Chapter 13: The Energy Balance of the Earth

Goals of Period 13

Section 13.1: To describe the energy balance of the Earth
Section 13.2: To discuss climate and weather patterns
Section 13.3: To define the biosphere
Section 13.4: To illustrate unpredictability in the environment
Section 13.5: To discuss computer simulations and the environment

13.1 The Energy Balance of the Earth

The Earth receives a constant influx of solar energy. Some of this sunlight is immediately reflected by clouds or snow cover back into space. Most of the rest is absorbed by the atmosphere or the surface of land and oceans and converted into thermal energy. The warming effect of sunlight is very familiar to everyone. However, if all of the thermal energy were trapped by the atmosphere, it would to warm up our environment very quickly to the point where rocks, for example, would melt. What actually happens is quite different.

In effect, all of the solar energy incident on the Earth eventually escapes back into space. There is a balance between the influx of solar energy and an outflux of radiant energy back into space. That is, in addition to simply reflecting sunlight back into space, the Earth's surface and atmosphere behave as any other heated object by radiating energy with a spectrum characteristic of its temperature. The spectrum is primarily in the infrared. Figure 13.1 illustrates the overall energy balance of the Earth.

Fig. 13.1 The Energy Balance of the Earth

This is not the end. We have simply said that all of the incident solar energy escapes back into space either reflected as visible light or radiated as infrared radiation. There is much going on in the atmosphere, on the land, and in the oceans that depends on solar energy. Without the influx of sunlight, the atmosphere and surface of the earth would cool very quickly. The atmosphere would condense and solidify. The oceans would freeze solid. Life as we know it cannot thrive under these conditions.

13.2 Climate and Weather Patterns

How does solar energy power the weather? This is a simple question with a complex answer. We cannot discuss all of the dynamics of the weather. However, the following discussion gives a taste of the complexity. The weather, and more generally the overall climate, is important for obvious reasons. For example, the colder it is, the more energy we need to warm our homes. The weather also provides sources of power, such as wind power and water power, suitable for human needs. We will see how solar energy is responsible for powering the weather.

First we consider the water cycle. Solar energy, incident on the world's oceans, evaporates water. The rising water vapor condenses on small dust particles in the air to form clouds. Under the right conditions, the water precipitates as rain or snow to the Earth's surface where it eventually returns to the oceans. If precipitation falls on land, the water may flow downhill as rivers to the ocean. Energy of water flowing in rivers, water power, is a valuable source of energy for people.

Clouds are an integral part of the water cycle and play an important role in the energy balance of the Earth. Clouds have two competing effects. The first is a cooling effect, since clouds reflect incoming sunlight. The second is a warming effect, since clouds prevent infrared radiation from escaping into space; water vapor is a "greenhouse gas." We note that it is difficult, if not impossible, to predict what would happen if there were either a significant increase or decrease in the global cloud cover.

Next, we consider how air is set in motion by solar energy. If air is unevenly heated, it will tend to flow. Consider what happens when sunlight passes through the air and is absorbed by the ground. The ground and the air immediately above it are warmed. The warmed air will rise with cooler air from above replacing it leading to a flow or convection of the air. Hot-air balloons use this principle that warm air rises.

On a larger scale, since the Earth is warmed rather unevenly by solar energy, great air masses are set in motion. The warm air tends to rise over the cooler air. As we will see in more detail, regions near the equator are heated more than regions closer to the poles. The result is a general tendency of air to be exchanged between the equatorial region and the polar regions. The rotation of the Earth causes the moving air to swirl, as in the familiar storm patterns we see on television weather reports. This extremely complex behavior of the moving and swirling air masses, and other factors such as the amount and type of precipitation, determine the general climate of a given area. On a smaller scale, moving air is wind. The energy of the wind is a valuable source of energy.

13.3 The Biosphere

The part of the world in which life can exist is called the biosphere. Living things depend on many factors, however solar energy is the source of energy on which they ultimately depend. As already pointed out, the warmth provided by sunlight is an example of how living things depend on solar energy. Living things also depend on solar energy for photosynthesis, a process we discussed in Chapter 7. Green plants contain chlorophyll that they use to convert solar energy into chemical energy. The chemical energy produced by the green plants is stored as chemical energy in the energy of sugars and carbohydrates.

Besides using the chemical energy in their own metabolism, green plants are at the base of the food-chain. Animals and non-green plants, such as mushrooms, consume green plants or other animals who consumed green plants for their own sustenance. For example, people may eat animals who ate grass and mushrooms, which grow on rotting wood. Ultimately, living things derive their sustenance from solar energy.

Much of the energy we use is derived from organic material. Plant material or animal waste used as a fuel is called ***biomass***. Wood is an example of biomass when it is burned to heat a home. Another example of biomass is alcohol. Alcohol, distilled from fermented corn, is commonly added to gasoline to form gasohol in a ratio of about 10% alcohol and 90% gasoline.

