THE PHYSICS
OF CLIMATE CHANGE

An Apollo book,
first published in the UK in 2021 by Head of Zeus Ltd

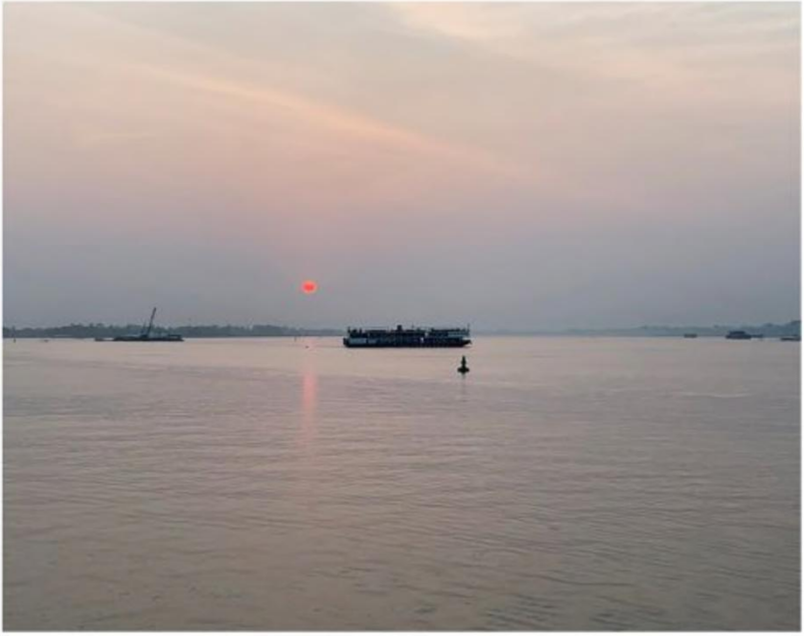
A catalogue record for this book is available from the British Library.

ISBN (HB): 9781800244788
ISBN (E): 9781800244795

Head of Zeus Ltd
5–8 Hardwick Street
London EC1R 4RG
WWW.HEADOFZEUS.COM

TABLE OF CONTENTS

FOREWORD



1

EARLY ONE AFTERNOON IN JANUARY OF 2020, I FOUND MYSELF sitting alone at the bow of a riverboat traveling down the Mekong River from Phnom Penh to Ho Chi Minh City. I was finishing preparations for a lecture and enjoying the sunshine and breeze while watching the busy river traffic. Everywhere, there were barges relentlessly digging up sand from the river bottom for later use, among other things, as concrete for building products. According to the Mekong River Commission, sand mining has caused the riverbed to lose 1.4 meters of elevation since 2008.

As I looked around, I began to feel a growing sense of sadness combined with loneliness. Sadness because the lecture I had just finished preparing for travelers on the boat involved the nature and physics of climate change—with a focus on the potential impact for the Mekong Delta. During my research, I had come to realize how a confluence of factors made this region, home to sixty million people—at least fourteen million of whom depend directly on the health of the Mekong Delta—the epicenter of a Perfect Storm, where even the more conservative predictions of global climate change in the next thirty years may devastate the entire area and the lives of the people who live in it.

Many of my fellow shipmates, a few of whom joined me up front as the afternoon wore on, were as of yet unaware of the fragility of the landscape that then surrounded us, and I wasn't eager to burst their bubble later that evening.

After the discussions following my lecture a few hours later, it became clear that while some of the realities were unpleasant, the well-meaning and interested laypeople who had gathered on the boat wanted information to put this global existential issue in perspective. They wanted to figure out how to separate the wheat from the chaff, to see what was at stake, and learn what possible future impacts humanity might and might not be able to affect. That was when I decided to write this book, and I thank my shipmates for inspiring me.

