Chapter 7

Sun, Water, and Weather

What does the sun have to do with the weather? What does the sun have to do with water? These issues, and the corollary issue of possible human involvement, are at the center of our interest here.

The most obvious parts of the weather system that we experience regularly are the seasons (if you do not happen to live in the tropics or places like San Francisco): spring, summer, fall, and winter. We know it is relatively hot in the summer and cold in the winter and that days are longer in the summer as compared with the winter. We also know that when we have summer in the Northern Hemisphere, we have winter in the Southern Hemisphere and vice versa. In the last chapter we were able to calculate the approximate average temperature on Earth based only on the average amount of light we receive from the sun and the resulting thermal radiation Earth emits back into outer space. We were not interested in regional variations on Earth. I will start to explore the issue of regional variations in this chapter and expand on this issue in the next chapter, where we discuss modeling of the weather system. For this purpose we need a model of the orbit Earth takes around the sun. Two types of motion will be considered:

1. The spinning of Earth around the polar axis takes approximately 24 hours per revolution and determines the oscillations of day and night.
2. The orbital motion of Earth around the sun determines the length of the year, around which the seasons oscillate. The orbit of Earth around the sun is shown schematically in Figure 7.1.

The orbit spans an approximate circle with the sun at the center. However, this is only an approximation—Earth actually traces an elliptical orbit (an ellipse is a geometrical shape that can be obtained by stretching two opposite ends of a circle) in which the sun is at one of the foci. Such a trajectory provides a quick intuitive explanation for the seasons: when Earth is closest to the sun, near the small elliptical axis, it should be hot and therefore summertime. When Earth is farthest from the sun, near the long elliptical axis, we receive less solar energy and it should be wintertime. It is a nice intuitive explanation, but it is wrong. For starters, if this had been the source of the seasons, we should have gotten a cycle of four: two alternating
Figure 7.1. Schematic representation of Earth’s orbit around the sun. Seasons are marked for the Northern Hemisphere.

summers and winters, but instead we have a cycle of two—one summer and one winter per year. Also, this explanation does not account for the alternating seasons between the Southern and the Northern Hemispheres.

**Spatial Variations in the Climate**

A mechanism that accounts for all the seasonal observations is shown in Figure 7.1. Seasons exist because of the tilt of the axis of rotation of Earth relative to the elliptical orbit that Earth traverses around the sun. Presently, the angle of this tilt is 23.5°. Let us have a look at summer in the Northern Hemisphere (right side of Fig. 7.1): the North Pole is inclined toward the sun and the South Pole is inclined away from the sun.
The boundary between day and night is always perpendicular to the Earth–sun line. Because of the polar axis’s tilt, the lengths of the day and night change with the latitude: during the northern summer, the day is longer than the night. As we approach the North Pole, there is no night at all: a 24-hour day is not only an expression but also a reality. Half a year later, when Earth is on the other side of the sun, the season and the relative lengths of day and night reverse. On the equator, there are no seasons in the regular sense—no summer, spring, winter, or fall. However, we can have a “wet” season and a “dry” season. The lengths of day and night are approximately the same throughout the year. Around June 21 (the summer solstice), days in the Northern Hemisphere are the longest and nights are the shortest because the angle between the polar axis and the Earth–sun axis reaches its maximum of 23.50. On that day the Northern Hemisphere receives its maximum amount of solar radiation. The same will be observed 6 months later in the Southern Hemisphere. What is the reason that June 21 is the beginning of summer (in the Northern Hemisphere) and December 21 is the beginning of winter, instead of both dates being the heights of summer and winter respectively? The reason is that around 70% of the surface of Earth is covered by oceans. The oceans heat and cool much slower than the land. This “memory effect” of the oceans postpones the heights of summer and winter by about a month and a half. All of this tells us that the tropics receive approximately the same amount of solar energy year round, whereas as we go toward the poles, the amount of solar energy varies with the seasons. This distribution of incoming solar energy generates large temperature differences between the regions. Temperature differences like these create an opportunity for a heat engine (the same kind of engine that was discussed in Chapter 5 using the internal combustion engine and electrical power stations as examples). These engines were discussed in the context of converting heat into mechanical work. The global heat engine also converts heat into mechanical work. The mechanical work comes in the form of global air and water circulations that are the key to the understanding of global weather systems. Thus the oceans play a major role in the connection between the global energy distribution and the global weather system.

