1 INTRODUCTION: THE DIVERSITY OF PLANETARY CLIMATES

Climate is the average weather—long-term properties of the atmosphere like temperature, wind, cloudiness, and precipitation, and properties of the surface like snow, glaciers, rivers, and oceans. Earth has a wide range of climates, but the range among the planets is much greater. Studying the climates of other planets helps us understand the basic physical processes in a larger context. One learns which factors are important in setting the climate and how they interact.

Earth is the only planet with water in all three phases—solid, liquid, and gas. Mars has plenty of water, but it's almost all locked up in the polar caps as ice. There's a small amount of water vapor in its atmosphere but no standing bodies of liquid water. Venus has a small amount of water vapor in its atmosphere, but the Venus surface is hot enough to melt lead and is too hot for solid or liquid water. Thus by human standards, Venus is too hot and Mars is too cold. The classic "habitable zone," where Earth resides and life evolved, lies in between.

Things get strange in the outer solar system. Titan, a moon of Saturn, has rivers and lakes, but they're made of methane, which we know as natural gas. The giant planets have no solid or liquid surfaces, so you would need a balloon or an airplane to visit them. The climates there range from terribly cold at the tops of the clouds to scorching hot in the gaseous interiors, with warm, wet, rainy layers in between. Some of the moons in the outer solar system have oceans of liquid water beneath their icy crusts. The solar system's habitable zone could be an archipelago that includes these icy moons, but the crusts could be tens of kilometers thick. Their subsurface oceans are beyond the scope of this book.

The diversity of planetary climates is huge, but the basic ingredients are the same—the five elements H, O, C, N, and S. A fundamental difference is the relative abundance of hydrogen and oxygen. In the inner solar system—Earth, Mars, and Venus—the elements are combined into compounds like oxygen (O_2), carbon dioxide (CO_2), nitrogen (N_2), sulfur dioxide (SO_2), and water (H_2O). In the outer solar system—Jupiter, Saturn, Uranus, and Neptune—the elements are combined into compounds like methane (CH_4), ammonia (NH_3), hydrogen sulfide (H_2S), and water. Saturn's moon Titan has an atmosphere of nitrogen and methane, and Jupiter's moon Io has an atmosphere of sulfur dioxide. The composition of a planetary atmosphere has a profound effect on its climate, yet many of the processes that control the composition are poorly understood.

The underlying physical processes are the same as well. Temperature is a crucial variable, and it is largely but not entirely controlled by distance to the Sun. The temperature of the planet adjusts to maintain thermal equilibrium—to keep the amount of outgoing infrared radiation equal to the amount of absorbed sunlight.

Clouds and ice reflect sunlight, leading to cooler temperatures, but clouds also block outgoing infrared radiation, leading to warmer temperatures down below. Many gases like water vapor, carbon dioxide, methane, ammonia, and sulfur dioxide do the same. They are called greenhouse gases, although an actual greenhouse traps the warm air inside by blocking the wind outside. An atmosphere has nothing outside, just space, so the greenhouse gases trap heat by blocking the infrared radiation to space. Venus has clouds of sulfuric acid and a massive carbon dioxide atmosphere that together reflect 75% of the incident sunlight. Yet enough sunlight reaches the surface, and enough of the outgoing radiation is blocked, to make the surface of Venus hotter than any other surface in the solar system. Gases like nitrogen (N_2) and oxygen (O_2) do not block infrared radiation and are not significant contributors to the greenhouse effect.

The wind speeds on other planets defy intuition. At high altitudes on Venus, the winds blow two or three times faster than the jet streams of Earth, which blow at hurricane force although they usually don't touch the ground. In fact, Earth has the slowest winds of any planet in the solar system. Paradoxically, wind speed seems to increase with distance from the Sun. Jupiter has jet streams that blow three times faster than those on Earth, and Neptune has jet streams that blow ten times faster.