*

I am not a climate scientist. You may wonder why a particle physicist and cosmologist would wade, literally, into this subject. Because others, whose future depends on the policies governments enact and who also have to assess the discrepant claims emanating from politicians and the media, are not climate scientists either. If it isn't possible to explain the scientific principles and predictions associated with climate change in a straightforward and accessible fashion, then what hope is there for any rational public discourse and decision-making on the subject?

If the goal is to create something that provides readers a reasonably informed perspective of this subject in particular, where does one begin?

First off, it is worth recognizing that climate change science is *not* rocket science. Having once written a book about rocket science, or at least imaginary rocket science, I decided I was in a good position to judge. And the urgency of the issue is surely greater than pondering the possibilities of space travel in the twenty-third century, as fascinating as those might be.

Next, the details of large-scale supercomputer climate models that make detailed predictions about the future are complex and intimidating, but the underlying physics governing global warming is nevertheless straightforward and grounded in basic science. As a plus, it turns out there are historical twists and new connections between scientific disciplines that add spice. And for those who are particularly interested, a wealth of data is now freely available for anyone to follow up with on the web.

*

I am fortunate to have been educated by a number of climate change experts who are both colleagues and friends. For over a decade, I was chairman of the Board of Sponsors of the Bulletin of the Atomic Scientists. When I joined the board in 2006, we chose to include climate change as an additional existential threat when we decided upon the setting of the famous Doomsday Clock. Each fall, we would host a symposium to discuss scientific and technological challenges, then the science and security board, which included various climate experts, would further discuss the issues raised during the symposia when we decided on how to set the Clock. Later, I was fortunate to host several scientific meetings and public events on climate change. Most recently, the Origins Project Foundation I lead organized the Mekong cruise I lectured on.

I am thankful for the discussions I had with colleagues during these years, including James Hansen, Richard Somerville, Susan Solomon, Dan Schrag, Tony Haymet, Raymond Pierrehumbert, and the late Wallace Broecker, among others, many of whom also provided me with useful data and figures. I thank these individuals for their intellectual and personal generosity.

Numerous friends, colleagues, and experts were also kind enough to review this book at various stages. I am deeply indebted in particular to Richard Dawkins, Dan Schrag, Penn Jillette, Richard Somerville, Neil deGrasse Tyson, William Frucht, Sheldon Glashow, Keith Ogorek, and John Dahl for critically reading, commenting on, and improving this manuscript. I am also indebted to the numerous scientists who provided me with permission to reproduce figures from their work in this book. Any errors that remain are, of course, my own.

The support and encouragement I received from a host of people during and after the writing of this book have been particularly important. I was surprised and dismayed as numerous publishers and editors I reached out to indicated to me that they thought the only marketable books on climate change would be ones that appeal to emotions and communicate only to the true believers through a sense of doom and gloom. Since they are in some sense the gatekeepers for what information the public gets, this demonstrated to me how important it is to combat that perception with a book that could provide actual information the public can use to make informed decisions about how to respond to what they might read in the papers or hear from politicians.

The science behind climate change is accessible and interesting, and it should be the basis of arguments and policy discussions. Appealing purely to emotion or using scare tactics should not be the way to encourage action, just as encouraging inaction by denying the evidence and underlying science is inappropriate.

When I reached out beyond the publishing community to friends, colleagues, and fans of earlier books, I was encouraged to find that a book of this character was just what many people felt was needed, and that it should be distributed broadly. I thank all of those who helped reinforce my conviction that this book was necessary and who helped energize my efforts to make sure it reaches people who may find it useful for themselves or in their discussions with others. In particular, Susan Rabiner, Jahm Najafi, Thomas Houlon, Patty Barnes, Marylee MacDonald, Pamela

Paresky, and Richard Dawkins all helped me explore a variety of publishing options in my efforts to ensure that this book ultimately reached readers in its present form.

Happily, at the end of this process, I found the marvelous editor and publisher, Adam Bellow. From our very first discussion, it was clear we shared the same vision for the book and the need to ensure that science and reason and free and open dialogue remain an important part of the social fabric. I am very happy this book found a receptive home through Adam at Post Hill Press.

