1 Introduction

"How inappropriate to call this planet Earth when clearly it is Ocean."

Arthur C. Clarke (Lovelock, 1990)

1.1 From Blue Marbles to Pale Blue Dots

Human curiosity and ingenuity have given rise to some truly remarkable ways to look back at our home planet. It is the twenty-first century, and many of us have the ability to view planet Earth from just about any distance, angle, zoom factor, or map layer (including the seafloor) using a device that fits in a pocket. Sure, scholars have suspected planet Earth is round for thousands of years and have long been aware of the fragile dimensions of our atmosphere and ocean compared to the massive spherical rock to which they cling, but all without actually *seeing* it. You may be surprised just how recently we acquired such a basic perspective on our home planet.

A short history of planetary selfies takes us to March 1946, on Santa Monica Boulevard in Hollywood, California. Modern civilization was in full swing. Two World Wars fully behind us, Charlie Parker and Miles Davis (Figure 1.1) were recording the eventual Grammy Hall of Fame title *Ornithology*, and yet we had no idea what Earth looked like from anywhere but Earth! That started to change later that year, just a thousand kilometers due east in the desert of New Mexico, where a group of rocket scientists sent a heisted German V-2 rocket to altitudes where the line is blurred between atmosphere and outer space. This was the first photograph of our home planet taken from "space" (105 km), using a black and white 35 mm camera and dropped back to the sand in a rugged tin can (Figure 1.2). It wasn't much by twenty-first-century standards, but what a profound sight for humanity and a society so endlessly preoccupied with our own affairs. This snapshot gave our atmosphere a three-dimensional character; one can perceive space between the clouds and their shadows on the ground. One may also appreciate from this vantage point how little regard the climate has for sovereign borders. Cloudy skies were finite, and even oceans that seemed impossibly far away weren't so far at all.

Figure 1.1 [Year 1947, distance 0 km] Photo taken on the surface of Earth by William Gottlieb of Charlie Parker and Miles Davis playing at the Three Deuces jazz club in New York ca. August 1947. The first photo *of* Earth (from space) was taken less than one year earlier. Credit: William P. Gottlieb/Ira and Leonore S. Gershwin Fund Collection, Music Division, Library of Congress.

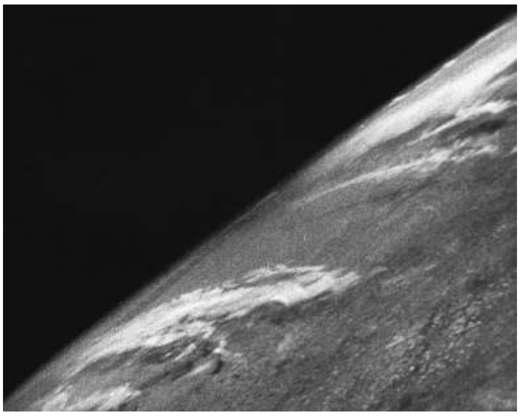

Figure 1.2 [Year: 1946, distance: 105 km] The first photo of Earth from space, taken from aboard a German V-2 rocket launched from White Sands Missile Range in New Mexico on October 24, 1946. Credit: U.S. Army White Sands Missile Range/Johns Hopkins Applied Physics Laboratory.

Since that first photograph of Earth from space in October 1946, humans only continued to go farther up, but never stopped looking back. John Glenn snapped a color photo in 1962 while orbiting Earth; even 266 km wasn't far enough away to frame the whole planet in a single shot, but both the roundness of Earth and the dominance of water were vividly clear (Figure 1.3). It wasn't until the late 1960s when the "whole" Earth was captured on film, ironically because of how irresistible a visit to the barren lunar surface was. Two iconic photos of Earth were captured by separate Apollo crews en route to the Moon: *Earthrise* in 1968 and the *Blue Marble* in 1972 (Figure 1.4). Perhaps the most profound photographic perspective on planet Earth that humanity ever acquired came from a distance so great it could hardly be seen at all. Just as the Voyager 1 spacecraft was leaving our solar system, astronomer Carl Sagan convinced NASA administrators to point Voyager's camera back toward the inner solar system and take one, final photo of home