The Astronomical Origin of Past Climate

These movements of Earth relative to the sun have the most direct impact on both the amount of energy that Earth receives from the sun and its geographic variations and thus on early climate. These movements are not constant—they vary in periodic ways. The first scientist who was able to quantitatively correlate the periodicities of the astronomical cycles with the history (Chapter 3) of the glacial–interglacial cycles of Earth’s climate was the Serbian physicist Milutin Milankovic (1879–1958). The elliptical orbital motion of Earth around the sun changes
with a periodicity of around 100,000 years.\(^1\) The tilt of the axis of Earth’s rotation relative to its orbital motion changes with a periodicity of around 41,000 years. The rotation axis also wobbles (precession) like a spinning top with a periodicity of around 23,000 years. A cursory look at the glacial–interglacial cycles over the last 400,000 years, using data derived from the Vostok ice core and shown in Figure 3.2, shows a clear periodicity of 100,000 years—thus the elliptical orbital motion of Earth around the sun seems to be the dominant factor. However, a careful analysis of these data reveals that all three periodic motions play roles. Extension of the ice-core analysis performed by the European Project for Ice Coring in Antarctica (EPICA) team (Chapter 3) to earlier times and further extension of the ocean-core drilling analysis to even earlier times show that earlier than 400,000 years ago, the 100,000-year glacial–interglacial periodicity breaks down and gradually shifts to a 41,000-year periodicity that is characteristic of the tilt of the rotational axis. The reasons for these shifts are unclear.

**Latent Heat and the Water Cycle**

In Chapter 5 we learned that when we heat a substance, its temperature will increase. But this is not always the case. A substance can experience a phase transition (converting from solid to liquid or from liquid to gas) without a change in temperature. I will concentrate here on the conversion from liquid to gas. The main difference between liquid and gas is that in a liquid state the molecules attract each other, whereas in the gas phase these attractive forces are considerably smaller relative to the energy of motion of individual molecules. In the ideal case, there are no attractive forces between the gas molecules, and each molecule behaves as though it is completely independent of other molecules. A gas like that is called an *ideal gas*. All gases behave very much like an ideal gas at sufficiently high temperatures and low pressures. We discussed such a gas in Chapter 2, where we used its properties to calculate the amount of carbon dioxide in the atmosphere. When a liquid is converted into a gas, the attractive forces between the molecules at the liquid–gas interface break. The amount of energy it takes to break these forces and transform a given amount of liquid into a gas is called the *latent heat of evaporation*. It is an extensive property that depends on the amount of evaporated liquid. The usual unit of weight this quantity is associated with is the mole (remember Chapter 1) because when we compare different substances, we would like to compare the same number of molecules. For water, one mole weighs 18 g (the sum of the atomic weights of two hydrogen atoms and one oxygen atom). The latent heat of evaporation of water is 45,000 J/mole at the boiling point of water. This translates into 2.5 million J/kg of water. Referring back to our discussion of units in Chapter 1 (Appendix 1),

\[
4180 \text{ J} = 1 \text{ Cal}.
\]
So in units of Calories, we need approximately 600 Cal to evaporate 1 kg of water at its boiling point. Because the definition of a Calorie is the amount of heat needed to raise the temperature of 1 kg of water by 1°C, we can see that evaporation takes a lot of energy, and it is the most crucial link between the global energy balance and the global water cycle.

The inverse of evaporation is condensation—the energy needed to evaporate a liquid we then get back when the same amount of water vapor condenses to a liquid. There are two basic ways to evaporate a liquid (or the inverse—condense a gas): either we add heat to the system or we do not add heat to the system. If we add heat to the system, then we first increase its temperature until we reach the boiling point of the liquid, at which the temperature will stop rising and energy instead will go into breaking the forces of attraction between molecules, causing the liquid to boil. The other possible way to evaporate liquid is without heating the system. In that case, equilibrium is established between the liquid and the atmosphere above the liquid. Let us examine this equilibrium in some detail. For evaporation to take place without extra energy from a heat source, liquid molecules need to find energy to escape the attractive forces that keep them together with other molecules. The temperature of the liquid (in Kelvin) measures approximately the average energy per molecule. This means that approximately half the molecules have energy higher than the average and the other half have energy that is lower. (Let us not dwell here on differences between average and mean; when we have so many molecules, these two quantities are basically the same.) Few molecules have energy much higher than the average—that is, high enough to break from the attractive forces with the rest of the molecules and evaporate. Once these molecules evaporate, the remaining liquid is left with less energy and the smaller amount of energy will redistribute among the remaining molecules—thus lowering the temperature of the liquid. (The average energy will come out lower than before because the molecules with the highest energy have left.) This process is known as evaporative cooling and is the main natural mechanism available to us in order to cool ourselves on a hot day—we refer to this as sweating. This is also a way for many homes throughout the world to provide cooling in hot temperatures by using water sprinklers on the roof that facilitate evaporation of the water. The reverse process of water condensation takes place by collision of water molecules in the gas phase, reestablishing the attractive forces between molecules. The equilibrium between evaporation and condensation depends on the temperature and the concentration of the vaporized liquid in the atmosphere.

