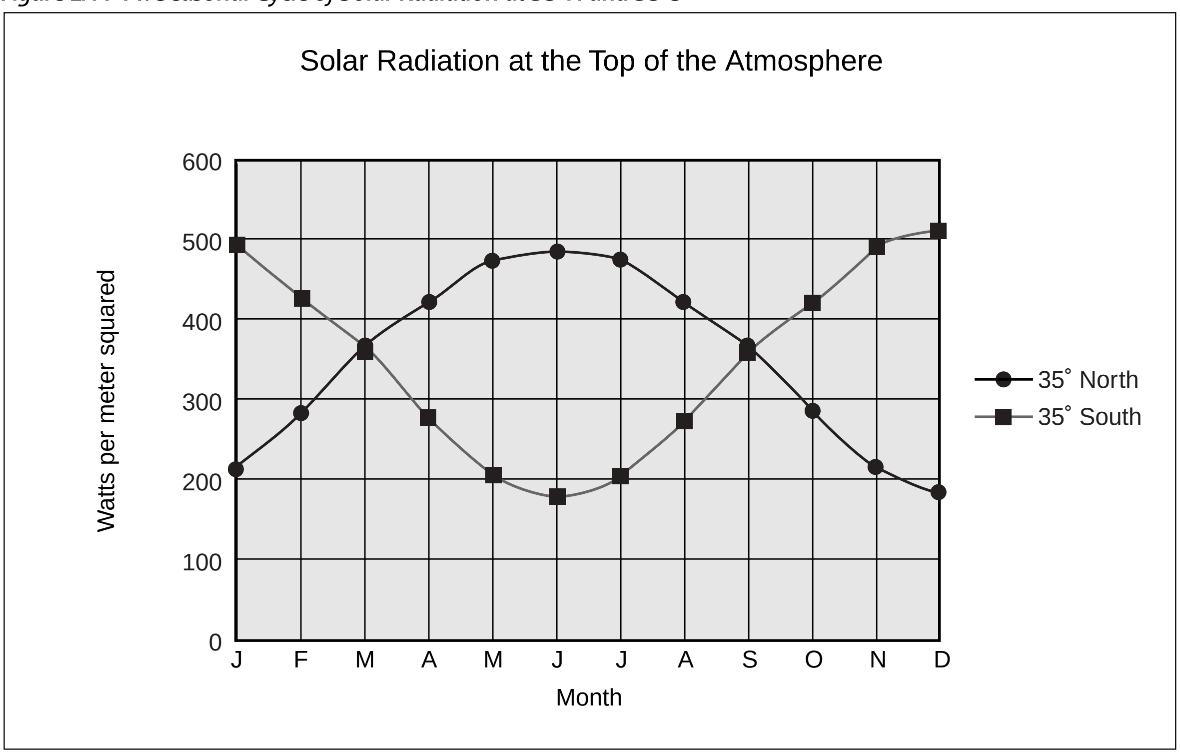
The Atmosphere through the Seasonal Cycle

Temperature

The relationship between air temperature and the number of daylight hours is a familiar seasonal change to people in mid and high latitudes. The air in the lowest layer of the atmosphere is warmed through its contact with Earth's surface. During the summer (July in the northern hemisphere and January in the southern hemisphere), when the elevation of the sun is high, the more concentrated input of energy from the sun and the increase in daylight hours warm the surface which in turn warms the air. During the winter (January in the northern hemisphere and July in the southern hemisphere), when the amount of solar radiation is spread over more surface area because the elevation of the sun is low and there are fewer daylight hours, the sun warms the surface less, resulting in less heating of the air. Compare the distribution of solar radiation in January and July (Figure EA-I-7) with the temperature distribution in January and July (Figure EA-I-13) respectively.

It takes time for Earth's surface to warm and for the atmosphere to fully respond to these changes in surface warmth. The time when the solar radiation is the strongest outside the tropics is in June in the northern hemisphere and December in the southern hemisphere. See Figure EA-I-14. This is when the solstices occur. However, gen-

Figure EA-I-14: Seasonal Cycle of Solar Radiation at 35° N and 35° S



erally temperatures are warmest about two months later, in August in the northern hemisphere and February in the southern hemisphere. See Figure EA-I-15. This is due to the amount of time required to heat the upper layer of the oceans and the lower layer of the atmosphere.

Precipitation

At low latitudes, seasonal temperature changes are not as dramatic as in middle and high latitudes, but there is usually a definite seasonal change in precipitation patterns. Equatorial regions often experience "wet" and "dry" seasons.

Figure EA-I-15: Seasonal cycle of maximum surface air temperature at Kingsburg High School in the United States (located at about 35° N) and Shepparton High School in Australia (located at about 35° S)

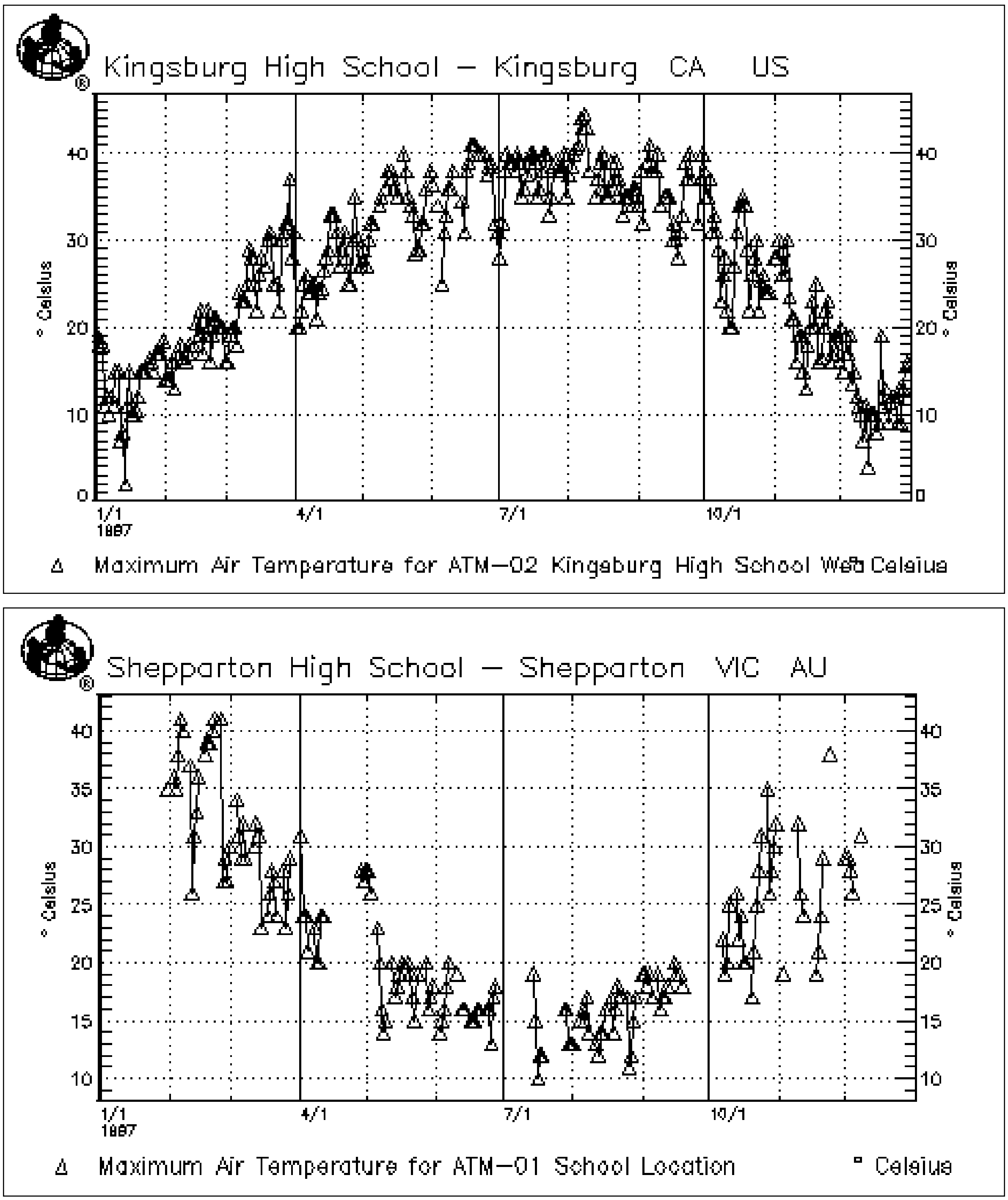
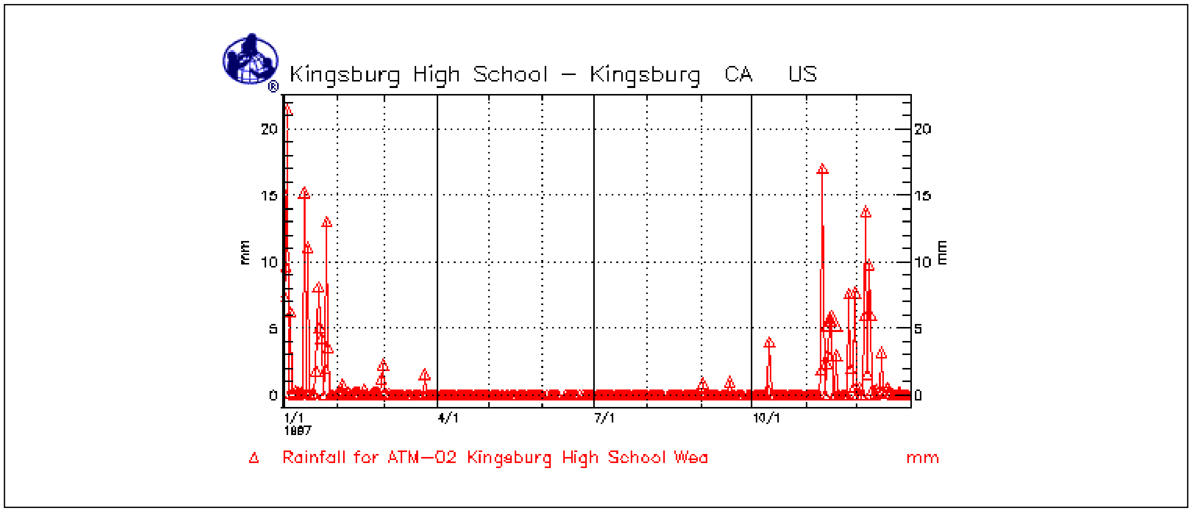
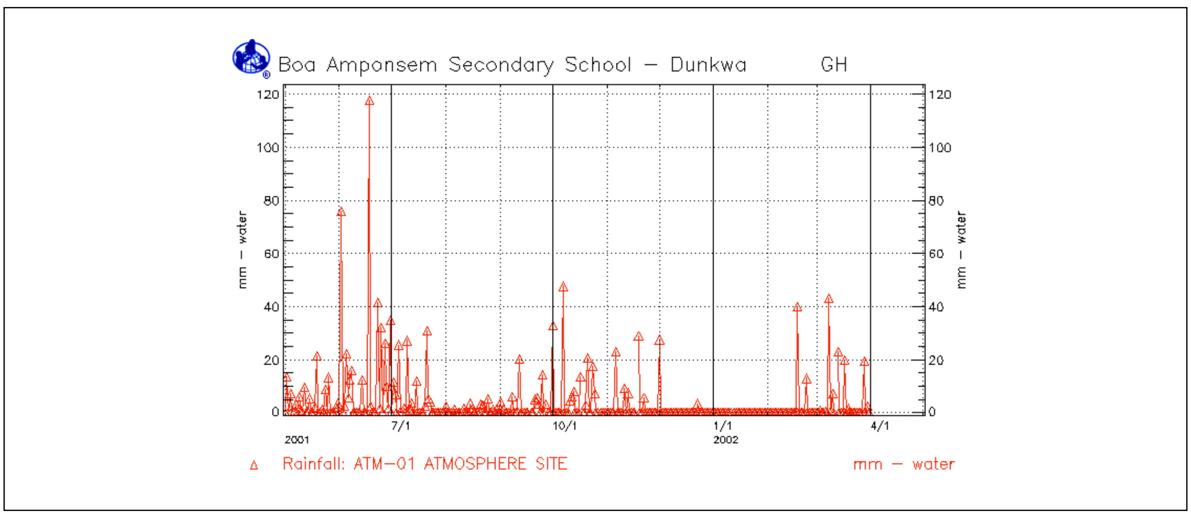
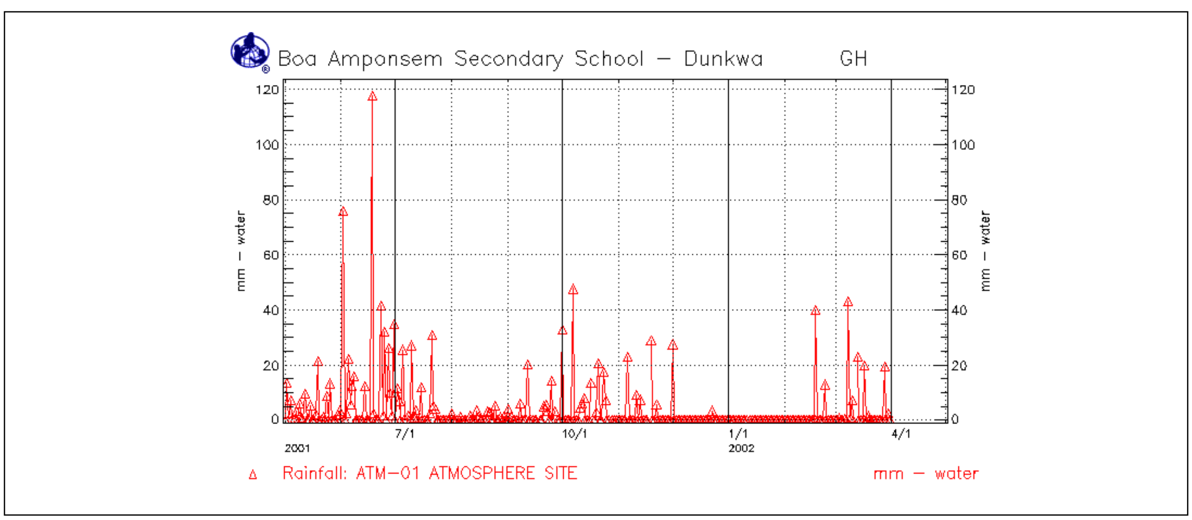