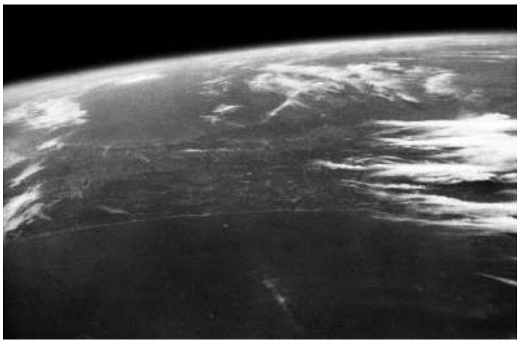

Figure 1.3 [Year: 1962, distance: 266 km] Photo of Earth taken by astronaut John Glenn on February 20, 1962 aboard the Mercury spacecraft during his flight as the first American to orbit the Earth. Credit: NASA/John Glenn. (A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

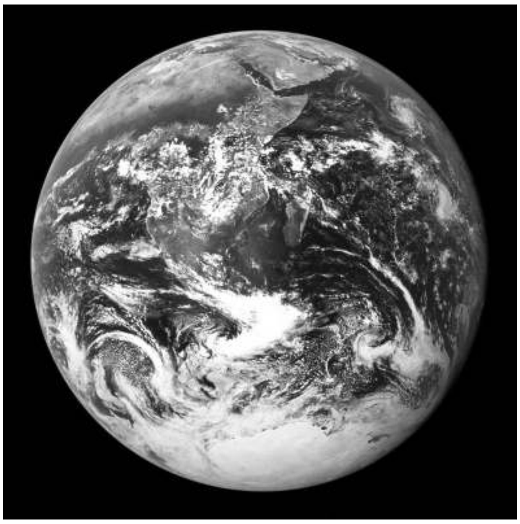

Figure 1.4 [Year: 1972, distance: 29,000 km] Photo of Earth, dubbed "Blue Marble," taken by the crew of Apollo 17 on December 7, 1972 while en route to the Moon. Photo credit: NASA/Apollo 17 crew. (A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

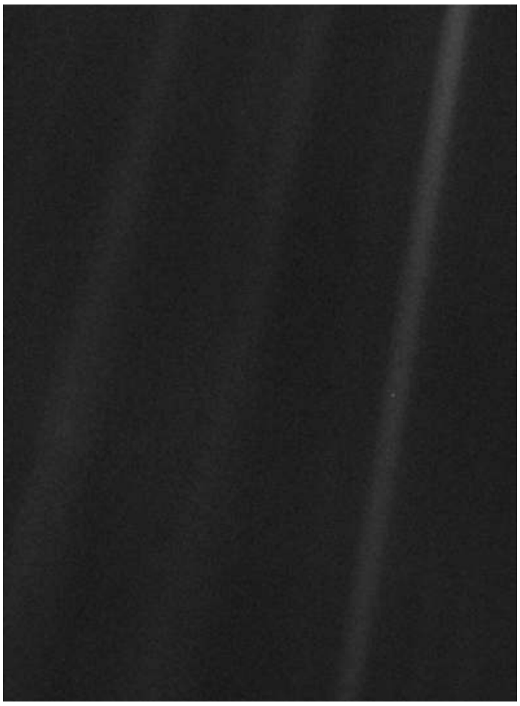

Figure 1.5 [Year: 1990, distance: 5,954,572,800 km] Photo of Earth, dubbed "Pale Blue Dot," taken by the Voyager 1 space probe upon leaving the Solar System on February 14, 1990. Credit: NASA/Voyager 1. (A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

(Figure 1.5). The resulting image, taken in 1990, inspired deep contemplation about our place in the universe. As Sagan himself offered: "There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment the Earth is where we make our stand" (Sagan, 2004).