*

Climate change, evolution, and the Big Bang are all empirical facts, not speculation, and the relevant data validate fundamental theoretical expectations. This convergence reflects science at its best and most powerful. And it is the science I will concentrate on in this book. I will not advocate for specific policies; that is the purview of politicians, advocacy groups, and political movements. I will, however, be unabashed about the seriousness of the challenges we now face so the risks and possible consequences of inaction are manifest.

It would be disingenuous to imply that my agenda, while primarily scientific, did not also have an associated political purpose. But it is not one characterized by terms like liberal or conservative. It is simply this: Climate policy will ultimately be determined by various competing interests. Whether these reflect the broader interests of the public at large, whose lives, after all, will be most affected, is not obvious. In this, as in all things, governments usually follow rather than lead. Events of the past several decades, reaching a particular crescendo in the past four years, have validated the fact that democracy depends on an informed electorate, as well as informed legislators, if it is to function effectively.

It is in large measure our choice, which of the possible futures afforded to us will be that experienced by our children and grandchildren. We should enter into that future with our eyes wide open.

CHAPTER 1

A RIVER LIKE NO OTHER

> I thought how lovely and how strange a river is. A river is a river, always there, and yet the water flowing through it is never the same water and is never still. It's always changing and is always on the move. And over time the river itself changes too.
>
> —Aidan Chambers, *This Is All*

To travel down the Mekong River near its delta is to experience a waterway like no other in the world. Unnavigable for much of its 2,800-mile length, it is the longest river in Southeast Asia and the twelfth-longest river in the world. By the time the river flows past Phnom Penh in Cambodia and onward into Vietnam, the low-lying and flat terrain causes it to spread out into many separate branches. The Mekong basin covers an area the size of France and Germany combined. On average, the river is almost a mile wide and is far wider at many points. Khone Falls, on the Laos-Cambodian border, is the widest waterfall in the world. Its series of rapids and falls are almost seven miles wide, with a drop of seventy feet! All told, the river disgorges over 475 billion cubic meters of water each year into the sea, and it provides food and water for sixty million people.

*

The transformation of the river near the end of its journey to the sea is beautifully captured in John Keay's masterful book *Mad about* *the Mekong*, which retraces one of the nineteenth century's most remarkable and harrowing triumphs of exploration. In 1866, the French Mekong River Commission of twenty men embarked on a two-year journey up the Mekong, traveling a distance longer than the entire length of Africa, to map the full system. They started in Saigon and ultimately made it all the way to the Yangtze in China. Thirteen men survived the journey.

Keay poetically describes the Mekong's final push to the sea:

> The Mekong falls only six meters in its last eight hundred kilometers, but so low-lying is the Delta that the river in flood appears, and often is, the highest thing around. The land is so flat that from an upper deck you must allow for the curvature of the Earth's surface in counting the tiers of a distant pagoda... After forcing its way for thousands of kilometers through mountain gorge and deepest forest, it is as if the river can scarcely believe its good fortune. Like a sluice released, it wells across the plain, exploring the arroyos, tugging at pontoons, basking in backwaters and generally making the most of its first and last unimpeded kilometers...The Delta is said to produce more rice than any area of comparable size in the world. Beneath the glinting panes of water lie meadow and mud at no great depth. But rice-growing being a form of hydroponics, for the last six months of the year the fields are lakes and the landscape is a waterscape.

As lyrical as this description is, it still misses several of the river's most unique features. Because the lower Mekong Delta south of Phnom Penh lies just above sea level and is exceedingly flat, the shallowness of the river produces a striking annual variation. At Phnom Penh, the river is joined by the Tonlé Sap river and lake system. Depending on the season and the river's varying height, the direction of the Tonlé Sap actually changes. At times, it becomes a tributary, flowing into the Mekong. During flood season, the flow reverses, and the floodwaters flow along the Tonlé Sap into its large lake.