**The Water Cycle**

About 70% of the surface of Earth is covered by water. The solar-driven evaporation of water from the oceans is the driving force for the water cycle and is responsible for all the fresh
water needed to sustain the biosphere, including humans. As the water evaporates, it rises in the atmosphere together with hot, dry air. As the hot air rises, it moves to regions with lower atmospheric pressure—a process discussed in Chapter 2. In a sense this hot air is performing mechanical work similar to the gas in a car engine that expands by pushing the piston in a cylinder. The energy to perform this mechanical work comes from the internal energy of the humid air, and thus the air’s temperature will fall. As the hot air expands and cools, it can hold less water vapor and eventually becomes saturated. At this point some of the water vapor will condense into tiny water droplets to form clouds (about 1 million cloud droplets are contained in one raindrop). In the presence of small dust particles (0.5–20 μm in diameter) that can act as condensation seeds, the cloud formation can start below the saturation pressure. Clouds are categorized as low clouds (below 2.5 km above Earth), middle clouds (2.5–6 km above Earth), or high clouds (above 6 km above Earth). All clouds are white, but when viewed from the ground some appear gray or dark gray according to their depth and shading from the higher clouds. When cloud particles become too heavy to remain suspended, they fall as precipitation in the form of rain or snow. Water that falls on land runs off over the surface as streams, or percolates into the ground to become groundwater. It can return to the atmosphere again by evaporation or transpiration (evaporation of water from plants). Eventually both the surface water and the groundwater find their way back into the oceans.

This cycle is often referred to as the water cycle and is shown schematically in Figure 7.2. The driving force of this cycle is solar energy. The cycle involves redistribution of two key ingredients essential to the survival of much of the biosphere, and as a result, any man-induced climate changes are of major importance. The two key ingredients are water and mineral deposits. The strong connection between energy distribution, water distribution, and the distribution of salinity among the water reservoirs will be discussed next.³

The energy balance (Fig. 6.5) determines the average global temperatures for separate regions. Any disturbance of these balances results in temperature changes that lead to climatic changes. In Box 7.1 I provide a quick analysis of an important ingredient in this balance. The box shows a quantitative connection between the energy budget discussed in the previous chapter and the global water distribution presented in Table 7.1. I try to calculate there, from first principles, the amount of energy spent on water evaporation. My starting point is the recorded average monthly global precipitation. Again I use simple geometric modeling to calculate the amount of water involved in the precipitation and then I calculate the amount of energy needed to evaporate this amount based on the heat of evaporation of water.
Figure 7.2. The water cycle