Each successive photograph of Earth, down to the naming of the infamous Voyager 1 shot – the *Pale Blue Dot* – further illuminated the significance of the ocean to humanity. We don't live in it, yet we cannot live without it. The ocean covers about 70 percent of the planet; one can even spin a globe (or Google Earth) to an angle from which hardly a speck of land can be seen. Likewise, we've also come to understand what a vital role the ocean plays in global climatology, which is exactly the motivation of this book. There are so many wonderful and important books on descriptive physical oceanography and geophysical fluid dynamics, but this book adopts a perspective on the ocean's physics from the very point where it interacts with the atmosphere vis-à-vis climate dynamics. How does the ocean work, and how does it fit into climate and Earth system science writ large? This is now, and will continue to be, a crucial field of study to be applied to the management, sustainability, and continued habitability of the global environment.

From the first black and white TIROS images in 1960 to state-of-the-art satellite altimeters measuring global sea level variations with centimeter precision, to the very latest profiling float dropped into the sea (of which there are nearly 4000 active at a given time), we are probing Earth's dynamic climate system, including the ocean, continuously and from every angle. Much like a doctor examining a patient, this endeavor to "look back" at our home planet in such a multitude of ways has enabled us to carefully monitor its internal rhythms as well as detect and diagnose longer-term changes. Many of the variations to be examined, as we shall throughout this book, are perfectly natural and are expressions of the rich dynamical cooperation between the ocean and atmosphere. Unfortunately, some of these variations are not natural, and are cause for grave concern about the overall health of the global environment.

Sustained measurements of atmospheric carbon dioxide (CO_2) taken from high above the North Pacific Ocean since 1958 have revealed an exponentially growing concentration – an increase by about 93 ppm as of 2018. What is remarkable about this trend is not only the amount – it is roughly the amount by which CO_2 varied across the ice age cycles of the Pleistocene epoch – but the *pace* at which it is rising. Human activities, in particular fossil fuel combustion, are increasing CO_2 concentrations faster than at any time in at least the past million years, and we may be on course to reach nearly 1000 ppm by the end of the twenty-first century (Figure 1.6). The ocean plays a key role in mediating the response to this forcing for the entire climate system, including the atmosphere, *and* delivers some of the major impacts directly. The ocean has already absorbed some 30 percent of the anthropogenic CO_2 emitted, which is a double-edged sword at the front lines of climate

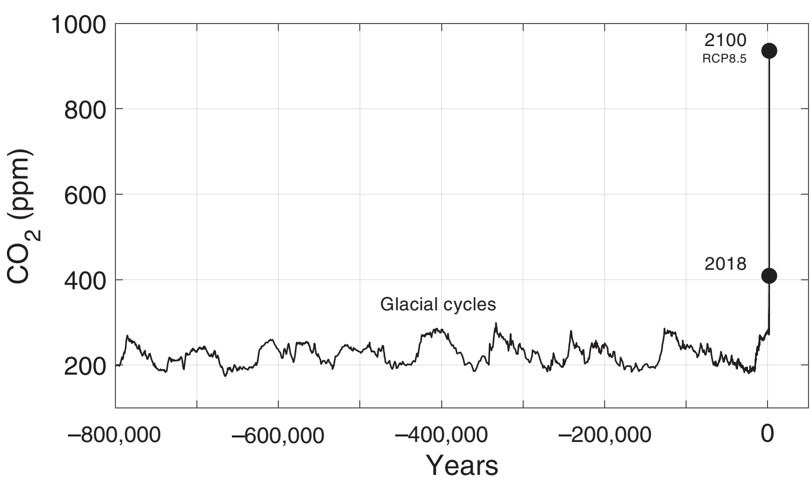

Figure 1.6 Atmospheric concentration of carbon dioxide (parts per million) since about 800,000 years ago from Antarctic ice core records, direct measurements at Mauna Loa Observatory, and future predictions based on unmitigated fossil fuel emissions.

change. On one hand, that's 30 percent less CO_2 remaining in the atmosphere, which at least temporarily dampens the level of greenhouse forcing. On the other hand, the CO_2 entering the ocean has severe consequences for marine life (e.g., through ocean acidification). Thus, physical oceanography acts as something of a mediator between climatic change and the other various subdisciplines of oceanography, including marine biology and chemical (or biogeochemical) oceanography. Meanwhile, the ocean is also absorbing the majority of the excess heat trapped near the surface by greenhouse gases. Due to the great heat capacity of water, the ocean has served to slow the overall warming of the climate system as we humans feel it, but the upper ocean has indeed warmed and expanded. The more visceral consequences of climate change, such as rising seas and worsening tropical storms, are striking but still remain dependent on how much CO_2 we decide to emit over the coming decades. Central to understanding just about any flavor of climate variability, from El Niño to global warming and beyond, are the physical laws governing the exchanges of energy between the ocean and atmosphere, and how these exchanges ultimately control the circulation of both fluids. These chapters aim for such a literacy of ocean physics for students across the Earth and climate sciences.