Beyond its annual ebbs and flows, the Mekong Delta experiences a daily surge that, while not unique in the world, is nevertheless rare enough to have aroused the fascination of the earliest Western visitors—and surprise all the rest of us who first learn about it. For much of the year, the delta experiences only one high tide from the surrounding China Sea each day.

While former Fox TV host Bill O'Reilly notoriously claimed that no one knows why the tides happen, in fact none other than Sir Isaac Newton explained the fundamental physics behind the tides when he developed his law of universal gravitation in the seventeenth century. As Newton described it, the gravitational force of the moon on the Earth varies as the inverse square of the distance between the moon and the Earth. Therefore, the side of the Earth nearest the moon, being slightly closer to the moon than the center of the Earth, is pulled with a stronger gravitational force than the average force on the Earth. Similarly, the side of the Earth opposite the position of the moon is pulled toward the moon with a smaller force. Ignoring for a moment the motion of the moon around the Earth, as the Earth rotates, one would expect two bulges to occur in the world's oceans: one on the side facing the moon and another on the opposite side. Roughly speaking, the first occurs because the water is pulled away from the Earth, and the second because the Earth is pulled away from the water. Looking down on the Earth-moon system, one would expect schematically to see something like Figure 1.1.

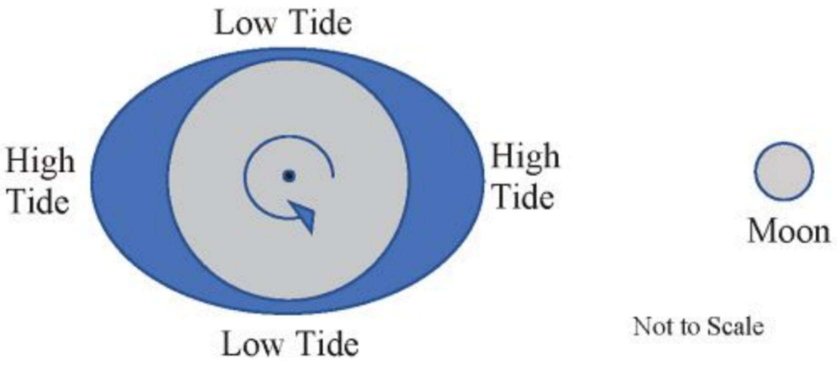


Figure 1.1[2]

As the Earth rotates fully once each day, each spot on the Earth would therefore be expected to experience two high tides and two low tides, as Newton famously described.

In practice, understanding the tides is more complicated. Water on Earth cannot instantaneously relocate to the equilibrium configuration shown in the figure, but must move from place to place, and flow rates depend on local conditions, including ocean depth. The rotation of the Earth and the motion of the moon must also be considered, as must the position of the sun.

Happily, however, we don't need to take all that into account to understand how two tides a day can turn into one tide a day. The key is to recognize that the moon does not orbit around the Earth's equator as the Earth rotates each day. The plane of its orbit is tilted relative to the Earth's axis, varying between eighteen and twenty-eight degrees relative to the equatorial axis of the Earth over an eighteen-year period. Consider the Earth-moon system in a frame where the Earth's axis of rotation is vertical (Figure 1.2).

The tidal response of the ocean, using the reasoning from the figure shown earlier, is seen in Figure 1.3.

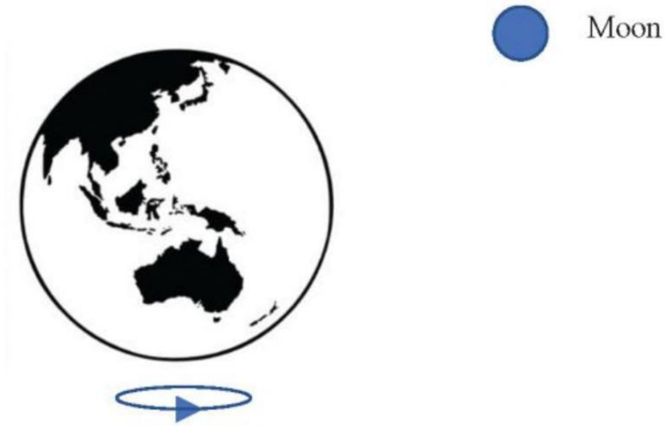


Figure 1.2[3]