Related to biomass are the fossil fuels such as oil, coal and natural gas. These materials were formed when huge amounts of organic matter were buried millions of years ago. Under favorable conditions of high pressures and temperatures, the buried organic matter was transformed into the fossil fuels. Because fossil fuels originated as biomass, we may consider the chemical energy of fossil fuels as a derived from solar energy. However, fossil fuels are not renewable on a useful time scale, and burning them releases carbon dioxide and other potentially harmful chemicals into the atmosphere.

13.4 Unpredictability and the Environment

In this period we will use relatively simple and familiar systems as examples to illustrate the essential features of more complicated systems such as the weather and the global climate. To begin, we define and classify a system according to its general nature. Any entity that changes with time is called a ***system***. Specifically, a system will be characterized by a *sequence of events* and a *set of rules* that define the possible events and any relation between these events.

In discussing decay of unstable nuclei, we pointed out that the decay was random, but with predictable aspects. That is, during one half-life, one half of the unstable nuclei will decay and one half will not. However, given 100 unstable nuclei, it is impossible to predict which 50 will decay and which 50 will not. Furthermore, with a number so small as 100, we cannot be sure that exactly 50 will decay during one half-life. What we can say is that for many, many samples of 100 nuclei, *on average* 50 nuclei per sample will decay during one half life.

In the case of weather, the question of predictability becomes even more complicated. Weather is an example of a deterministic system. However, sometimes weather is predictable and sometimes it is not.

Deterministic Systems

A ***deterministic system*** is a system in which there is a well-defined relation between successive events. Specifically, not only do the rules of the deterministic system define which events are possible, but they also provide a method with which each successive event may be determined from the previous events.

Deterministic systems are familiar in everyday experience. A swinging pendulum is one example. Newton's Laws govern its motion and many other physical systems. In the pendulum system, each successive motion evolves continuously out of the previous motion. The position and velocity of the pendulum bob completely characterize the future motion of the pendulum.

Under given circumstances, however, behavior in a deterministic system can be predictable only in principle. In more complicated systems, such as weather systems, there are many variables that uniquely describe each event and complicated relations between these events. The evolution of such complicated systems is difficult or impossible to predict reliably. Nevertheless, these complicated systems are deterministic and not random.

Sensitive Systems

We now consider such sensitive systems. A ***sensitive system*** is a deterministic system that exhibits an inherent long-term unpredictability. The essential reason for this long-term unpredictability is that the system is greatly influenced by small disturbances or perturbations. That is, small changes can produce very large results. Such as system is often referred to as a chaotic system.

The actual long-term behavior of any deterministic system depends on its initial conditions. However, a system can be so sensitive to its initial conditions that the long-term behavior of such a system does not *appear* to depend on these initial conditions. For contrast, if we are given the initial conditions of a predictable system, its long-term behavior can be reliably forecast. Small disturbances will not significantly influence the long-term behavior of such a predictable system.

Some systems can behavior chaotically under some circumstances and predictably under others. Determining under which circumstances a given system is chaotic is not easy. However, a practical method to identify chaos is as follows: Observe the behavior of two identical deterministic systems, each beginning with similar, but not identical, initial conditions. If the future course of events of these systems remains similar, the systems are predictable and non-chaotic. However, if the future course of events of these systems diverge so that each behaves completely differently from the other, the system is unpredictable and chaotic.

The sensitivity to initial conditions or small perturbations is popularly called the ***butterfly effect***. The butterfly effect is named from the apparently unpredictable nature of weather patterns. The flapping wings of a butterfly may eventually influence the future course of the weather on the other side of the Earth. However, we cannot take this too literally, since the weather does not always behave chaotically. In a sensitive system, small influences lead to large changes in overall behavior.

Nearly 50 million residents of the eastern United States and Canada experienced first hand the result of a small perturbation to a sensitive system when a major power failure occurred on August 14, 2003. This power failure lasted more than 24 hours for many utility customers and was much more extensive than the 1977 blackout in New York City described in the lecture video, The Hidden City.

The initial condition responsible for the 2003 power outage appears to have been untrimmed tree limbs that sagged onto several power lines, causing the lines to short circuit. Actions that could have prevented the shorted lines from causing a major blackout were not taken due to problems with the computer and alarm systems of the energy company's control room. These failures were exacerbated by a technician who fixed a malfunctioning computer program but forget to turn it back on before leaving for lunch. Throughout the afternoon of August 14 additional power lines failed. However, no action was taken by the electric utility to prevent a major power outage due to the inoperative alarm system, computer failures, and operator errors. Approximately four hours after the first indication of problems, the power line failures cascaded into a blackout across eight states and two Canadian provinces. A very large effect – the worst blackout in our nation's history – appears to have been caused by small perturbations – tree limbs overhanging power lines and a forgetful technician.