1.2 Climate is a Coupled System

The last several decades have seen a steady convergence of two fields: atmospheric science and oceanography. Today, you are more likely to find a university where these two disciplines have been deliberately blended into a single department (e.g., Atmospheric and Oceanic Science), rather than historically as standalone departments. It was not always recognized just how closely related these two fields are, nor how important it is to foster cross-disciplinary research to solve the many riddles of climate. Atmospheric scientists now appreciate that the ocean is more than just a two-dimensional boundary condition, and physical oceanographers have learned how difficult it is to predict the ocean currents without accounting for the evolution of the wind field both near and far. In fact, some of the most important climatic phenomena are impossible to describe, let alone predict, without invoking *coupling* between the ocean and atmosphere.

There is perhaps no more famous an example of this coupling, evidenced by its awkwardly constructed name, than the El Niño–Southern Oscillation (ENSO). In what *must* have been a strictly oceanographic phenomenon, the occasional warming of waters off the coast of Peru in the eastern tropical Pacific around Christmastime was long known as El Niño. Historically, the science around El Niño involved ocean temperature, currents, etc., but only *local* weather impacts (driven by the warmer-than-usual ocean). Meanwhile, on the other side of the world, Sir Gilbert Walker was poring over meteorological records at the Indian Meteorological Department and discovered a vast seesaw pattern in atmospheric pressures across the Indian and Pacific Oceans whose strength also varied from year to year (then termed the Southern Oscillation) (Walker, 1923). It wasn't until the late 1960s that meteorologist Jacob Bjerknes successfully argued that the variations in the Walker cell and the occasional warmings in the eastern equatorial Pacific Ocean were linked, hence the El Niño–Southern Oscillation (Bjerknes, 1969). It is quite fitting that Bjerknes' (and his father's) scientific career was dedicated to forecasting, because it was only after this recognition set in, and detailed study by teams of oceanographers *and* atmospheric scientists such as the Tropical Ocean–Global Atmosphere (TOGA) program of the 1980s and 1990s (McPhaden *et al.*, 1998; Figure 1.7), that ENSO could be predicted with any skill and the connections to seasonal weather anomalies around the globe were harnessed.

The implications of ocean–atmosphere coupling have global reach and extend throughout the depths of both fluids. At a basic level, though, the ocean and atmosphere achieve their coupling locally, and right at their physical interface – the surface. The ocean directly feels the atmosphere above through a multitude of physical processes, which can generally be categorized as fluxes of heat, freshwater, and momentum. We will break down the heat fluxes in the next chapter. Freshwater flux results from a local imbalance between precipitation and evaporation (Chapter 3) and helps determine the density, and thus the buoyancy, of water near the surface – a major driver of the global ocean circulation that we will learn more about in

Figure 1.7 Photo of a mooring that simultaneously probes both the upper ocean and lower atmosphere, part of the Tropical Atmosphere–Ocean (TAO) array in the tropical Pacific Ocean – an important legacy of the TOGA program. Photo credit: Kris Karnauskas.