<table>
<thead>
<tr>
<th>Watersource</th>
<th>Water volume, in cubic miles</th>
<th>Water volume, in cubic kilometers</th>
<th>Percent of freshwater</th>
<th>Percent of total water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceans, Seas, &amp; Bays</td>
<td>321,000,000</td>
<td>1,338,000,000</td>
<td>--</td>
<td>96.5</td>
</tr>
<tr>
<td>Ice caps, Glaciers, &amp; Permanent Snow</td>
<td>5,773,000</td>
<td>24,064,000</td>
<td>68.7</td>
<td>1.74</td>
</tr>
<tr>
<td>Ground water</td>
<td>5,614,000</td>
<td>23,400,000</td>
<td>--</td>
<td>1.69</td>
</tr>
<tr>
<td>Fresh</td>
<td>2,526,000</td>
<td>10,530,000</td>
<td>30.1</td>
<td>0.76</td>
</tr>
<tr>
<td>Saline</td>
<td>3,088,000</td>
<td>12,870,000</td>
<td>--</td>
<td>0.93</td>
</tr>
<tr>
<td>Soil Moisture</td>
<td>3,959</td>
<td>16,500</td>
<td>0.05</td>
<td>0.001</td>
</tr>
<tr>
<td>Ground Ice &amp; Permafrost</td>
<td>71,970</td>
<td>300,000</td>
<td>0.86</td>
<td>0.022</td>
</tr>
<tr>
<td>Lakes</td>
<td>42,320</td>
<td>176,400</td>
<td>--</td>
<td>0.813</td>
</tr>
<tr>
<td>Fresh</td>
<td>21,830</td>
<td>91,600</td>
<td>0.25</td>
<td>0.007</td>
</tr>
<tr>
<td>Saline</td>
<td>20,490</td>
<td>85,400</td>
<td>--</td>
<td>0.006</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>3,095</td>
<td>12,600</td>
<td>0.04</td>
<td>0.001</td>
</tr>
<tr>
<td>Swamp Water</td>
<td>2,752</td>
<td>11,470</td>
<td>0.03</td>
<td>0.0008</td>
</tr>
<tr>
<td>Rivers</td>
<td>509</td>
<td>2,120</td>
<td>0.006</td>
<td>0.002</td>
</tr>
<tr>
<td>Biological Water</td>
<td>260</td>
<td>1,120</td>
<td>0.003</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

How Much Energy Does It Take to Make Rain?

Figure 7.3 shows the average global rainfall.

The average rainfall over this period is about 2.7 mm/day, or on average, every place on Earth experiences a daily rainfall of 2.7 mm ($2.7 \times 10^{-3}$ m). In order to calculate the total quantity of water (in cubic meters) that falls daily per one unit area of Earth (1 m²),

$$\text{total daily amount of rainfall per } 1 \text{ m}^2 = \text{average daily rainfall} \times (1 \text{ m}^2) = 2.7 \times 10^{-3} \text{ m}^3 \text{ of water.}$$

Each cubic meter of water weighs 1 metric ton = 1000 kg, so the total weight of the average daily rainfall of water on 1 m² is $(2.7 \times 10^{-3} \text{ m}^3) \times (1000 \text{ kg/m}^3) = 2.7 \text{ kg}$.

It takes $2.5 \times 10^6$ J to evaporate 1 kg of water (latent heat of evaporation). Assuming that, on average, all the evaporated water results in rainfall (no average changes in
the atmospheric water contents), the solar energy that is required to evaporate this quantity of water is given by

\[
\text{weight of precipitation (in kg)} \times \text{latent heat of evaporation (in J/kg)} = 2.7 \times 2.5 \times 10^6 = 6.75 \times 10^6 \text{ J/m}^2.
\]

The solar power that is required to evaporate this water (given in watts) equals this amount of energy divided by the number of seconds in a day:

\[
\text{solar power required for evaporating the daily precipitation} = \frac{6.75 \times 10^6}{24 \times 60 \times 60} = 78 \text{ W/m}^2.
\]

In Chapter 6 I calculated that, based on a very simple geometrical model, Earth intercepts about 350 W/m². Our result here shows that 22% of this energy is spent on evaporation of water that results in precipitation.

This part is explicitly shown in Figure 6.4 as latent heat.

**Feedback and Clouds**

We refer to feedback when the result of a process changes the process itself. Negative feedback acts on a process to reduce the deviation from an expected outcome, thus stabilizing the process, and positive feedback amplifies the deviation from an expected outcome. Let us look at the correlation between global warming and the water cycle as an example. As the average temperature increases because of the presence of greenhouse gases (GHGs) in the atmosphere, the amount of water that evaporates from the oceans increases. Water vapor is probably the most important GHG (although it is not anthropogenic). Addition of a GHG should enhance the greenhouse effect and increase the temperature further. One might expect to have a runaway greenhouse effect that perhaps can produce a catastrophic result, such as the one described in the last chapter on the planet Venus. This is an example of a positive feedback that acts to destabilize the system. Fortunately, there are effects that act in the opposite direction. As was mentioned before, water evaporation does not simply increase water vapor concentration in the air. Most of the water vapor rises in the atmosphere, causing a reduction in temperature that leads to cloud formation. The clouds, at least looking from above, are all white, and they look like a blanket of snow. This blanket of clouds significantly increases the reflection of the incoming solar radiation, thus increasing Earth's albedo. This increase in albedo reduces the amount of absorbed radiation and thus acts to reduce the temperature. As a result we have two strong effects that act in opposite directions: one is the increase in water concentration
in the atmosphere that acts to increase the temperature by absorbing the outgoing infrared radiation, and the other is an increase in the albedo that acts to decrease the temperature by decreasing the amount of incoming solar radiation.