Example of a Sensitive System

Water flowing from a faucet illustrates a simple sensitive system. The chaotic nature of this system shows up as turbulent flow and is similar to much more complicated weather systems.

Consider water flowing from a non-aerated faucet. We assume that the flow is reduced so that there is a smooth but narrowing column of water emerging from the faucet. There is a specific location above the bottom of the column where the smooth flow breaks up into a turbulent flow. Above this location, where the column is smooth, the flow of water is predictable and not chaotic. Each molecule of water follows a well-defined path. However, below this location, in the turbulent part of the column, the water behaves chaotically. Figure 13.2 on the next page illustrates this situation.

We define the path of a small bit of water as a ***sequence of events***. The rules with which a path is determined are rather complicated because the path of the small bit of water depends on the flowing water surrounding it. However, we realize that this system is deterministic. The initial event is specified by how the tiny bit of water emerges from the faucet.

Figure 13.2 Predictable and Chaotic Water Flow

Consider two nearby bits of water emerging from the faucet. The flow of these two bits of water corresponds to two nearly identical systems with very similar initial conditions. As the two bits of water flow in the smooth column, they stay very close to each other. This smooth flow indicates a predictable, non-chaotic behavior.

However, when the nearby bits of water enter the turbulent flow, they bounce and splash about with the result that their eventual paths are very different. After the bits of water enter the turbulent flow, the most reliable prediction about their motion is to specify when they will hit the bottom. This turbulent flow is chaotic.

We saw another example of turbulent flow when discussing human-powered flight in Physics 103. The flow of air over the wing of an airplane is initially smooth and predictable, but as the air moves over the wing, it may become chaotic and result in drag. The lecture video *The Light Stuff* discussed several methods the Daedalis crew used to try to minimize drag.

13.5 Computer Simulations and the Environment

Computer Models and Chaos

The advent of the computer has provided a powerful tool to determine whether a complicated system might exhibit chaotic behavior, using a process known as ***computer simulation***. A computer is perfectly suited to solve a multitude of equations quickly and a computer simulation allows a person to carry out experiments without actually doing them. For instance, physicists write programs that predict the way particles in a star interact. By slightly changing initial conditions, they can simulate processes in a star to see if the results match observed phenomena. In this way, scientists can experiment with a star without having one in the lab. Computer simulations are beneficial when the event that needs to be studied could be dangerous, such as learning to fly a plane, or expensive, such as designing a building. Computer simulations are used extensively for these purposes, as well as for entertainment.

When many factors are involved in a problem, we can benefit greatly from a computer program that does the calculating for us. In this way, a large number of trials allow the experimenter to determine how the desired outcome might be brought about. Physicists and other scientists use computer simulations to study problems that have a complex mathematical base or that depend upon a large number of variables. The computer allows many calculations to be done quickly.

An important aspect of being able to do many calculations so fast is that we can determine which systems are stable and which systems are subject to large changes from small effects. For example, when simulating the weather we sometimes find that, in the near future, even if we make large changes in input data, we still get the same result. Suppose, for example, that in our locality all simulation calculations predict sunshine. As a result, we can say with certainty that there is a 100% chance of sunshine tomorrow. Likewise, if all the simulations produce rain for tomorrow, then we can predict rain with 100% certainty.

Often, however, some simulations predict one result – sunshine – and others predict another result – rain – in the same location at the same time. In this case, the system is behaving chaotically; the system is very sensitive to the initial conditions of the input data. If out of 100 simulations, 60 predict sunshine and 40 predict rain, then we say that there is a 40% chance of rain tomorrow.

Computer Simulations and the Environment

In predicting the environmental impact of actions we might take, we often find that we get only a prediction of the *probability* that a certain result will occur. This means that the system is unstable and is subject to chaotic behavior. When this occurs, it is a sign that we should undertake such action only with extreme caution because we cannot predict with certainty what the result will be. Questions of global warming often fall into this category, as discussed by Dr. Ellen Mosely-Thompson in the lecture video *Earth in the Hot Seat*. Dr. Mosely-Thompson points out that politicians do not like to be given answers to specific questions in terms of probable results. They are much more comfortable with knowing precisely what will happen if a given action is taken. This is a limitation of computer models of physical systems, even if we use very sophisticated analyses to set up such programs.

Problems with Computer Simulations

It is also important to remember that simulations are severely limited in their power, in that they can only reflect reality to the extent it is understood or the simulation is programmed to emulate. Many simulations model very complex systems. Stock market simulations predict the behavior of the stock market given conditions and events in the world. The world, however, is a very complex system and cannot be simulated in detail. For instance, a war in one part of the world can have great influence on the world economy – often in unpredictable ways. Another example might be a large investment company's decision to cash in on a heavily-invested stock. Their move can cause an avalanche of selling and affect the entire market. Even consumer confidence is important in this system. If many people are pessimistic about the economic future, investment can be affected. Simulations can only predict the predictable.