Chapter 8. Momentum flux is imparted locally onto the ocean surface from the wind (Chapters 4 and 5) and is propagated downward into the ocean's interior by friction; the spatial patterns of wind stress turn out to be very important in driving the upper ocean circulation (Chapter 6). In turn, the atmosphere is primarily influenced by the ocean through the exchange of heat and emission of radiant energy. For example, a warmer ocean surface emits more longwave radiation; evaporation and thus latent heat flux is also likely to be greater. Just how the atmosphere as a whole reacts to surface fluxes will also be examined in greater detail in Chapter 5, but it is abundantly clear that the equilibrium atmosphere is directly constrained by fluxes at the ocean surface. Particularly in the tropics, deep rising atmospheric motion and thus rainfall is all but a perfect reflection of warm sea surface temperatures (Figure 1.8). Come two-thirds of the way into this book, you will be able to look at either map in this figure and explain why the salient features look just so, and elaborate on the role of ocean–atmosphere interaction in setting those patterns. These are the fundamentals; such is how we will treat the system at first, before returning to what happens when we consider that – like the synergy between Charlie Parker and Miles Davis in live performance – all of these processes are

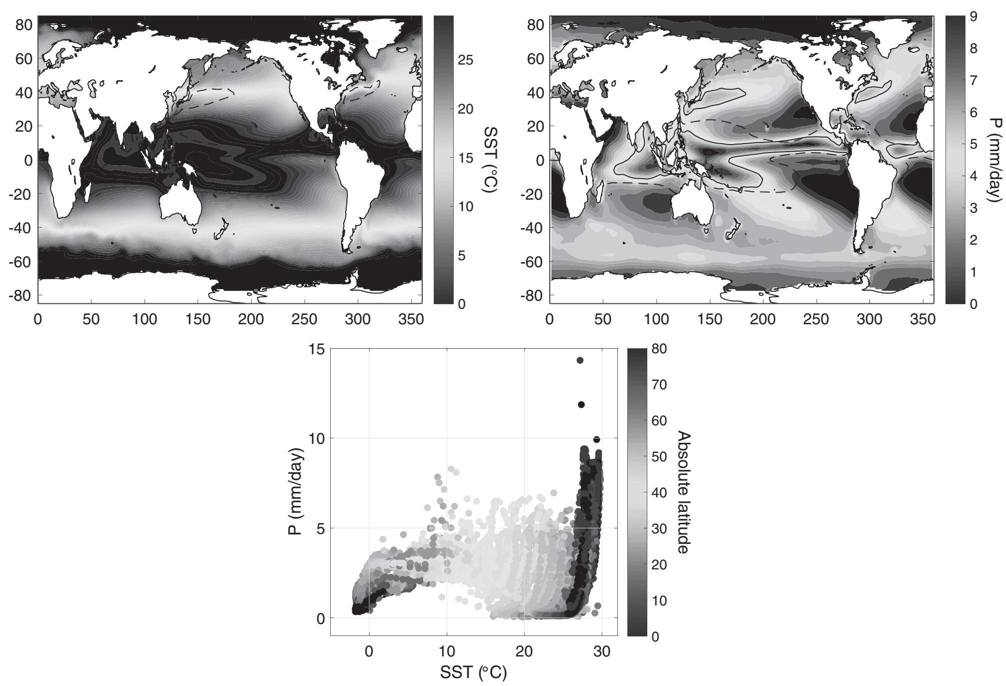

Figure 1.8 Maps of time-averaged sea surface temperature (SST; °C) and precipitation (mm/day) over the global ocean (top row), and their correspondence colored by the absolute value of latitude (bottom panel). On the SST map, the 27 °C and 5 mm/day contours are shown in solid and dashed, respectively, and vice versa on the precipitation map. SST and precipitation observations from the NOAA OIv2 and GPCP data sets, respectively; both averaged from 1982 through 2018. (A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

interactive and the actual state of the climate system is never in equilibrium for long, making way for feedbacks and a beautiful spectrum of climate variability.

1.3 Our Common Framework

As articulated above, the time has never been better to understand Earth's climate system and how it evolves. This is essentially a book about climate dynamics, but from the unique perspective of the upper ocean. To that end, a little math will go a long way. Three mathematical constructs permeate this book: **budgets**, **vectors**, and **partial derivatives**. When combined, they facilitate a deeper understanding of the workings of the ocean and its role in the climate system than words alone might. Even the student less familiar with these tools needn't worry; let's take a crash course.