Figure EA-I-16: Seasonal cycle of precipitation through the year at Kingburg High School in California USA, Reynolds Jr. Sr. High School in Pennsylvania USA, and Boa Amponsem Secondary School, Dunkwa, Ghana







The time of year at which these occur is dependent on many factors such as regional topography and proximity to large bodies of water.

Other localities show seasonal patterns in precipitation as well. See Figure EA-I-16. Some regions receive no precipitation for months at a time. In other locations precipitation is evenly distributed throughout the year. Some places have one rainy season and one dry season, while others have two of each during the year. The timing of rains within the year has a major effect on agriculture. Mediterranean climates are characterized by winter rains while other regions experience only summer rains.

Water Vapor and Relative Humidity

Since the saturation value for atmospheric water vapor is strongly influenced by temperature, both the absolute concentration of water vapor and the dew point temperature have a strong seasonal cycle. The highest concentrations of water vapor and the highest dew points occur during summer and the lowest in winter. Relative humidity tends to be highest during the rainy season. However, it can be high even in the winter when the air is relatively cold.

Clouds

In the tropics, a band of low pressure and cloudiness known as the Intertropical Convergence Zone (ITCZ) extends across the oceans. Global satellite imagery shows clouds that extend across oceanic regions, where thunderstorms are active. The average position of the ITCZ varies with the season, moving north in northern hemisphere summer and south in southern hemisphere summer. See Figure EA-I-17.

There are seasonal variations in clouds in other regions. Generally, there is greater cloud cover during the rainy season when observed cloud types are mostly nimbostratus and cumulonimbus. During warmer months, cumulus type clouds are most likely to be observed in most locations due to the heating of Earth's surface. During winter months, because there is less heating, stratus type clouds are more often observed. Vigorous frontal systems that occur during the spring and summer months at mid latitudes can, and often do, cause large thunderstorm clouds (cumulonimbus). Near the eastern coastlines, cooler water can bring stratus type clouds to the region year-round.

Aerosols

Aerosols are colloids consisting of liquid droplets or solid particles dispersed throughout a gas. Fog and mist are examples of liquids dispersed in a gas and smoke is an example of solid particles dispersed in a gas. Aerosols affect the optical thickness of the atmosphere being greatest during summer and least in winter. Other seasonal events can also influence the amount of haze, especially dust storms, forest fires and agricultural activities.

Atmospheric Composition

Atmospheric trace gas concentrations also exhibit distinct seasonal cycles. The longest record of a trace gas measurement is for carbon dioxide (CO_2) and its seasonal cycle reflects the seasonality of forest growth. Lowest concentrations occur in the northern hemisphere spring and summer as the biosphere uses CO_2 for photosynthesis. Concentrations increase during northern hemisphere autumn and winter as CO_2 is no longer taken up by vegetation growth, and decay of leaves puts CO_2 back into the atmosphere. This cycle is dominated by the larger extent of terrestrial vegetation in the northern hemisphere. See Figure EA-I-18.

Another important trace gas is ozone, which exists in the lower atmosphere as both a natural component, where its primary source is the stratosphere, and as a pollutant, where it is formed as a result of emissions from combustion sources. At northern middle latitudes, surface ozone peaks in the summer when sunlight is most intense and photochemical reactions happen most quickly, converting hydrocarbons and nitrogen oxides into ozone. At southern mid-latitudes, on the other hand, summer concentrations of surface ozone are lower because there are less emissions from combustion than in the Northern Hemisphere. In the tropics, surface ozone concentrations are generally highest in September and October because this is the time when widespread biomass burning occurs and gases from these fires generate ozone through photochemistry. Thus, the sea-

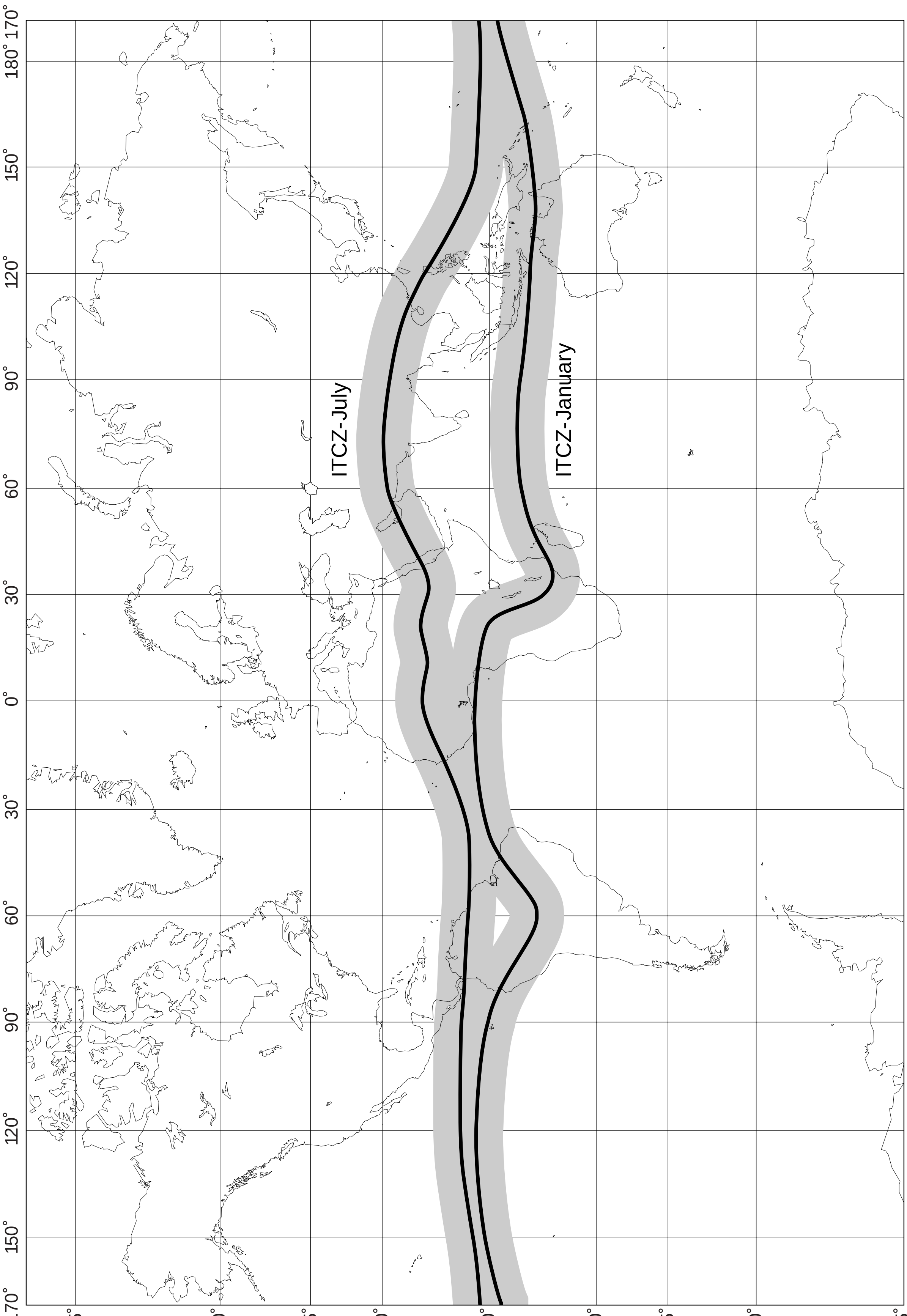


Figure EA-I-17: Average Positions of the Intertropical Convergence Zone (ITCZ) in January and July

