JONATHAN I. LUNINE
University of Arizona

Introduction

We live in unusual times for the Earth: over the last 0.1% of our planet's history, extensive caps of ice have covered the poles and vast glaciers have advanced and retreated across the continents. The effects on the Earth have been significant: the landscape and climate patterns have been reshaped, leading to extinctions and the birth of new species (including, perhaps, our own). For much of Earth's history before that, the planet was nearly ice free. Whether our own technological activities will drive the Earth back toward that state remains a politically charged and unanswered question.

While water ice is an ephemeral feature over much of the Earth for much of its history, it is an important and permanent part of most of the other objects in our solar system. This book treats the occurrence and significance of water ice and ices formed by other materials in the solar system. The findings discussed in the chapters are the results of almost four decades of spacecraft exploration of the planets, complemented by ground-based observations which themselves have been revolutionized by progress in electronic detectors, large telescopes, and airborne platforms.

Water ice exists at the Martian poles and just beneath the surface at high latitudes across the planet. It is known to be present on the surfaces of many of the moons of the giant planets, on Pluto and in comets, and less direct information suggests it to be a key component of the interiors of these bodies. The surfaces of the distant Kuiper Belt objects, thought to be leftovers from planet formation, probably have water ice as well, though a definitive answer will require continued observations using the world's largest telescopes. Water has even been detected, from the European Infrared Space Observatory, in the frigid atmosphere of Saturn's moon Titan. In addition, radar studies infer ice to be present at the poles of searing Mercury, protected in the shadowed floors of craters. The same may be true for Earth's Moon, where the Lunar Prospector spacecraft has indirectly detected the presence of water at the poles.

Why is water ice so ubiquitous in our solar system? The answer lies in the nature of the material from which the planets formed, the conditions prevailing in the solar system during and after formation, and in the properties of water itself. The elements from which the solar system (including ourselves) was made, other than the most abundant hydrogen and helium, originated in the nuclear fusion furnaces of a previous generation of stars. Oxygen is among the most common products of hydrogen fusion in many stars, and hence is ubiquitous in the molecular clouds from which new stars are born. Oxygen readily combines with hydrogen to make H_2O, or water. Other atoms with which oxygen can combine such as silicon, to make rocky minerals, are much less abundant than hydrogen; hence water is the most plentiful oxygen-bearing species in the cosmos.

To go from water molecules in the gas phase to water ice requires the right conditions. Astronomers observe disks of gas and dust around some newly formed or forming stars, and it is believed that such disks are the progenitors of planets. Simple models of disks show quite generally that they must be hot close to the central star and cooler farther out. Models of our own solar system in its primordial, or "solar nebula" phase, indicate that the gas beyond what is now the asteroid belt was cool enough to allow water to condense out in the form of water ice grains. These grains agglomerated into larger objects and became the seeds of giant planets, their moons and other bodies of the outer solar system. In the asteroid belt and inward in the disk, the gas was simply too hot to allow water to condense out but silicate (rocky) and metallic grains were present. These were the building blocks of the terrestrial planets Mercury, Venus, Earth, Mars, and Earth's Moon.

Other molecules in the gas of our progenitor disk could not condense out, or did so only at very great distances from the Sun (and hence extremely low temperatures) because of their particular chemical properties. These molecules, methane, carbon monoxide, nitrogen, differ greatly from water in terms of their tendency to form liquids and solids only at very low temperatures. Water condenses out at moderate temperatures because of a peculiar quality of the molecule, called hydrogen bonding, which also turns out to be important in water's critical function as a transport medium in biological processes. Without this property, the solar system from Jupiter outward might well have been much emptier than it in fact is, with only rocky grains available to form solid bodies. Even the giant planets themselves might have been absent or smaller, since the high abundance of ice grains in the solar nebula

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is thought to have quickly initiated their growth in the limited time available to assemble the planets.

Water ice in the outer solar system trapped many other kinds of molecules in naturally occurring pore spaces. As Owen describes in Chapter 3, icy bodies such as comets may have delivered water and other biologically important molecules such as methane to the Earth early in its history. The vast amount of water Earth received set our planet on a trajectory unique among all the solar system's planets – a world habitable for billions of years such that life could gain a foothold, evolve, and diversify. In Chapter 1, Bindschadler describes the myriad forms of water on Earth and its profound effects on our home world.

Moving from the Earth to the inner planets, water ice cannot exist today on the torrid surface of Venus, though our "sister" planet might well have played host to liquid water very early in its history. We expect no water on sunbaked Mercury either, but Butler discusses the remarkable discovery that the poles of Mercury are highly radar reflective and hence might contain water ice (Chapter 2). Because Mercury's poles are always perpendicular to the planet's orbit, crater floors right at or near the poles are cold enough to retain water. It is then natural to ask whether our own Moon might play host to water ice at its poles, and Butler discusses the evidence, pro and con, from the two recent robotic missions Clementine and Prospector.