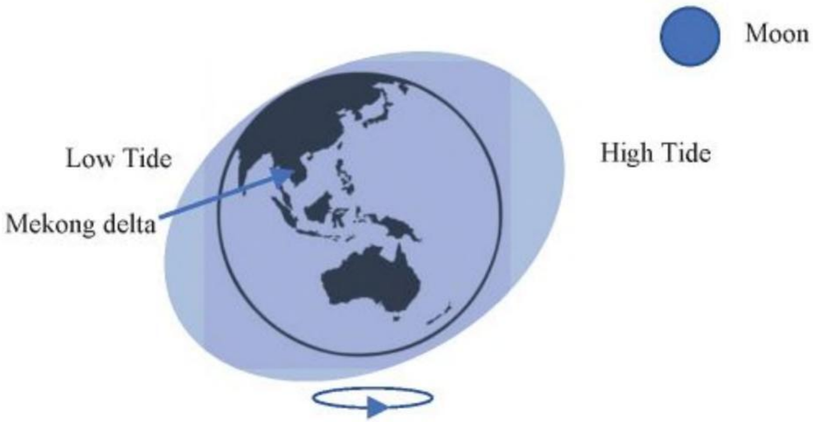


Figure 1.3[4]

The actual magnitude of tides and the relative size of the tides depend on local conditions. But roughly speaking, given the latitude of Vietnam and the position of the moon, as the Mekong Delta rotates around with the Earth, the seas in the region will tend to experience a high tide when southern Vietnam is on the side of the Earth facing the moon, where the bulge is big, and a low tide twelve hours later when it is on the far side, where the water has pulled away and there is no bulge.

I have belabored this issue not just because it involves a bit of astrophysics and is a frequent source of confusion, but because it plays an important role in the future of the Mekong ecosystem that will be relevant later. A large single daily tide impacts on the flow of the Mekong River itself. Again, to quote Keay:

> This diurnal mother-of-a-tide ought, of course, to spell disaster to the Delta. A salty inundation, albeit only once a day, would soon sour the world's most productive ricebowl and turn the green dazzle of paddy into maudlin thickets of mangroves like those along the Donnai below Saigon. What prevents such a disaster is the power of the mighty Mekong. The inrushing tide meets the outrushing river, and in the best traditions of ecological equilibrium they compromise. The river rises, its progress barred by the tide. The backing-up of the river by a big 'diurnal' is measurable as far upstream as Phnom Penh and beyond. But there and throughout the three to four hundred kilometers down to the sea, salination is barely detectable...The river thus defends the Delta from its deadliest foe since the rising waters are overwhelming its own, not the China Sea's.

The Mekong has the richest density of freshwater fish in the world and is home to what is estimated to be over one thousand species of fish. Directly supporting a population of over fourteen million people, a greater population of freshwater fish is harvested from the Mekong each year than from all the lakes and rivers in the US combined. Over the course of the year, its floods bring water and silt to nourish rice paddies, making the Mekong delta the world's most productive rice bowl.

While some of the most dramatic potential global impacts of climate change might not become manifest for many decades, centuries, or even millennia, the Mekong may be one of the first casualties in the battle to head off Earth 2.0. The shallowness of the river, the flatness of the delta, and the flooding caused both by the seasonal weather and the delicate balance of tides and river dynamics make the Mekong Delta particularly sensitive to even small near-term changes in any of these systems.