Figure EA-I-18: The seasonal variation of carbon dioxide (CO_2) in the atmosphere from 1986 through 1988 measured at Mauna Loa Hawaii

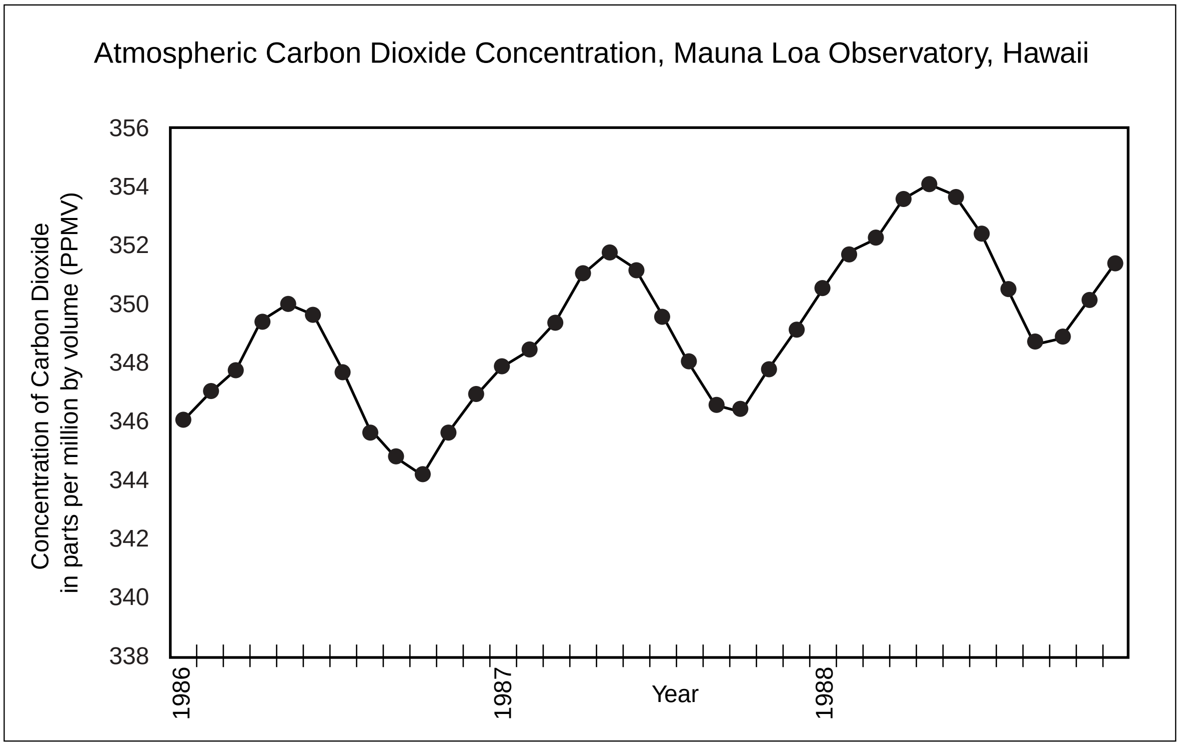
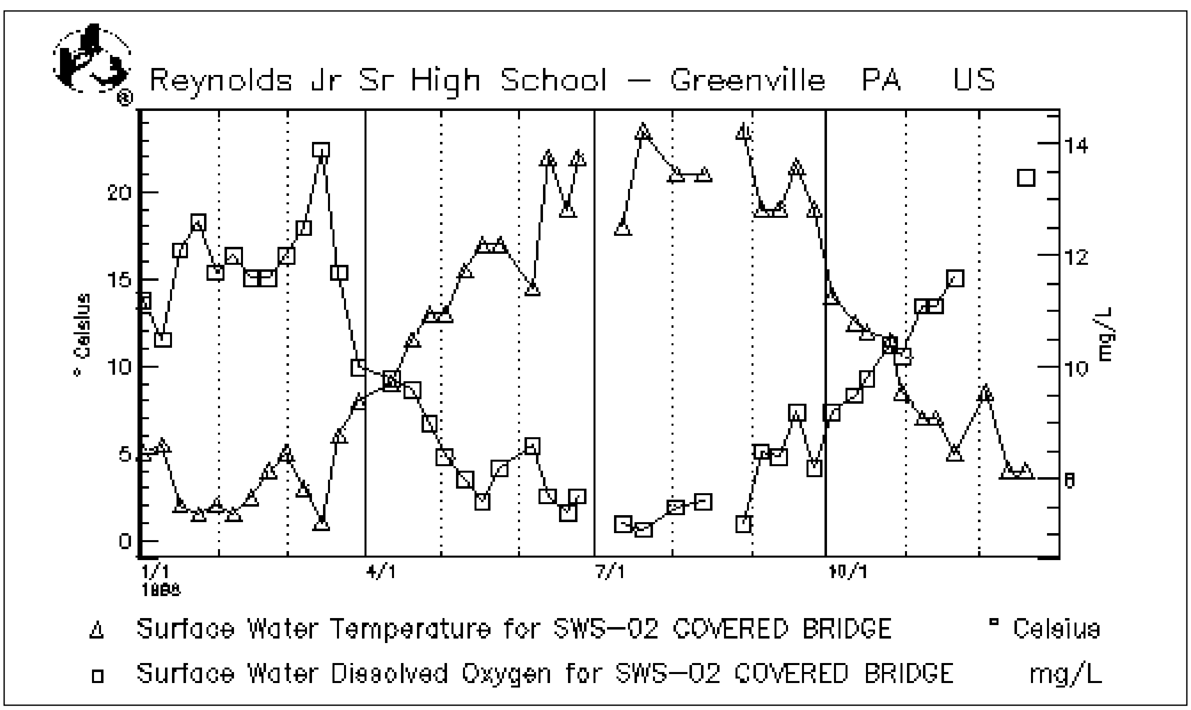


Figure EA-I-19: Surface water temperature and dissolved O_2 at Reynolds Jr. Sr. High School in 1998



sonal cycle of surface ozone concentrations is affected by human activity and is quite variable depending on where observations are made.

Surface Water through the Seasonal Cycle

The physical and chemical characteristics of a body of water are influenced by the seasonal cycle through changes in solar radiation, precipitation, air temperature, wind patterns and snow and ice melting. Figure EA-I-19 shows how temperature and dissolved oxygen (DO) varies throughout the year. The saturation level of DO is inversely related to temperature (i.e. as temperature increases the amount of DO that can be dissolved in water decreases). The observed pattern in any given water body depends on the amount of biological activity.

Seasonal Turnover in Lakes

Many lakes show seasonal patterns of vertical mixing. Lakes in either warm temperate or cold temperate zones show one mixing event (or turnover) in the year. In other temperate regions that bridge temperatures of cold and warm temperate zones or at high elevations in subtropical regions, there are two turnovers. The spring turnover occurs after ice melts. Ice floats because it is less dense than water, which is most dense at 4˚C. As water warms to near 4˚C, the surface water may become more dense than bottom water and sink. Relatively little wind energy is required to mix the whole lake (spring turnover). As spring progresses, the top layers of the lake become warmer and thus less dense. The colder, more dense water remains on the bottom, and a zone of rapid temperature change occurs between the warmer layer on the top and the colder layer on the bottom. This is known as *thermal stratification.* In the fall, with less solar radiation reaching the water and greater heat loss from the surface at night, the temperature stratification breaks down. Eventually the mixed layer extends downward, until the temperature and density differences between the mixed and bottom water become so slight that a strong wind in autumn can overcome any resistance to mixing and the lake undergoes a turnover.

Plant Growth in Lakes, Estuaries, and Oceans

Seasonal changes in water temperature, sunlight, and nutrient availability affect plant life in water bodies.

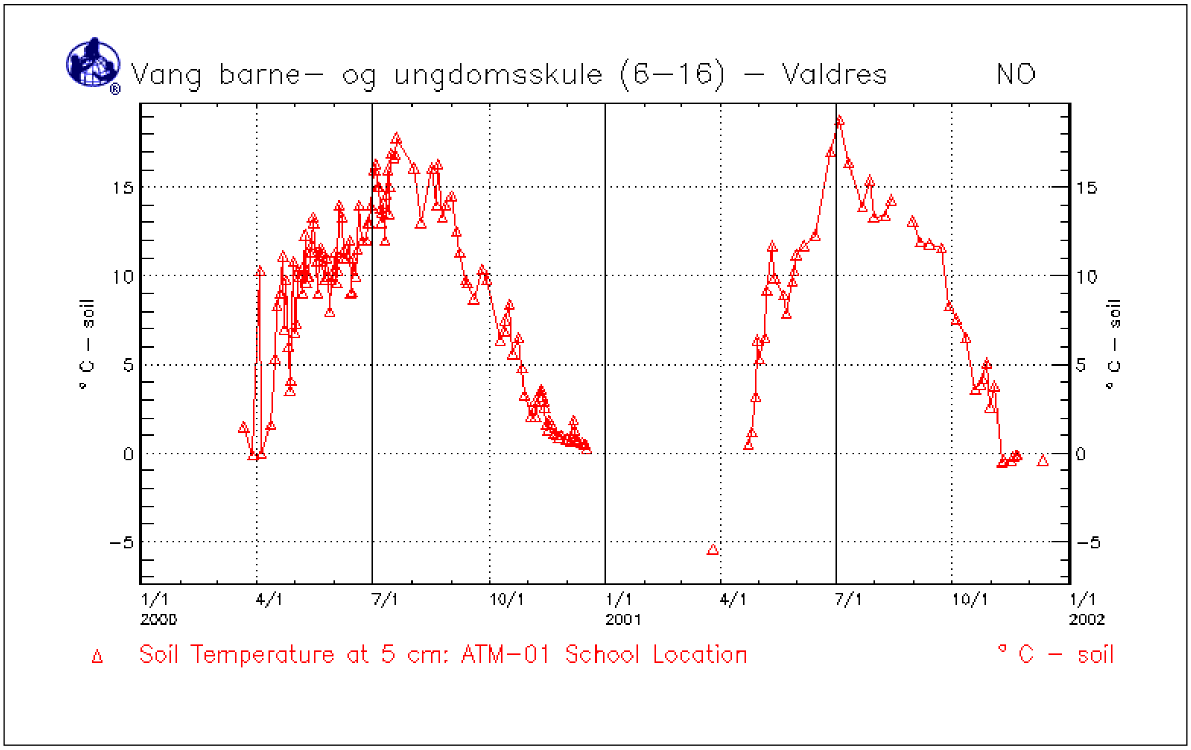
Nutrients tend to fall through the water column, and vertical mixing usually returns nutrients to near the surface and may promote rapid growth in phytoplankton. Increases in plant growth trigger changes in the entire food chain and can result in increased animal growth and reproduction, as well as increased bacterial decomposition. In temperate areas, increases in water temperature and sunlight availability in the spring combine with seasonal increases in nutrients mixed up from deeper water to promote rapid growth. In tropical areas, where sunlight amount and temperature change little throughout the year, changes in wind patterns can result in vertical mixing in oceans, seas and large lakes.