Mars certainly received its share of cometary water ice, and the early climate of the red planet may have been warm enough to allow liquid water, and perhaps even life, to exist for a time. In Chapter 4, Mellon reviews the search for evidence of this ancient warm epoch, as well as explaining where water exists today on Mars and how it affects the Martian atmosphere and surface. Mellon also critically considers the exciting but difficult possibility of extraction of water from the Martian poles and crust for human colonies of the future.

Moving outward from Mars, through the asteroid belt, we come to many diverse sites of water in the outer solar system. The exotic geology of the icy moons of the giant planets is the subject of Schenk's chapter (Chapter 5). The Galileo orbiter mission around Jupiter found very strong evidence for a possible liquid water ocean beneath the icy crust of the moon Europa, the smallest of Jupiter's four giant galilean satellites.

Out in the regions far from the Sun we also find ices of other molecules. Ammonia, methane, and carbon dioxide may have been incorporated in some moons, particularly those of Saturn, Uranus, and Neptune. Saturn's galilean-sized moon Titan appears to have acquired enough methane so that it now possesses a complex, non-biological organic chemical cycle between its thick atmosphere and haze-shrouded surface. This frigid moon, bigger than Mercury but likely composed at least half of water ice, may teach us something of the chemical steps leading to the formation of life. The US–European joint Cassini–Huygens mission began its trip to the saturnian system in October 1997, and will tell us more about this mysterious moon, the smaller icy moons, and the beautiful rings of Saturn, which at least in part are composed of water ice.

At the fringes of the solar system temperatures are so low that water ice is like rock, and ices of other molecules dominate. In Chapter 6, Stansberry describes the bizarre worlds Triton (a moon of Neptune) and Pluto. Both contain vast deposits of nitrogen, methane, and carbon monoxide ices, and both worlds have climates that are characterized by the seasonal cycling of these exotic ices into atmospheres and back on to their surfaces. Pluto and its moon Charon both contain water ice on their surfaces, and Triton presumably does too, though there the water may be hidden by a more prodigious inventory of other ices.

Finally, we come to the Kuiper Belt objects and comets, relics of the early stages of assembly of the planets from tiny grains. Discovering water ice on these small objects is surprisingly difficult, as Cruikshank describes in Chapter 7, but new technologies applied on progressively larger telescopes have brought success to the search. The identification of many other ices and organic molecules on comets, and now Kuiper Belt bodies, lends credence to the notion that Earth and its sister planets inherited these molecules (at least in part) from the deep outer solar system.

The search for the presence and nature of water ice throughout the solar system is an effort largely enabled by humankind's newfound talent for the exploration of the solar system. As with all such endeavors, planetary exploration has had its fits and starts, but the current generation of robotic explorers are remarkably diverse and capable. Their findings and promise of discoveries yet to come are suggestive of a future in which we will rely increasingly on direct sampling and analysis to understand the nature and origin of solar system ices.

From the point of view of a dispassionate extraterrestrial viewing our solar system, water ice is far more abundant and far more pervasive in its effects than liquid water. In fact, other than the water clouds of the giant planets and the putative ocean beneath Europa's surface, only Earth bears liquid water at present. And yet it is liquid water that provides the universal solvent without which life as we understand it could not exist. It is the delicate balance between atmospheric evolution and geological (and perhaps biological) processes that has maintained a terrestrial climate equable for liquid water over almost all of Earth's history. There is therefore much magic in the subtle difference between water as liquid and water as ice: without the former there might be no intelligence to contemplate the latter's importance in the solar system.

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ROBERT BINDSCHADLER
NASA Goddard Space Flight Center

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The history and significance of ice on Earth

We know more about the ice on Earth than on any other planet. Depending on where we live and the severity of our winters, many of us have familiarity with ice or its softer sibling, snow. Some of us play on it, while others curse the hardships it can bring. Caught up in these personal contacts, we rarely stop to appreciate its special properties, what its presence on this planet has meant for the habitability of Earth, and how it continues to affect the shape and size of the continents upon which we live.

Snow usually is delivered to us on the wings of chilling winter storms. Most rain begins as snow at great altitudes. Yet the majority of terrestrial ice occurs beyond our sight, as ice sheets and glaciers, confined to high latitudes of the planet and to its higher elevations. These remote, frozen reservoirs hold nearly 80% of the freshwater on Earth. While glaciers may seem plentiful, the vast Antarctic ice sheet contains nearly 90% of this ice, the Greenland ice sheet another 9%, leaving the smaller ice caps and glaciers throughout the world with only the remaining 1% (Fig. 1.1).