The weather is otherworldly. At least it is unlike what we are used to on Earth. Mars has two kinds of clouds—water and carbon dioxide. And Jupiter has three kinds—water, ammonia, and a compound of ammonia and hydrogen sulfide. Mars has dust storms that occasionally enshroud the planet. Jupiter and Saturn have no oceans and no solid surfaces, but they have lightning storms and rain clouds that dwarf the largest thunderstorms on Earth. Saturn stores its energy for decades and then erupts into a giant thunderstorm that sends out a tail that wraps around the planet.

Many of these processes are not well understood. Our Earth-based experience has proved inadequate to prepare us for the climates we have discovered on other planets. The planets have surprised us, and scientists often emerge from a planetary encounter with more questions than answers. But surprises tell us something new, and new questions lead to new approaches and greater understanding. If we knew what we would find every time a spacecraft visited a planet, then we wouldn't be learning anything. In the chapters that follow, we will see how much we know and don't know about climate, using the planets to provide a broader context than what we experience on Earth.

We will visit the planets in order of distance from the Sun, starting with Venus and ending with planets around other stars. Most planets get one or two chapters. Usually the first chapter is more descriptive—what the planet is like and how it got that way. The second chapter is more mechanistic—describing the physical processes that control the present climate of that planet. The chapters are augmented by sections called boxes, which contain equations and constitute a brief textbook-type introduction to climate science.

Chapter 2 is about the greenhouse effect and climate evolution, for which Venus is the prime example. Chapter 3 is about basic physical processes like convection, radiation, Hadley cells, and the accompanying winds, with Venus as the laboratory. Mars illustrates the "faint young Sun paradox," in which evidence of ancient rivers (chapter 4) contradicts results from astronomy that the Sun's output in the first billion years of the solar system was 70% of its current value. Mars also allows us to talk about the fundamental physical processes of condensation and evaporation (chapter 5), since exchanges of water vapor and CO_2 between the atmosphere and polar ice determine the climate of Mars. Titan allows us to study a hydrologic cycle in which the working fluid is not water (sections 6.1–6.3). Titan is an evolving atmosphere, close to the lower size limit of objects that can retain a sizeable atmosphere over geologic time (section 6.4). Below this limit, the atmospheres are tenuous and transient (section 6.5).

Jupiter is almost a cooled-down piece of the Sun, but the departures from solar composition tell a crucial story about how the solar system formed (chapter 7). The giant planets are laboratories for studying the effect of planetary rotation on climate (chapter 8), including the high-speed jet streams and storms that last for centuries. Chapter 9 is about Saturn, a close relative of Jupiter, although the differences are substantial and hard to understand. Uranus spins on its side, which allows us to compare sunlight and rotation for their effects on weather patterns (section 10.1). Neptune has the strongest winds of any planet (section 10.2), and we speculate about why this might be. The field of exoplanets—planets around other stars (section 10.3) is full of new discoveries, and we only give a brief introduction to this rapidly expanding field.

This book was written for a variety of readers. One is an undergraduate science major or a nonspecialist scientist who knows little about planets or climate. This reader will learn a lot about the planets and something about the fundamental physical processes that control climate. We go fairly deep into the physical processes, but the emphasis is on intuitive understanding. We touch on convection, radiation, atmospheric escape, evaporation, condensation, atmospheric chemistry, and the dynamics of rotating fluids. There are good textbooks and popular science books on planetary science[1,2,3,4] and there are multiauthored specialized books about individual planets.[5,6,7,8,9] There are also good textbooks on atmospheric science.[10,11,12,13] Therefore another potential reader is a student of atmospheric science who has learned the relevant equations and wants to step back and think about the fundamental processes in a broader planetary context. Finally, there are the climate specialists and planetary specialists who want to know about the mysteries and unsolved problems in planetary climate. Such readers might solve some of the many mysteries about planetary climates and thereby help us understand climate in general.