Most of the plant production takes place in surface and near surface waters where light is available for photosynthesis. During the summer months there is little vertical mixing in some lakes and estuaries. Organic matter falls from the surface to deeper waters and is eaten by animals or decomposed by bacteria. These organisms require oxygen. Respiration, lack of vertical mixing and warm temperatures can lead to low oxygen levels. In some places the summer can become a critical period for fish and other creatures that live in bottom waters.

Streams and Rivers

Streams and rivers can show seasonal changes in the amount and composition of water resulting from changes in precipitation, evaporation, snowmelt, and run-off. How these factors affect the biota are areas of active research. Soluble chemicals which have accumulated in the winter snow pack tend to be concentrated in the first melt water and can cause rapid changes (usually decreases) in the pH of streams. The first big rain storm following a prolonged dry period also washes chemicals that have accumulated on roads and other land surfaces into water bodies. The volume of water flowing in a stream or river often affects its water quality. Low flow conditions can permit the buildup of nitrates or the depletion of dissolved

Figure EA-I-20: Seasonal cycle of the 5 cm soil temperature at Vang barne-og ungdomsskule in Valdres, Norway from January 1, 2000 to January 1, 2002.



oxygen. Floods and major rain storms wash large amounts of debris into waterways and can reshape the entire flood plain of a river or stream while transporting soil particles to new locations.

Soil through the Seasonal Cycle

Soil Temperature

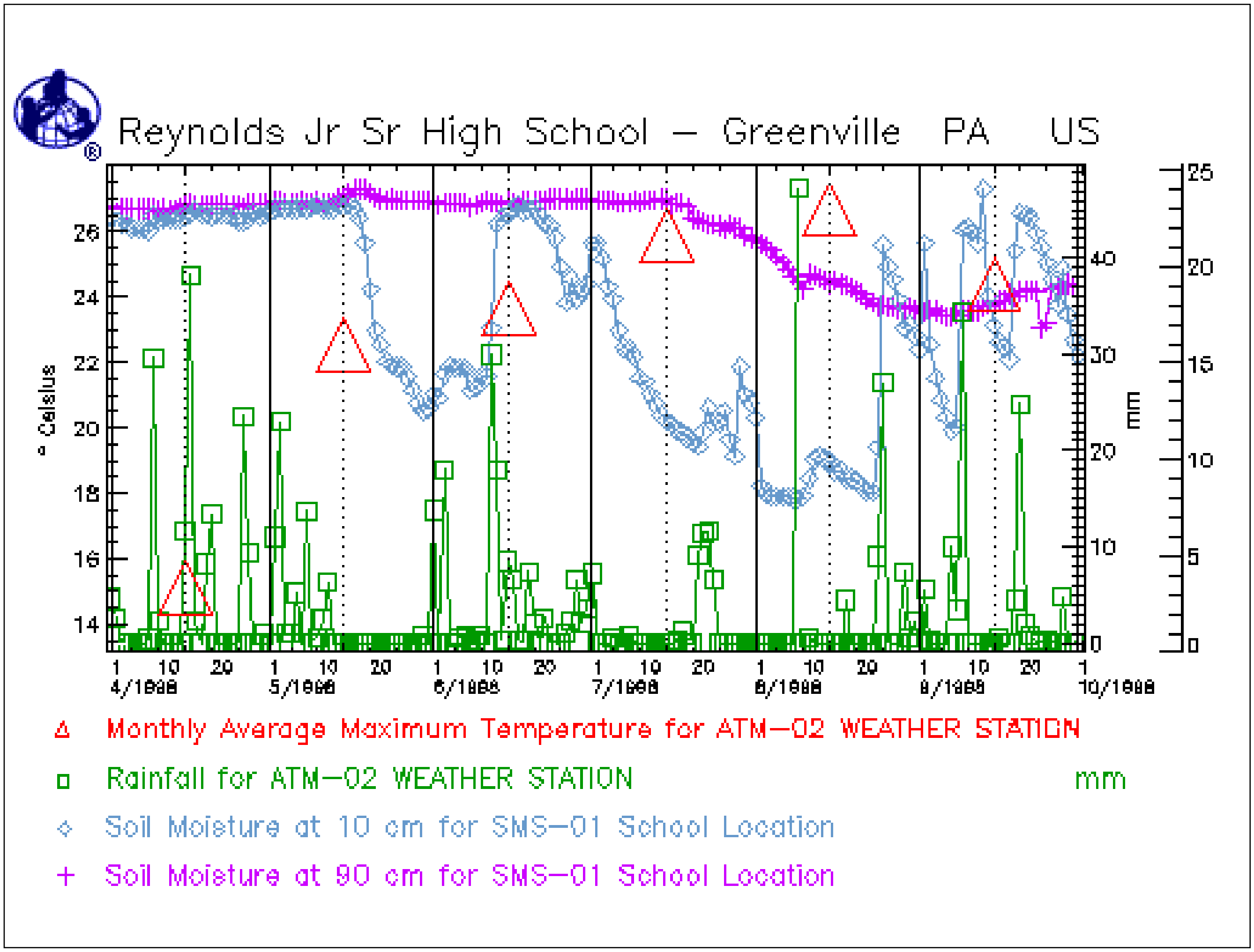
As with the atmosphere and water bodies, the most obvious seasonal change in soils is in their temperature. As the sun gets higher in the sky in the spring the increase in solar radiation warms the surface, increasing the soil temperature.

The soil undergoes a strong daily (diurnal) as well as seasonal cycle in temperature, especially at mid latitudes. See Figure EA-I-20. The soil cycle lags slightly behind the air temperature cycle so that, in general, the soil temperature is slightly warmer than air at night, and is slightly cooler than air in the morning. The lag time will depend on the particle size distribution, the amount of organic matter, and the amount of moisture in the soil. The cycle is most evident at the surface of the soil and decreases with depth. Soil scientists use the temperature at 50 cm to define the Mean Annual Soil Temperature (MAST) which stays relatively constant from year to year. This temperature cycle in soils is important in that it has a strong effect on phenology, influencing when plants will "green up" in the spring, or "die back" in the fall. It also affects the insulation needed for pipes that are buried in the soil to prevent freezing in the winter, and is used to control temperatures in basements and storage areas which are below ground.

Soil Moisture

Another characteristic of soil that changes through the seasonal cycle is the soil moisture. The main source of soil moisture is precipitation. The seasonal variation in soil moisture is controlled by seasonal variations in precipitation and snow melt and by the effect of seasonal variations in temperature on evaporation. See Figure EA-I-21. For example, if the rainy season occurs during the winter, the soil water content will be high, while the summer will be a time of increasing tempera-

Figure EA-I-21: Maximum air temperature, precipitation, and soil moisture at 10 and 90 cm at Reynolds Jr. Sr. High School in Pennsylvania USA from April 1, 1998 to October 1, 1998.



ture leading to higher evaporation and dryer conditions in the soil.

Decomposition

The decomposition of organic material is also affected by seasonal changes. The microorganisms that perform the decomposition process require moisture and heat in order to thrive. Thus, the rate of decomposition of organic material is dependent on the soil temperature and moisture. All of these vary through the seasonal cycle, and so there is a seasonal cycle in the rate of decomposition of organic material. This seasonal cycle may not be as simple as that exhibited by temperature and moisture. This is because the soil microorganisms may die or become inactive when conditions are too hot, too cold, too dry, or completely saturated. In general, the more decomposition, the more CO_2 and N_2O are produced and exchanged into the atmosphere.

Land Cover and Phenology through the Seasonal Cycle

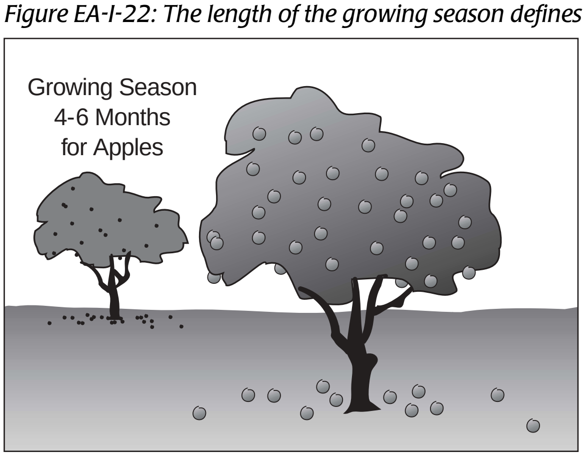
Phenology is the study of living organisms' response to seasonal and climatic changes in the environment in which they live. The GLOBE measurements in the Phenology protocols (this chapter) focus on plant phenology. Seasonal changes include variations in day length or duration of sunlight, precipitation, temperature, and other life-controlling factors. The plant growing season is the period between green-up and green-down (*senescence*). See Figure EA-I-22. Green-up and senescence can be used to examine regional and global vegetation patterns, interannual variation, and vegetation responses to climate change. A change in the period between green-up and senescence may be an indication of global climate change.