Other chapters of this book describe ices of exotic compositions that can be found elsewhere in the solar system. How boring then that on Earth we can only experience water ice! Not to be outdone by our interplanetary neighbors, our “water planet” contains water ice that manifests itself in a dazzling array of forms. This is most true at the small scale of single snowflakes. The hexagonal (or six-sided symmetry) of the ice crystals leads to a variety of snowflake forms (needles, plates, and the well-known dendrites) depending on the precise temperature conditions at the formation site. With near limitless possibilities of the conditions for formation, each snowflake ever created has been unique.

Nature’s icy smorgasboard extends to larger scales, too. Extensive sheets of frozen ocean can be razor thin to many kilometers thick. The pattern of fractures and raftings of these sheets is constantly changing. Even the thicker, kilometers-thick ice sheets defeat any attempt at singular characterizations. Some move rapidly, others slowly; some receive a great deal of precipitation, while others are starved for snowy nourishment; some are windy, polar deserts where shifting snow replaces

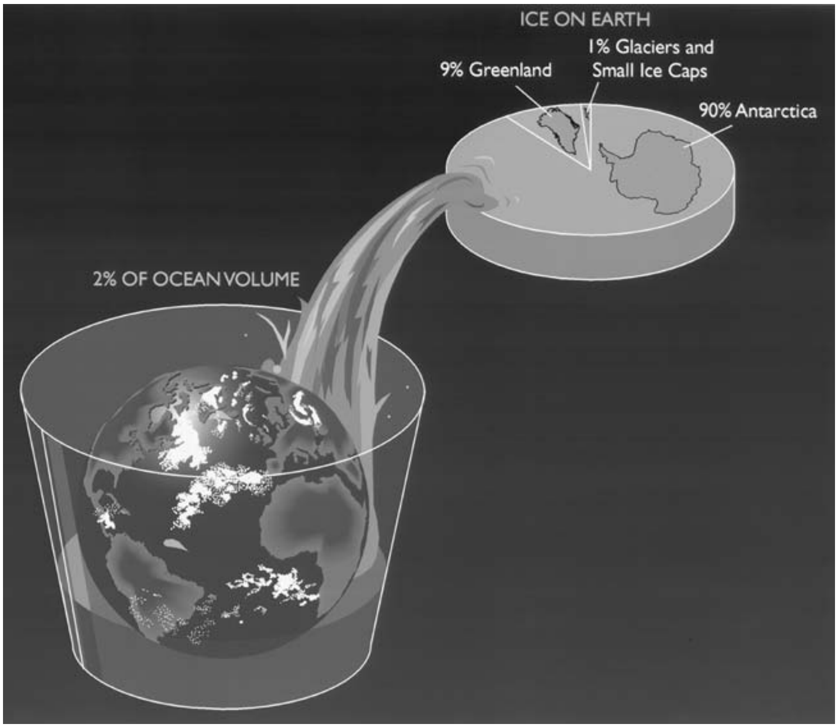

Figure 1.1 The present volume of ice on Earth accounts for 2% of water in any form. This fraction has grown to be more than 5% during the cold "glacial" periods. The ice is disproportionately shared between hemispheres with the Antarctic ice sheet accounting for 90% of the ice mass, the Greenland ice sheet another 9%, leaving the remaining 1% distributed elsewhere across the planet as smaller ice caps and mountain glaciers. *Credit:* R. Bindschadler/NASA.

sand in the ever-changing barren landscapes, while others are deadly calm, permitting the formation of sparklingly large lacy single crystals. Most are bitterly cold, yet some glaciers extend into very warm climates. Indeed, ice can be found on all continents except Australia, dominating the polar regions and nearly touching the equator in Africa, South America, and even Indonesia.

Ice can be studied in many ways that lead us to learn more about the climate of our planet. An understanding of terrestrial ice provides a basis of understanding from which to embark on investigations of other planets in our solar system.

The water planet

Hydrogen and oxygen are abundant on the Earth (Toby Owen explains why in Chapter 3). The abundance of these elements, along with the temperature resulting from our distance from the Sun – conveniently warmed an extra amount by greenhouse gases in our

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atmosphere – allow water and ice to occur in ample supply, making Earth the "water planet." Earth's oceans provide a huge water source from which the ice sheets draw and return H_2O. The amount of gaseous water vapor in the atmosphere is extremely small by comparison. The total amount of water on Earth has remained relatively fixed.

Water defines the color of the planet, prescribes the shapes of the continents, and makes this world immanently habitable. The particular thermal conditions attributable to the presence of so much water have only recently been attained, but as life on this planet was establishing itself, so the ice on the planet was establishing a record of growth and decay.