In technical terms we are looking for a way to determine the radiative forcing of clouds (from Chapter 6). There is an extensive ongoing effort to determine the role clouds play in the energy balance. The modeling of cloud forcing is difficult because clouds are very dynamic and move easily. As will be discussed in the next chapter, the most important present limitation on climate modeling is the size of the grid that one can put in the model. Clouds are small by today’s modeling standard. Nevertheless, the present consensus is that clouds have small negative radiative forcing, which means that the increase in the albedo narrowly wins over the increased absorption of the infrared radiation.

**Salinity**

The total global supply of fresh water constitutes about 1% of the total water supply. About 60% of the fresh water supply is locked in frozen ice caps. The availability of fresh water is one of the most pressing issues society now faces, and some of the political issues associated with that will be discussed in Chapter 13. Because 70% of the surface of Earth is covered by oceans, and water on the planet is conserved, it is obvious that there is no shortage of water—there is a problem only with fresh water.
Seawater is a complex solution of nearly 60 chemical elements. The most abundant (aside from water itself) is common salt. The molecular structure of common salt is NaCl. Na stands for an atom of sodium, and Cl stands for an atom of chlorine. Common salt constitutes about 78% of the total dissolved solids in the ocean. Degree of solubility is usually expressed in units of parts per thousand (ppt)—that is, how many grams of common salt per 1 kg of water (or how many pounds of common salt per 1000 pounds of water). The range in the oceans is between 32 ppt and 37 ppt with an average around 35 ppt or 35 g per 1 kg of water. In the polar regions the salinity is lower, and it can get below 30 ppt.

The evaporation process evaporates pure water, leaving the salt behind. So the resulting precipitation in the form of rain or snow is relatively salt-free—it is fresh water. In the North Pacific, rainfall is greater than evaporation, so the average salinity is lower. In parts of the Indian Ocean, evaporation is greater than precipitation, and as a result the salinity is higher.

Pure water freezes around 0°C (32°F), and the freezing temperature decreases by approximately 0.3°C for each 5 ppt increase in salinity. At 35 ppt seawater begins to freeze at around –2°C (29°F). Sea ice first forms as salt-free crystals near the surface.

How did the sea become salty? The evaporated salt-free water condenses in clouds and then returns to Earth through precipitation as rain or snow. The precipitation that falls on land drains through rivers or groundwater back to the oceans (Fig. 7.2). On its way, this water dissolves many of Earth’s minerals, carrying them to the oceans. In a sense the water cycle is trying to equalize the distribution of minerals between land and sea. This is another manifestation of the second law of thermodynamics (discussed in Chapter 5) in which nature always tries to maximize disorder. If I have two items piled separately, nature will always tend to mix them up if there is a way to do so. This is what the water cycle is doing with the land minerals. Why, in that case, is the composition of Earth minerals different from the composition of the water in the ocean? The minerals that end up in the oceans can precipitate on the ocean floor, and some of them incorporate into the ocean’s biota. Common salt does neither and ends up dissolved in the water.

**The Human Influence**

In these complexities in the climate system, where do humans play a role? One of the central arguments on the societal causes of climate change is the claim that one cannot separate “natural” causes (i.e., causes that do not depend on human activities) from human-induced (i.e., anthropogenic) causes. In the next chapter I start with a description of present efforts to separate the two through modeling, and the rest of the book is focused on human activities that are directly related to climate change—specifically, our energy use. From the issues
discussed in this chapter, it is clear that human activities have nothing to do with the astronomical periodicities that influence our climate or with the direct role that the ocean plays in the climate system. In Chapters 2 and 4 I presented the data that support the direct human influence on the chemical composition of the atmosphere through emission of GHGs such as carbon dioxide, methane, and others. These changes in the atmospheric chemical composition directly influence the energy balance and thus the climate. The temperature change, in turn, has a direct influence on the water cycle that induces, among other things, changes in the salinity distribution of the oceans. These changes affect Earth’s ability to equalize regional temperature differences through ocean currents and thus directly affect our local climate, the climate we experience.