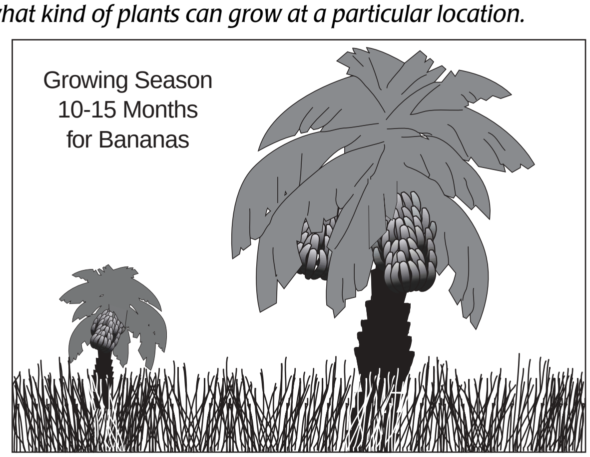
Plant green-up is initiated when *dormancy* (a state of suspended growth and metabolism) is broken by environmental conditions such as longer hours of sunlight and higher temperatures in temperate regions, or rains and cooler temperatures in desert areas. As plants begin green-up, leaf chlorophyll absorbs sunlight for photosynthesis. Photosynthesis fixes carbon dioxide from the atmosphere.

With the start of green-up, plants also begin to transpire water from the soil to the atmosphere. This affects atmospheric temperature, humidity, and soil moisture. During green-down, through leaf fall, plants reduce water loss when water supply is greatly limited during winters for temperate plants, and during dry spells for desert plants.

Monitoring the length of the growing season is important for society because the length of the growing season has a direct effect on food and fiber production and thus on society's ability to support itself. Therefore, in investigating this seasonal variation, GLOBE schools are providing information to scientists so that they can better understand the Earth system and how it responds to various influences and to society so that it can be better prepared to adapt to variations in the length of the growing season.

Figure EA-I-22: The length of the growing season defines what kind of plants can grow at a particular location.





The Earth System on Different Spatial Scales

The Earth as a System at the Local Scale

Components

Each of the GLOBE investigations requires students to choose a study site or a set of sample sites where they will take their measurements. At each of these sites many of the components of the Earth system investigated by GLOBE students are present. At the hydrology study site, for example, air, soil and a body of water are all present. Terrestrial vegetation is often present as well, and for a number of sites, snow or ice – elements of the cryosphere – are present at least some of the year. Figure EA-I-23 is a photograph of the hydrology study site at Reynolds Jr. Sr. High School in Greenville, Pennsylvania, USA where students can identify each of these components and can examine where interactions between the components take place.

Some examples of these interactions are:

- Evaporation and exchange of heat between air and water.
- Exchanges of water and gases between the air and vegetation.
- Exchanges of water and nutrients between soil and the root systems of grasses and trees.
- Evaporation and exchange of heat and gases between air and soil.
- Exchanges of water, chemicals, and sediments between soil and water at the sides and bottom of a water body.
- All of the Earth system components are exposed to the sunlight. This exposure to sunlight affects the temperatures of the various components, the photosynthesis in plants, rates of decomposition in soils, and chemical cycles.

Cycles: Energy, Hydrologic, and Biogeochemical

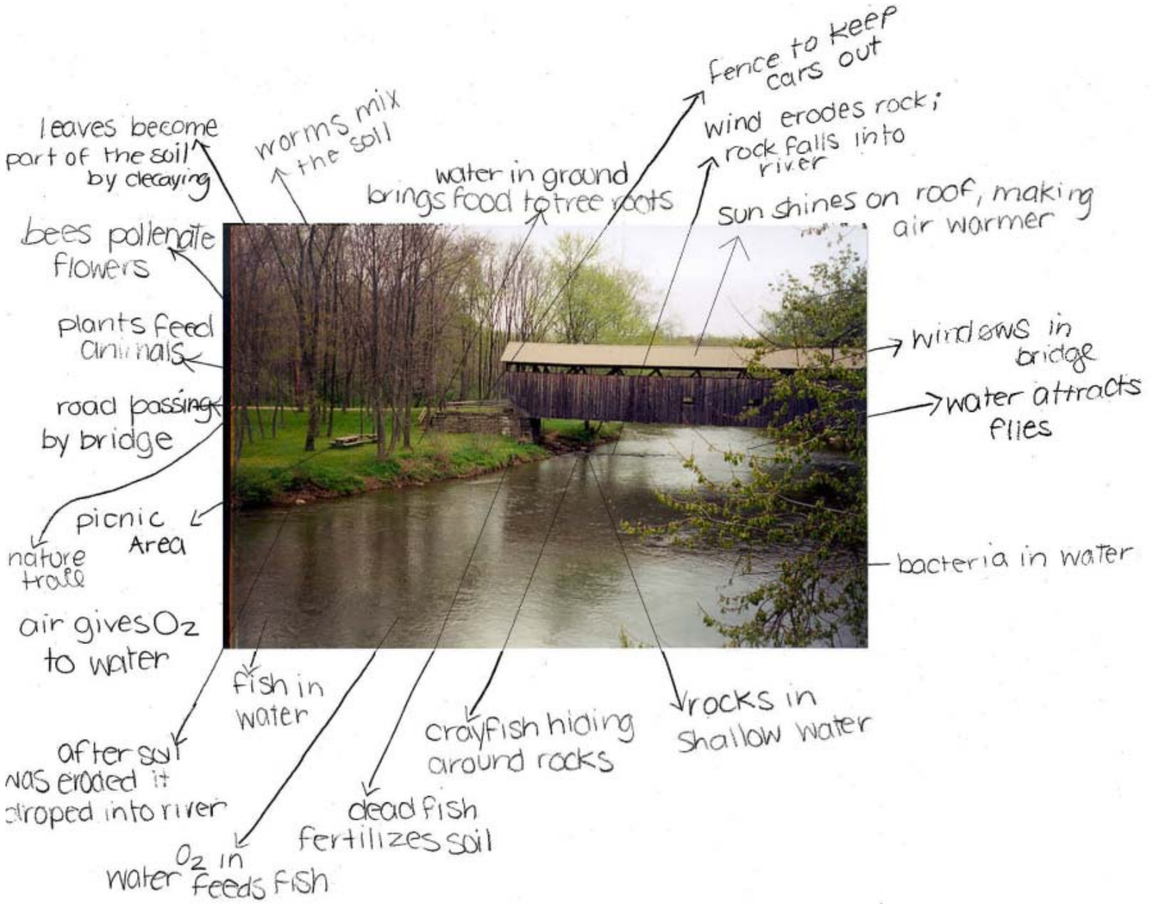
The exchanges among the air, water, soil, and terrestrial vegetation are parts of the energy cycle, the hydrologic cycle, and the various biogeochemical cycles. As an example, let's consider how energy and water are cycling through this site (Reynolds Jr. Sr. High School) and discuss pH, which influences the biogeochemical cycles.

Sunlight strikes the surface of the river as well as the trees, grass, and pavement on the bank. Some of the energy in the sunlight heats the water and the land surface, raising the temperature of the surface soil and water. The remaining energy is reflected back up into the atmosphere. Depending on the cloud cover, some of this energy may be reflected again toward the surface. Water from the river and the soil evaporates, cooling the surface and taking energy into the atmosphere. When the temperature of the air is lower than that of the surface, the air is warmed through contact with the land and water. When the reverse is true, the land and water are warmed through contact with the air. As the soil warms, energy is stored in it. As the river flows, it carries away any energy stored through the warming of the water. Similarly, the air brings energy with it or carries energy away. Precipitation may be warmer or colder than the surface, and the exchange of energy between the rain or snow and the surface will also provide heating or cooling.

GLOBE measurements allow you to track some of the flow and storage of energy. The key measurements are those of the air, surface water, and soil temperatures. With these you can calculate the direct energy exchange between the atmosphere and the surface. Temperature, soil moisture, and relative humidity measurements enable the calculation of evaporation rates from the land and water surfaces. You can compare the amount of energy lost from the surface through evaporation to the direct heat exchange with the atmosphere and determine at what times one is more significant than the other.

In the hydrologic cycle, water is exchanged among the air, river, soil, and land vegetation. Precipitation forms in the atmosphere and then falls onto

Figure EA-I-23: Photograph of the hydrology study site at Reynolds Jr. Sr. High School in Greenville Pennsylvania USA annotated with various interactions between components of the Earth system



the surface – the water, soil, plants, and pavement. Water flows off the pavement and into the soil. Some flows across the surface or through the soil into the river. The various grasses and trees take in water through their roots and lose this water to the atmosphere through their leaves. Some water evaporates from the soil and from the surface of the river. If the surface is colder than the dew point of the air, moisture in the atmosphere will directly condense on the surface. Water also flows into the site from upstream and up hill and flows downstream, out of the site, in the river.

GLOBE measurements of precipitation capture most of the inputs of water from the atmosphere. The flow of water in the river can be calculated if you know the slope of the river bed, the depth profile across the river, and the level of the water. Some hydrology study sites are located on rivers where flow is monitored by government agencies, and these discharge data can be obtained from public databases. Storage of water in the soil can be calculated by measuring soil porosity and soil moisture. Evaporation rates can be calculated by measuring relative humidity and air and surface temperatures. You can see how the soil moisture responds to precipitation and to dry periods as well. You can study whether the river level is influenced by local inputs or primarily controlled by what happens upstream.

The chemical composition of the precipitation can alter the composition of the river water and of the soil, and affect plant and animal life. It can also impact the rate of decomposition of organic material in the soil and of rocks and minerals in the river bed. The pH of precipitation is determined by the gases and particles which dissolve in rain drops and snow flakes. Carbon dioxide in the air tends to give precipitation a pH of about 5.6, while other constituents move this figure up or down. Most combustion-related gases lower pH, while alkaline airborne soil particles raise pH. Chemistry is happening in the soil and the river water as well. If the alkalinity of either is high, the pH will not respond significantly to the different pH of precipitation, but if it is low, the pH will change. Over time, the pH of the soil may change due to the cumulative effects of precipitation. Ultimately the pH of the river reflects the pH of the surrounding soil, of precipitation, and of the water upstream.

GLOBE measurements of the pH of the precipitation, soil horizons, and surface water, and the alkalinity of the surface water enable you to examine the question of how the river pH responds to precipitation events and floods. Over time, a school's dataset may show changes in soil pH. pH variations through the soil profile may also illustrate how pH is changing.