It is not just the highly publicized dire predictions of climate change that can have a dramatic impact on many people's lives. The Mekong Delta is a canary in a coal mine for climate change, and that is one reason I have begun this book by describing it and why I shall return to discuss the specific predictions and impacts for the Mekong region at the end of this book. But more than this, precisely because of its unique character, its richness, and its direct impact on a large surrounding population, the demise of the Mekong would have an impact far beyond the confines of Southeast Asia.

While the particular circumstances of the Mekong are unique, various other locations around the world live with similar fragile balances of opposing ecological forces, from the lowlands of Bangladesh to the everglades of Florida and the mouth of the mighty Mississippi. Climate change as a global issue may manifest itself in a thousand different ways in a thousand different places. But just as no man is an island, in an interconnected world, no single place and no single country is likely to be completely immune from the impact of even seemingly small changes first detected on the other side of the planet.

CHAPTER 2

HISTORY AND NUMBERS: HALF EMPTY OR HALF FULL?

> Some people see the glass half empty,
> some see it half full. I always saw the coffin half full.
>
> — Woody Allen, *Apropos of Nothing*

If you observe something you have never seen before, how do you determine if it is good or bad? Or if it is anomalously big or small? Dangerous or benign?

Perspective is everything, of course, but how can we gain it? The problem is numbers alone can be deceiving. The same data viewed in different contexts can appear to present a vastly different picture. Is the glass half-full or half-empty? This was the problem facing those who were first presented with estimates of carbon dioxide (CO_2) concentrations in the Earth's atmosphere.

In 1953, Charles David Keeling had just begun a postdoctoral position at Caltech. Originally he was working on a project to extract uranium from granite, but then moved to another geochemical problem: investigating how carbonate achieves equilibrium in a mixture of water, limestone, and atmospheric CO_2. To do this, he needed to construct a precision device to measure CO_2 extracted from the air and water.

To test his apparatus, he measured the CO_2 concentration in various locations in Pasadena but found significant variations, which he figured were probably due to locations of heavy industry. So he took the equipment up to a more isolated spot: Big Sur, near

Monterey, California. During every afternoon he measured the same value of CO_2 concentration in the atmosphere, 310 parts per million (ppm). He started taking samples during both night and day to get better estimates and discovered a diurnal pattern he hadn't anticipated. At night, there was more CO_2 in the air than there was during the day. Also, with great prescience, he measured the ratio of ^{13}C to ^{12}C and discovered this ratio was smaller at night than during the day.

Checking a meteorology book, Keeling discovered that the concentrations he measured were representative of uniform mixing with the "free-atmospheric" concentrations that prevailed over the continent. However, at night there was a lower boundary layer so the air measured was more heavily influenced by concentrations near the ground, where local plant and soil respiration would be systematically more important. This interpretation was confirmed by a decrease in the $^{13}C/^{12}C$ ratios at night, as plants preferentially respire ^{12}C.

In 1956 Roger Revelle at Scripps Institution of Oceanography and Harry Wexler at the US Weather Bureau joined with Keeling to suggest a bolder global measurement of CO_2 during the upcoming International Geophysical Year (1957–58) at a variety of remote locations presumably unaffected by local contamination, including the South Pole station and at Mauna Loa in Hawaii.

In March 1958 Keeling installed his first infrared gas analyzer at Mauna Loa, and on its first day of use, it recorded a concentration of 313 ppm. This was the first reading in what has become one of the most significant continuous terrestrial scientific projects ever carried out. It has been ongoing for the last sixty-two years and has given the world its first quantitative assessment of the impact of global industrial activity on the composition of the atmosphere.

Over the first few months of its installation, Keeling noticed a surprising monthly increase in CO_2 concentrations up until May. After this it declined again until October, and this pattern repeated in 1959. It was as if the Earth was breathing in and out once each year.

It actually is, due to the existence of life on our planet.