1.3.1 The Budget Paradigm

The next three chapters build an understanding of what controls the heat, salt, and momentum of the upper ocean using a consistent budget framework. Such budgets are nothing more than usable, mathematical expressions of conservation laws. They are partial differential equations rearranged into **Eulerian** statements of what matters and how. Eulerian means taking the perspective of a fixed point within the fluid, rather than following the fluid (which would be a "Lagrangian" perspective). Each of our budgets have a similar structure that will quickly become familiar. The **terms**, or groups of variables, in our budget equations usually represent external influences on the budgets in question, plus processes internal to the fluid itself (such as ocean currents moving heat around, or swirling eddies mixing salty and freshwater together). Such terms in each budget have physical meaning that you will very soon recognize and think about like second nature. They will then serve as the basis for all of the subsequent chapters; fortunately, we will mostly be scaling them down in an attempt to explain the ocean and climate with as few unnecessary complications as possible.

1.3.2 Vectors

Our budgets will contain some vector expressions, because the ocean variables that these budgets aim to diagnose (temperature, salinity, and currents) can be affected by the three-dimensional currents within the ocean. Vectors and vector calculus are deep subjects that years of mathematical coursework can be dedicated to. Here is what you need to know about vectors in order to understand the material in this book. We live in a three-dimensional world (as in the Cartesian dimensions x, y, and z), which means seawater at any particular location might be moving a little bit eastward, southward, too, and sinking all at the same time. Constituting both a speed and direction, vectors are useful for describing fluid velocity. Specifically, anything in motion like wind or an ocean current should be described by a combination of how rapidly it is flowing in the x direction (i.e., eastward or westward), which we'll assign to the variable u (all scalar variables will be italicized throughout this book), how much it is flowing in the y direction (i.e., northward or southward), which we'll call v, and how much it is flowing in the z direction (i.e., upward or downward), which we'll call w (Table 1.1). These velocity components u, v, and w are just the usual derivatives of position with respect to time (dx/dt, dy/dt and dz/dt) and so will each have units of meters per second (m/s). Earth scientists – especially atmospheric scientists and oceanographers – like to refer to the x dimension as **zonal** and the y dimension as **meridional** (while "vertical" is just fine for the z dimension), so u is referred to as the zonal component of velocity (or just "zonal velocity"), and so on. Finally, although we generally neglect these from our notation, it is worth a reminder that unit vectors $\hat{\imath}$, $\hat{\jmath}$, and $\hat{k}$ (pronounced "i-hat," and so on) point in the zonal, meridional, and vertical directions, respectively, with a magnitude of 1 m/s.

So, when one wishes to describe the velocity of a fluid like seawater at some particular time and geographic location, one may write it as $u\,\hat{\imath} + v\,\hat{\jmath} + w\,\hat{k}$, or simply **V** for short (vectors will be bolded throughout this book). This is a good time to bring up one of the *operations* out of the vector calculus playbook that we'll use from time to time: the dot product, which is rather simple – in our application of it, anyway. To take the dot product (·) of two vectors, say $(2\,\hat{\imath} + 3\,\hat{\jmath} + 5\,\hat{k}) \cdot (1\,\hat{\imath} + 4\,\hat{\jmath} - 2\,\hat{k})$, we simply multiply the zonal, meridional, and vertical *components* from the two vectors with one another, yielding $2\,\hat{\imath} + 12\,\hat{\jmath} - 10\,\hat{k}$. This will take on physical significance when, for example, we "dot" velocity vectors with spatial gradients (which are composed of partial derivatives) of seawater properties such as temperature to define an important process known as advection.

1.3.3 Partial Derivatives

Did you forget what a partial derivative is? No problem! Even if you have taken years of partial differential equation (PDE) courses, you may not be accustomed to applying them in an Earthly context and so you, too, could use a little practice evaluating them by eye. If you recall that a derivative is the rate of change of some

Table 1.1 Symbols used for velocity components and unit vectors for the three Cartesian dimensions, and the names commonly used in physical oceanography and climate science to refer to them.

Cartesian dimension	Velocity component	Unit vector	Climate jargon
x	u	$\hat{\imath}$	Zonal
y	v	$\hat{\jmath}$	Meridional
z	w	$\hat{k}$	Vertical