Biogeochemical cycles also promote exchanges between the different components of the Earth system. Examples of these exchanges include:

Exchanges between air and water:
- transfer of oxygen, carbon dioxide, nitrogen, water vapor (through evaporation) and other gases

Exchanges between water and soil:
- storage of water in the soil
- percolation of water through soil into the water bodies or ground water carrying chemicals and particles
- runoff processes.

Exchanges between the soil and land cover:
- use of water stored in soil by the roots of the land cover
- use of nutrients stored in soil
- substrate for plants
- heat storage for plants and microorganisms
- air spaces for exchange of oxygen and carbon dioxide during respiration and photosynthesis

Exchanges between air and land cover:
- evapotranspiration process.

Exchanges between air and soil:
- precipitation and evaporation processes
- heat and energy transfer
- exchanges of gases produced in the process of decomposition of organic material and microbial respiration.

The rates of the exchanges of chemicals between the different components of the Earth system depend on a number of factors. These factors include the type of chemical reactions occurring within the different components, the temperature of the components, the concentrations of the various gases in each of the components and the motion of the components at the interface which promotes exchange.

Earth as a System at the Regional Scale

The processes that allow the components of the Earth system to interact on a local scale, such as a hydrology study site, may also act at the regional scale. See Figure EA-I-24.

What Defines a Region?

The regional scale is larger than the local scale and is generally characterized by some common feature or features that differentiate it from neighboring regions. Regions can be defined in different ways. They can have natural boundaries, human-made boundaries, or political/social boundaries. Some examples of regions are:

Natural

- a watershed
- a mountain range
- a river basin
- a desert
- a plain
- a peninsula

Human-made boundaries

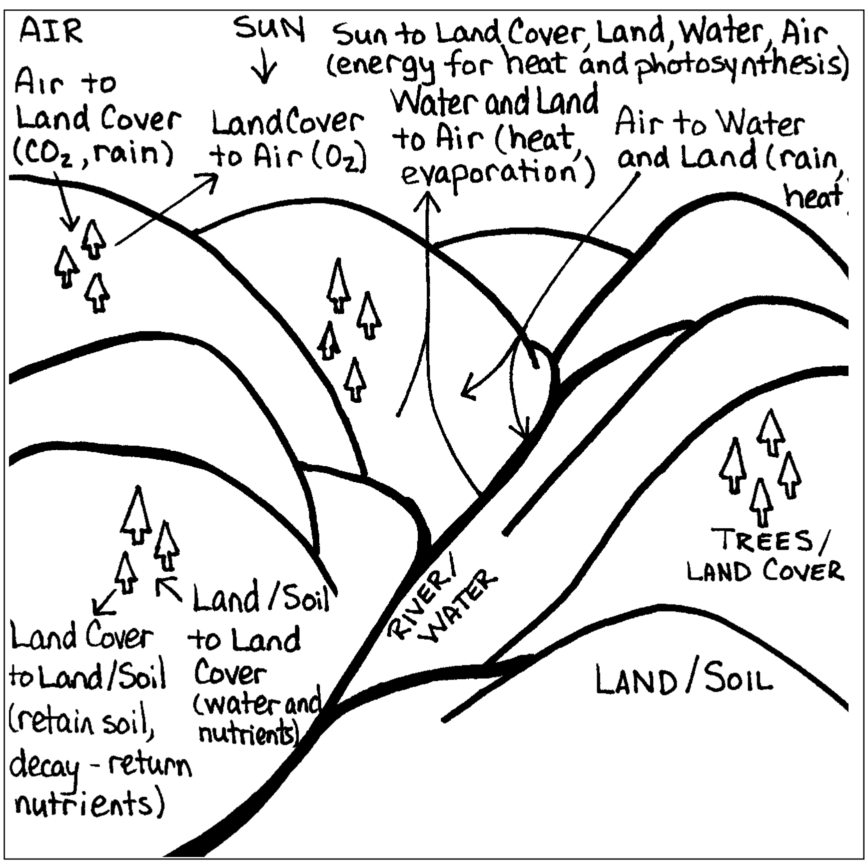
- a watershed in which a boundary is a dam
- an area larger than a local study site bounded by highways, railroads, and bridges
- a natural area surrounded by populated regions or a populated region surrounded by a natural area
- a park or game preserve

Political/social boundaries

- a state or province
- a country

Many of the processes that cause the interactions between the different components of the Earth system at the regional scale are the same as those at the local scale. However, to quantify the magnitude of the processes, measurements generally must be taken at numerous locations throughout the region. For example, if one wants to study the urban heat island effect, temperature mea-

Figure EA-I-24: Diagram of Earth System at the Regional Scale Indicating Interactions Among the Different Components



surements are required within the urban area as well as in the surrounding countryside. Furthermore, temperatures will differ between areas with lawns, plants, and trees, and those which are almost completely covered by buildings and pavement; what is observed in an area that is primarily residential may differ from that in a commercial or industrial area. So in order to get a better representation of the entire urban area, measurements from multiple sites are needed from different sections within the urban environment.

Likewise, suppose you want to develop a hydrologic model for a watershed of a river that flows into an estuary along the coast and the only GLOBE schools in the watershed are near the mouth of the river (where it enters the estuary). Using only these data for the entire watershed may lead to inaccuracies because temperature, precipitation, soil types and textures, and land cover, among other things, may differ greatly throughout the watershed. Measurements must cover more of the watershed to give an accurate model. The lack of spatial coverage for many data is a problem scientists frequently face. Sometimes a gross approximation is the best that a scientist can do with limited data. Hence, the more GLOBE schools taking data, the better!

Inputs and Outputs

In order to understand the Earth system at the regional scale you must consider the inputs and outputs to the region, in addition to the interactions among the components within the region. See Figure EA-I-25 The region may be somewhat closed in the sense that liquid water may not leave it, or it may be open with rivers flowing through it. The atmosphere will always be bringing inputs from outside and carrying outputs away; these include energy, water vapor, trace chemicals, and aerosols. The moving air also brings weather systems into and out of your region, which will affect air temperature, cloud cover, and precipitation.

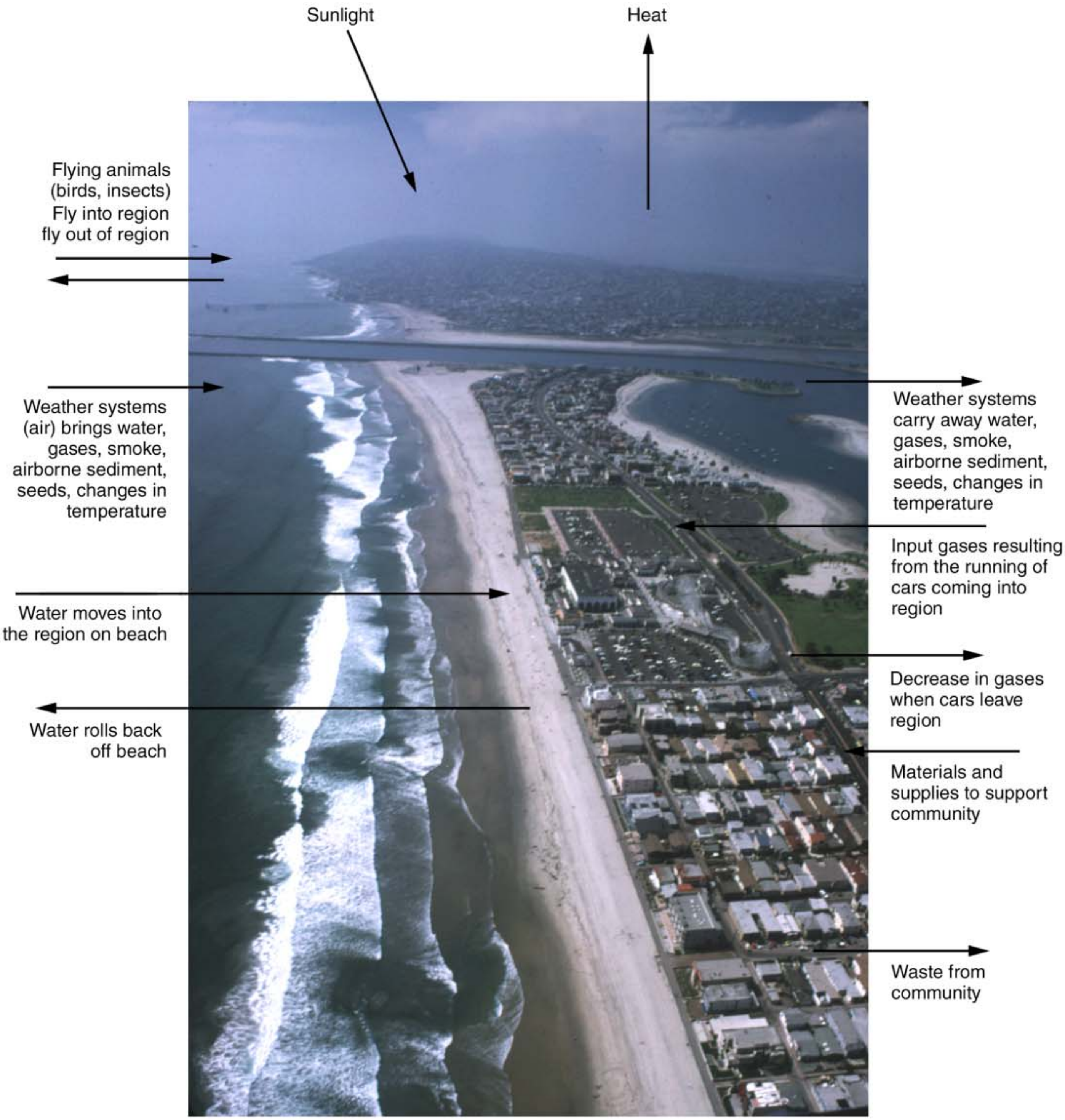
Atmospheric inputs and outputs can greatly affect a region. The air entering your region will bring with it characteristics from upwind. These characteristics can include smoke from an industrial plant or agricultural burning, seeds from a forest or grassland, or moisture evaporated from lakes or rivers. The impact of these characteristics on your region must be considered. Likewise, what leaves your region in the atmosphere will influence other regions. As the atmosphere moves it carries trace gases from a region where they are produced to places where there are no local sources of these chemicals. The worst examples of air pollution happen where air is trapped, usually by mountains or by an *inversion layer* (a layer of air in which the temperature increases as you move from bottom to top) in the atmosphere. The winds also can carry away significant amounts of moisture and dust from a region. Plumes of Saharan dust are so prominent at times that they can be seen on satellite cloud images and the dust is blown all the way across the Atlantic Ocean.