Period 13 Summary

13.1: Energy Balance of the Earth: The total energy in to the Earth from the Sun must equal the total energy radiated out to prevent the Earth from heating up.

Of the total energy influx from the Sun (mostly UV, visible, and near infrared radiation)

30% is reflected off of water vapor and particles in the atmosphere and never reaches the Earth,

20% is absorbed by air and clouds and

50% is absorbed by the surface of the Earth.

To preserve the Energy Balance and prevent the Earth from heating up, 100% of the total energy absorbed by the Earth must be radiated away from the Earth (mostly as far infrared radiation).

13.2 Water Cycle: Solar energy drives the water cycle

Water from oceans and lakes evaporates when radiation from Sun warms the water surface.

Water vapor rises, is cooled, and condenses on dust particles, forming clouds.

When clouds become saturated, precipitation falls as rain or snow.

Precipitation eventually runs back into lakes and oceans and the cycle repeats.

Winds: Solar energy contributes to winds

Heated air at the equator rises to higher latitudes. Cooler air from higher latitudes flows toward the equator. This convection mixes warm air equator air with cooler high latitude air.

The spinning of the Earth (Coriolis effect) also produces global wind patterns.

Local wind patterns, such as ocean breezes, occur because land surfaces heat up and cool off more quickly than water surfaces, causing convection.

13.3 Biomass: Solar energy produces biomass fuel sources. Examples of biomass:

Any plant material (wood, straw, etc.) or animal waste (dung) used as fuel.

Alcohol used as fuel, such as the ethanol added to some gasoline, is made from fermented corn or grain.

Fossil fuels (coal, gas, oil) are plant materials subjected to high temperatures and pressures for long periods of time. Fossil fuels began as biomass.

13.4 A system is characterized by a sequence of events and a set of rules that define the possible events and any relation between these events.

In a deterministic system, there is a well-defined relation between successive events. Each successive event may be determined from previous events.

Period 13 Summary, Continued

Some deterministic systems are inherently sensitive to the initial conditions of the event. In sensitive systems, small changes to initial conditions can result in large differences in outcomes. Two similar sensitive systems that start off with very similar initial conditions can behave very differently after a short time. This is known as the butterfly effect.

The outcome of a sensitive system (sometimes called a chaotic system) is too uncertain to discuss in other than probabilities, such as a 40% predicted chance of rain tomorrow.

13.5 Computer simulations are useful when the event that needs to be studied could be dangerous, such as learning to fly a plane, or expensive, such as designing a building, or very complicated involving many variables.

Simulations can model the different outcomes of sensitive systems when the system's initial conditions are changed.

Computer simulations limited in that they can only reflect reality to the extent it is understood or the simulation is programmed to emulate.

Period 13 Exercises

E.1 Which of the following is **NOT** an example of biomass?

a) alcohol distilled from fermented corn
b) firewood
c) dried animal waste
d) uranium
e) **ALL** of the above are examples of biomass.

E.2 Which of the following sources of energy are **NOT** derived from solar energy?

a) wind power
b) water power
c) geothermal power
d) **NONE** of the above is derived from solar energy.

E.3 A procedure that may be used to determine whether or not a system is sensitive is to observe two such systems, such with very similar initial conditions. The system is sensitive if which of the following is **TRUE**?

a) Both systems behave identically after some time.
b) Both systems behave very differently after some time.
c) Both systems behave chaotically.
d) Both systems behave predictably.

E.4 Which of the following statement regarding computer simulations is **TRUE**?

a) Computer simulations are unbiased.
b) Computer simulations can handle fewer calculations than a human could.
c) Computer simulations are more complicated than the actual situation.
d) Computer simulations can be used to model situations that have many parts to them.
e) Computer simulations can always be used to make very accurate predictions.

E.5 How well a computer simulation can predict the future behavior of a physical system can depend on

a) the reliability of the data describing the system.
b) whether the system can be represented by a mathematical model.
c) whether the physical system can be described well by a finite number of variables.
d) how well the model of the system represents the system.
e) **ALL** of the above factors can influence the accuracy of the simulation.

Period 13 Review Questions

R.1 What is the energy balance of the earth? What could happen if this balance is upset?

R.2 What is the water cycle? How does solar energy play a role in the water cycle?

R.3 What is biomass? What are some advantages of using biomass as fuel?

R.4 What could happen to the outcome of a sensitive system that experiences small changes in its initial conditions?

R.5 In what circumstances are computer simulations useful? What are some of the limitations of computer simulations?