Early glaciations

Geologists have found no evidence for the presence of ice during the first half of the Earth's 4.6 billion year history. This, despite the fact that the Sun's lower luminosity would have warmed the Earth 10%–20% less than today. The compensating influences were probably an atmosphere exceedingly rich in carbon dioxide and other greenhouse gases, capable of warming the air an additional 20 K, and younger, thinner, and warmer tectonic plates heated by the Earth's molten interior.

The first glaciation event occurred 2.3 billion years ago. It is suggested that a sudden increase in photosynthesis activity caused by biota bursting forth on the aquatic scene drained massive amounts of carbon dioxide from the atmosphere greatly reducing the greenhouse effect, cooling the planet. Subsequent to this climatic event, there is a puzzling period of 1.4 billion years (up to 900 million years ago) when no further glaciations took place. Some paleoclimatologists believe that erosion has simply eliminated the glaciation record over this interval. Others believe ice formation was successfully discouraged by the presence of thin, warm tectonic plates devoid of the higher elevations where ice preferentially initiates and suppresses the equator-to-pole transport of heat that effectively cools the polar regions.

At least six more distinct glaciations occurred during the next 800 million years. The first four were of continental scale between 900 million and 500 million years ago. The evidence is contained in the chemical composition of the rocks that were formed during this period. The last two glaciations, during the last 500 million years, were milder,

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taking place in the midst of generally warm climates. These two glaciations occurred at ancient high latitudes as the continental plates were locked in their Gondwanaland configuration. Even the Sahara basin took its turn in the polar regions and was covered by an extensive ice sheet. At the end of this geological period, the plates forming Gondwanaland rearranged themselves to form Pangea.

The last 100 million years have been marked by the slow dispersal of Pangea – a process continuing today as oceans widen, mountains rise, and plate boundaries grind and shudder. Reconstructions of paleoclimatic conditions improve dramatically over this last 100 million years of history because the records in ocean basins are intact, if growing, and less erosion of the terrestrial record has occurred. Oceanic circulation appears to have stabilized some tens of millions of years ago, leading to the formation of the Antarctic ice sheet 12–14 million years ago. Northern hemisphere glaciation was initiated several million years later. These ice sheets are still with us today; however they have fluctuated in size by significant amounts.

Ice sheets, sea level, and climate

Presently, only 2% of the Earth's water exists in frozen form. However, our present climate is as warm as any Earth has experienced for the past million years. Thus, this 2% figure is a minimum (at least for the past few million years). Climatologists call these warm periods "interglacials" because they occur between colder "glacials" when ice sheets and glaciers are more extensive. The last million years clearly show the oscillatory behavior from glacial to interglacial and back again. While ice sheets waxed and waned, sea level fell and rose in lockstep, first exposing and then submerging coastal areas of all the continents. Over the past million years, sea level has risen and fallen over 125 meters (Fig. 1.2).

The clearest view of a glacial period that paleoclimatologists have pieced together is of the most recent glacial period that ended just 20,000 years ago. It also appears to have been one of the more extreme glacial periods. Large ice sheets, up to 5 kilometers thick draped themselves over the northern halves of Europe and North America (Fig. 1.3). In mountainous areas, these frozen mantles extended icy white fingers

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Figure 1.2 In the last quarter million years sea level has oscillated more than 150 meters. Our current warm interglacial period is extreme relative to this recent history and coincides with a high stand of the oceans. *Credit:* R. Bindschadler/NASA.

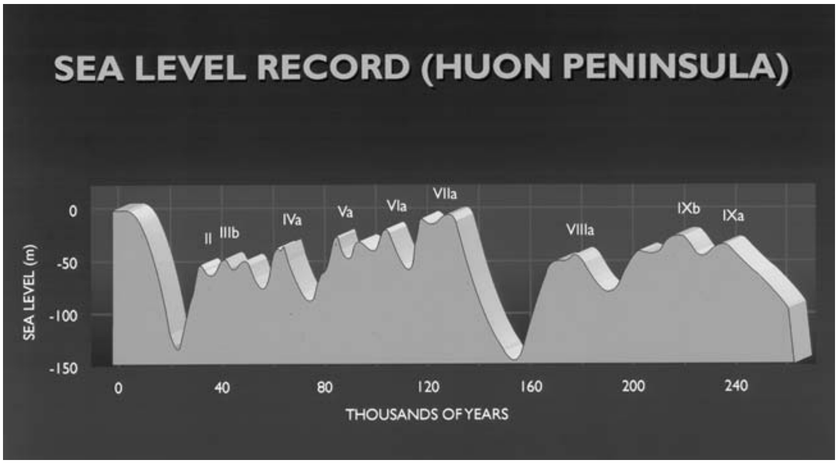

Figure 1.3 Northern Hemisphere ice sheets were far more extensive during cold glacial periods. This illustration depicts the pervasiveness of the ice sheets during the last glacial maximum 20,000 years ago. *Credit:* R. Bindschadler/NASA.