GLOBE schools across a region can cooperate to gain a comprehensive picture of the energy and water cycles within the region and to trace some parts of the biogeochemical cycles. In a watershed, the characteristics measured in the surface water of streams, lakes, and rivers can be measured at a variety of sites. These characteristics are strongly influenced by the microclimate of the region which is quantified by measurements of air temperature and precipitation, the soil character which may vary across the watershed and need to be measured in a number of places, and the land cover. Schools may combine their Landsat images to gain a complete satellite picture of the region and this can become the basis for a comprehensive regional land cover map. The dynamics of the watershed can be studied using GLOBE measurements of specific weather events, soil moisture and infiltration rates, and whatever data are available on the flow rates of the streams and rivers.

Earth as a System at the Continental/ Global Scale

The learning activities in this chapter that are designed to help your students understand the largest spatial scales of the Earth system focus on the continental scale. This is the largest practical scale for meaningful examination of GLOBE data, although it could be considered the largest regional scale. The global scale encompasses the

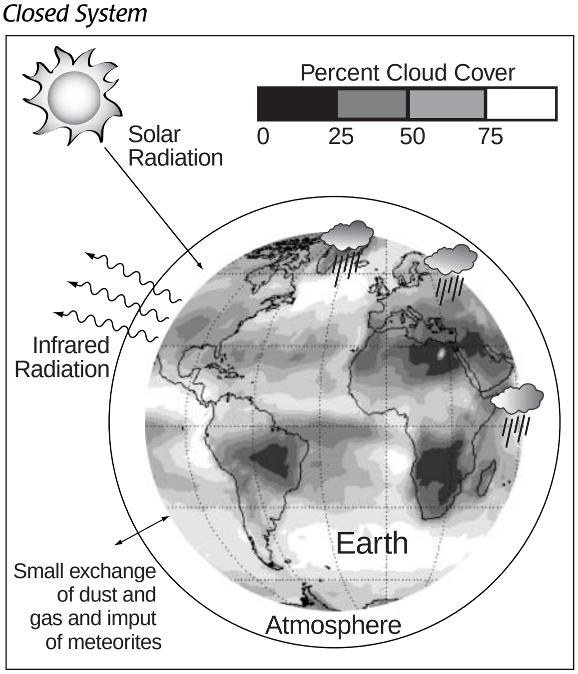
Figure EA-I-25: Photograph of the Earth System on the Regional Scale with Inputs and OutputS



© Weldon Owen Inc. 1998 *Over California* by Kevin Starr. Photography by Rog Morrison

whole Earth, all of the atmosphere, hydrosphere, pedosphere, cryosphere, and biosphere. If one includes the interior of the planet as well, at this scale, Earth is an almost *closed system* - one in which almost no matter enters or leaves. **Note:** An *isolated system* is one in which no *energy* or matter enters or leaves. See Figure EA-I-26. In fact, the Earth system is closed except for the input of energy from the sun, the balancing loss of energy to space, the extremely small loss of hydrogen from the top of the atmosphere, and the continuous input of gases, dust, and meteorites from space, and the few satellites which we have sent beyond Earth's orbit. Studies of Earth system science also treat the inputs of gases, energy, dust, and lava from Earth's interior and the recycling of material into the crust and upper mantle as external inputs to and outputs from an almost closed system. These exchanges with the interior of the planet tend either to happen on long time scales of tens of thousands to millions of years (geologic time) or to happen almost instantaneously and unpredictably. These latter phenomena, particularly large volcanic eruptions, play havoc with short-term climate predictions.

Figure EA-I-26: Diagram of the Earth as an Almost Closed System



How Do the Local, Regional, and Global Scales Interact?

Within the global Earth system the local and regional scales all contribute to how each of the components (the atmosphere, open waters, cryosphere, soil and terrestrial vegetation) interact with each other as a whole at the global scale. These interactions occur on many different time scales – the characteristic times over which processes or events occur.

All of the GLOBE measurements are taken at the local scale but they sample phenomena with various time scales. The maximum and minimum air temperatures address the daily time scale, while tree height and circumference indicate growth over an annual cycle, and characterization of a soil profile may document the results of thousands of years. Most of the learning activities also involve the local scale and shorter time scales. However, some of the learning activities, such as those in this chapter, broaden your perspective to the regional and global scales to help you understand how local scale environments fit into the regional and global scale contexts. These large scales involve changes over long and short periods. Today GLOBE measurements only cover a few years and primarily contribute to studies of current processes and phenomena. Eventually, as the GLOBE database extends further in time, the measurements will contribute to scientific studies on longer time scales of decades to centuries where there are currently major concerns about global climate change.

The following sections describe the various components of the Earth system in the context of the global scale. Understanding these largest spatial-scale processes will help you more fully understand the context for your local study sites, and how the Earth system connects us all.

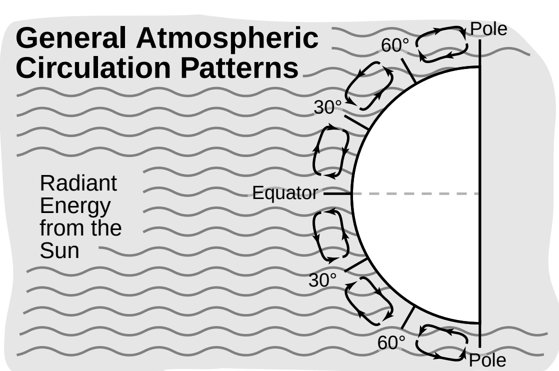
The Earth System Components at the Global Scale: The Atmosphere (Air)

The atmosphere is the gaseous envelope of the Earth. The local properties of the lower atmosphere vary on time scales of minutes to seasons and years. Winds change speed and direction, clouds form and dissipate, precipitation falls, humidity comes and goes, some trace gases such as ozone build up and then go away, and air temperature rises and falls. These local variations are caused by the daily and annual cycles in sunlight and some shifts in ocean circulation such as the El Niño/Southern Oscillation. The overall structure and composition of the atmosphere and the climate change more slowly, on time scales ranging from a decade to millions of years.

As illustrated in Figure EA-I-6. the tropics receive more energy from the sun per unit of surface area than the temperate or polar zones. In fact, even though the warmer tropics radiate more heat to space than high latitude regions, the tropics receive more energy from the sun than they radiate away! Where does this excess energy go? The circulation of the atmosphere and the oceans carries this energy, in the form of heat, to higher latitudes.

If we consider the average north-south motion of the atmosphere, warm air from near the equator rises and moves toward the poles. At roughly 30° latitude, the air cools, falls, and moves equatorward near the surface. A similar pattern exists in the polar zones, with air rising at roughly 60° latitude and falling at the poles. The tropical and polar zones bracket the temperate zones and drive their circulation patterns. As a result, the air in temperate zones moves poleward at low altitudes, rises at roughly 60°, returns equatorward aloft and falls at roughly 30°. The interaction of warm and cold air masses between 30° and 60° latitude produces the succession of low (storm) and high (fair weather) pressure systems that move from west to east in mid-latitudes. See Figure EA-I-27.

Figure EA-I-27 General Atmospheric Circulation Patterns



The Earth System Components at the Global Scale: The Hydrosphere (Bodies of Water)

The hydrosphere encompasses all the bodies of water on Earth including groundwater. At the global scale, it is the oceans and the larger seas that are important. The time scales on which the oceans vary range from a month near the surface, to over a thousand years for deep ocean circulation.

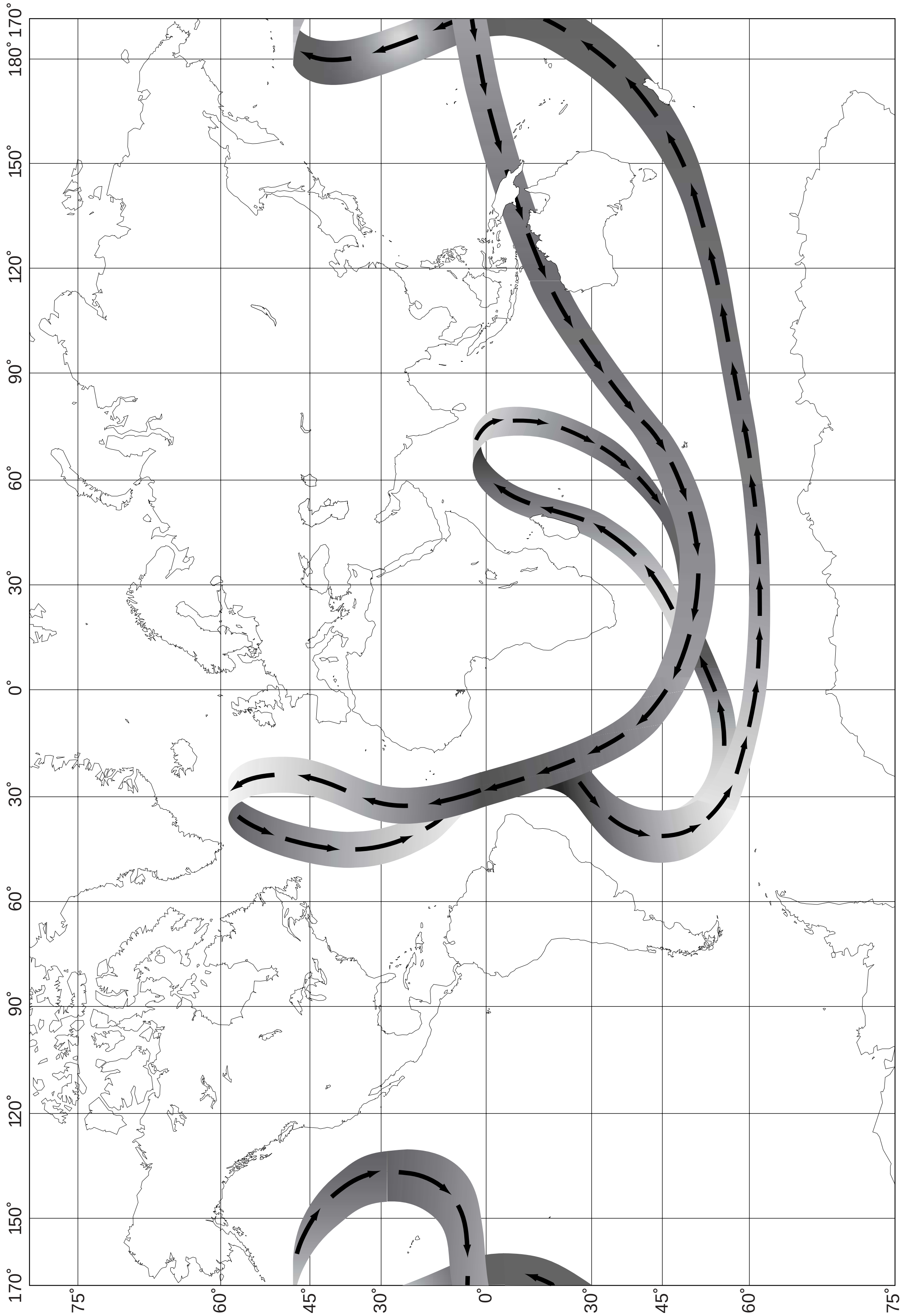
The ocean receives energy from sunlight transmitted through the atmosphere. The *albedo* (reflectivity) of the oceans is relatively low, about 0.1, which means that 90% of the solar radiation falling on the ocean surface is absorbed. The oceans also exchange long wave (thermal infrared) radiation with the atmosphere.

Ocean Circulation

Circulation within the oceans occurs through two basic processes. The first is the horizontal circulation of the upper ocean that is driven by forces induced by surface winds. This surface circulation is coupled to deep ocean circulation (thermohaline) that is driven by differences in the density of seawater due to changes in temperature and salinity. During winter in the polar regions, the ocean surface cools and sea ice forms. As the water freezes, most of the salt is left dissolved in the liquid water. This increase in salinity, particularly in the north Atlantic, causes the surface water to become dense enough to sink and to become bottom water. This bottom water flows toward the equator and eventually returns to the surface. Scientists call this global circulation of ocean waters a conveyor belt which connects the surface and deep waters of the Atlantic, Pacific, and Indian Oceans. See Figure EA-I-28.

The ocean surface is in direct contact with the atmosphere. Large exchanges of aerosols and gases take place at this boundary. Gases that are more abundant in the atmosphere, such as carbon dioxide, are taken up in the ocean water while gases formed in the oceans, such as methyl bromide, are released into the air and are the largest natural sources of some atmospheric trace gases. These processes happen much faster than the thermohaline circulation of the oceans. Today's surface seawater is in equilibrium with the present com-

Figure EA-I-28: The Large Scale Circulation of Water in the World's Oceans, Sometimes Called the Global Conveyor Belt



position of the atmosphere, but gases dissolved in bottom water reflect atmospheric conditions from roughly 1500 years ago. Through this gradual overturning of ocean water, gases, such as carbon dioxide, whose atmospheric concentration have increased over the last 1500 years, are gradually taken up by the ocean, lessening their abundance in the air.

Biological Activity

Biological activity is also affected by circulation patterns around the globe. There are areas, for instance, where *upwelling* occurs. Upwelling is the process by which deep, cold, nutrient-rich waters rise to the surface. *Phytoplankton,* microscopic plants floating in the water, form the base of the ocean food chain, and their abundance limits the populations of most other ocean creatures. Where ocean surface waters lack nutrients, growth and reproduction of phytoplankton are limited. Areas where upwelling occurs are generally nutrient-rich and highly productive and have large commercial fisheries.

Biological activity in the oceans plays a major role in the global carbon cycle. Phytoplankton in near surface waters take up carbon through photosynthesis. Some dead organic matter such as shells of microscopic organisms or fecal pellets from animals fall through the water column to the ocean bottom and become buried in sediments. Here in the deep ocean, the carbon in the organic matter is essentially removed from the atmosphere.

The Earth System Components at the Global Scale: The Cryosphere (Ice)

The Role of the Cryosphere in Energy Transfer

The cryosphere is the solid water component of the Earth system. The two main forms of ice are sea ice and continental ice. Either can be covered with snow. Ice has an albedo (reflectivity) that ranges from about 0.5 to 0.8. This is generally higher than what's underneath it. The albedo of newly fallen snow ranges even higher, up to 0.9. So, where covered by ice, Earth's surface reflects more than half the solar radiation falling on it back to space. Ice and snow also insulate Earth's surface, cutting off evaporation which removes a major source of heat to the atmosphere above.

Sea Ice

Sea ice is frozen seawater. If the water is salty, as it is in the ocean and the seas, during the freezing process the salt is left in the water, making the water saltier and denser, and the sea ice less salty. Sea ice floats on the ocean/sea surface and ranges from thin frazzle ice which has just formed and barely coats the surface, to thick ice, which has lasted through many years and may be up to 10 m thick. However the average ice thickness is 3 meters in the Arctic and 1.5 meters around Antarctica. Under the stress of wind and ocean currents, sea ice cracks and moves around. The cracks expose areas of relatively warm ocean water to the cold atmosphere during winter. In winter, this permits a large exchange of energy from high latitude oceans where the water temperature is just about freezing to the atmosphere where air temperatures are well below zero.

Sea ice has a large seasonal cycle and changes on time scales of a few weeks to a few months. The magnitude of these seasonal changes is very sensitive to climate conditions in the atmosphere and oceans, extending the time scales associated with sea ice variations from months to tens of thousands of years–the time scale for ice ages.

Land Ice

Continental ice includes ice sheets such as those in Antarctica (up to 4 km thick) and Greenland (up to 3 km thick), and valley glaciers (generally 10-100 m thick). Most of the fresh water on Earth is frozen in these ice sheets. Continental ice is formed from snow accumulating at the surface and compressing over time into ice. This process is very slow compared to the changes in sea ice. Ice sheets change on time scales ranging from months (for rapidly moving valley glaciers) to tens of thousands of years. These longer changes are associated with ice ages.

Even when frozen, water still flows from the mountains to the oceans. When snow falls in winter, melts in the spring, trickles into a mountain brook, flows into a stream and then a river, and finally into the ocean, the water's journey is completed in a year or less. When the snow falls on a glacier, the journey becomes much longer and lasts for many years. The deep layers of the

Greenland ice sheet which have been sampled with ice cores record conditions when snow fell over 250,000 years ago and are a major source of information about longer-term changes in climate.

The Earth System Components at the Global Scale: The Pedosphere (Soil)

The *pedosphere* is the portion of Earth's land surface covered by layers of organic matter and of weathered rocks and minerals which are less than 2.0 mm in size together with the organisms that live in these layers. The surface temperature of the pedosphere responds quickly to the daily and seasonal cycles in air temperature, changing on time scales ranging from hours to months. The albedo of bare soil averages about 0.3, meaning that 70% of the solar radiation falling on it is absorbed. However, there are many different soil types, so this number varies from place to place and from season to season. The land surface is often covered by vegetation which intercepts the sunlight before it reaches the soil.

Just like the atmosphere and the ocean, there are movements within the pedosphere and lithosphere that act to redistribute the energy received from the sun. Conduction, convection, and radiation processes all operate within the soil to redistribute energy within the soil profile. The rate and amount of distribution depends on soil properties such as the particle size distribution, bulk density, water content, and organic matter content.

The pedosphere forms as a result of the interaction of the five soil forming factors: parent material (the mineral or formerly living material from which the soil is derived), climate (both macro- and micro-climate), topography (including slope, position, and aspect), biota (plants, animals including humans, and all other organisms), and the amount of time for which each of the other factors has interacted. Four major processes occur in response to the soil forming factors: additions, losses, transfers, and transformations. The processes of addition include inputs such as heat and energy, water, nutrients, organic matter, or deposits of materials. Losses of energy and heat, water, nutrients from plant uptake or leaching, and erosion of soil material also take place. Transfers occur when materials within the soil, such as water, clay, iron, plant nutrients, or organic matter are moved from one horizon to another. Lastly, transformations include the change of soil constituents from one form to another within the soil, such as liquid water to ice, large particles to smaller particles, organic matter to humus, and oxidized iron to reduced iron. Each of the five factors and the corresponding four processes produce a localized soil profile with specific characteristics and horizon attributes.

Under well drained conditions, when respiration of organisms and roots in the soil is at its optimum, a great deal of CO_2 is produced. The percentage of CO_2 in the soil can be 10 to over 100 times greater than in the atmosphere above the soil. This soil CO_2 becomes a source to the atmosphere as it diffuses upward to the surface, or is released when the soil is disturbed from plowing or other turnover processes. Respiration is only one source of soil CO_2 to the atmosphere. Soil organic matter decomposition provides another very large pool of CO_2 and CH_4 to the atmosphere.

Nitrogen is the most abundant element in the atmosphere, yet it is not in a form that is available to plants, and is often the most limiting nutrient for plant growth. Soil organisms and certain processes help to convert atmospheric N_2 into a form plants can use. These forms are nitrate (NO_3^-) or ammonium (NH_4^+). Other organisms convert organic forms of nitrogen from plant and animal remains into plant-usable forms. Nitrogen can also be removed from the soil and become a source of nitrogen to the atmosphere and to ground or surface water.

The Earth System Components at the Global Scale: Terrestrial Vegetation (land plants)

Land plants connect the soil and atmosphere. Individual plants form this connection on time scales ranging from a few weeks to over 1000 years. However, land vegetation collectively affects the Earth system on time scales of seasons to thousands of years and longer. As land plants grow they reshape the environment around them. They shade the surface, block the wind, intercept precipitation, pump water from the ground into the air, remove nutrients from soil and some trace gases from air, hold soil against erosion, and litter the ground with leaves and twigs which eventually increase the organic content of the soil. In these ways, terrestrial vegetation plays a significant role in the energy, water, and biogeochemical cycles. The expansion and growth of forests in particular removes carbon dioxide from the atmosphere in significant amounts.

Educational Objectives

Students participating in the activities presented in this chapter should gain scientific inquiry abilities and understanding of a number of scientific concepts. These abilities include the use of a variety of specific instruments and techniques to take measurements and analyze the resulting data along with general approaches to inquiry. The Scientific Inquiry Abilities listed in the grey box are based on the assumption that the teacher has completed the protocol including the *Looking At the Data* section. If this section is not used, not all of the Inquiry Abilities will be covered. The Science Concepts included are outlined in the United States National Science Education Standards as recommended by the US National Research Council and include those for Earth and Space Science and Physical Science. The Geography Concepts are taken from the National Geography Standards prepared by the National Education Standards Project. Additional Enrichment Concepts specific to the atmosphere measurements have been included as well. The gray box at the beginning of each protocol or learning activity gives the key scientific concepts and scientific inquiry abilities covered. The following tables provide a summary indicating which concepts and abilities are covered in which protocols or learning activities.