Life has changed the composition of the Earth's atmosphere since its inception some four billion years ago, and it continues to govern the dynamics of CO_2 on the planet today. What Keeling was detecting was a modern annual cyclic version of the ancient processes of life that first produced the existing atmosphere on the planet today. He was directly observing, for the first time, the seasonal impact life has on the atmosphere in the Northern Hemisphere through the process of photosynthesis in plants, which converts CO_2 and water into organic compounds with O_2 as a residue. As Keeling later put it in a 1960 article, "We were witnessing for the first time nature's withdrawing CO_2 from the air for plant growth during summer and returning it each succeeding winter."

The second significant observation Keeling made between 1958 and 1960 at Mauna Loa was that the average concentration of CO_2 measurably increased during this period. If one considers comparable months each year, March CO_2 levels went from 313.4 ppm in 1958 to 314.4 ppm in 1960. A somewhat more dramatic effect was observed from samples taken from surface flasks collected at the South Pole, which increased from 311.1 ppm in September 1957 to 314 ppm in September 1959.

Were such small increases significant? Noting that the increase observed at the South Pole was consistent with what one would expect from the terrestrial combustion of fossil fuels, Keeling was nevertheless well aware that claiming a trend based on such a small time sequence was dangerous. Here is how he put it in his first paper for the Scripps Institution of Oceanography in March of 1960:

> Where data extend beyond one year, averages for the second year are higher than for the first year. At the South Pole, where the longest record exists, the concentration has increased at the rate of about 1.3 ppm per year. Over the northern Pacific Ocean, the increase appears to be between

> 0.5 and 1.2 ppm per year. Since measurements are still in progress, more reliable estimates of annual increase should be available in the future. At the South Pole the observed rate of increase is nearly that to be expected from the combustion of fossil fuel (1.4 ppm), if no removal from the atmosphere takes place. From this agreement one might be led to conclude that the oceans have been without effect in reducing the annual increase in concentration resulting from the combustion of fossil fuel. Since the seasonal variation in concentration observed in the northern hemisphere is several times larger than the annual increase, it is reasonable to suppose, however, that a small change in the factors producing this seasonal variation may also have produced an annual change counteracting an oceanic effect.

This skepticism is the hallmark of good science. Was the observed increase significant? If the expected annual output of CO_2 due to human industrial activity was smaller in magnitude than the seasonal variation itself, was it possible to claim a signal amidst the noise? What was the role of the oceans in possibly moderating this signal? Beyond this, did a CO_2 concentration of 310 ppm itself reflect anything important about the global dynamics of the planet as it is affected by life, including human life?

These were all important questions in 1960, some of which had been anticipated a few years earlier by the pioneering oceanographer Roger Revelle and his colleagues at Scripps. This is probably one of the reasons Revelle enlisted Keeling in his own effort. To begin to answer these questions, accurate measuring would have to be carried out from remote locations regularly for long periods. That, of course, is what has happened. Every day for the past sixty-two years at Mauna Loa, CO_2 has been measured by the technique first used by Keeling, involving infrared gas analyzers that measure the absorption of infrared radiation in atmospheric samples and compare it with absorption rates in samples with known calibrated CO_2 concentrations. The result has been one of the most famous plots in science, appropriately named the Keeling Curve. Scripps Institution updates the curve every day and presents the data for public consumption. Figure 2.1 shows the curve up to the day I wrote this chapter, when the CO_2 reading was 415.19 ppm.

The seasonal variation first observed by Keeling is obvious, but now so is the monotonic rise in the average value of the CO_2 concentration year over year that was first tentatively inferred by Keeling in 1960. Recall that, in 1958, the peak abundance was about 315 ppm. The value today is therefore more than 30 percent larger than the measured atmospheric abundance at that time.

What are we to make of this? As a physicist, the first thing I generally do is examine orders of magnitude, which usually give some perspective on any measurement. The CO_2 abundance has increased by about 100 ppm in sixty-two years. This is about 1.6 ppm per year. Recall that Keeling himself estimated the CO_2 generation by fossil fuel consumption in 1960 to be about 1.4 ppm, about the same order of magnitude.

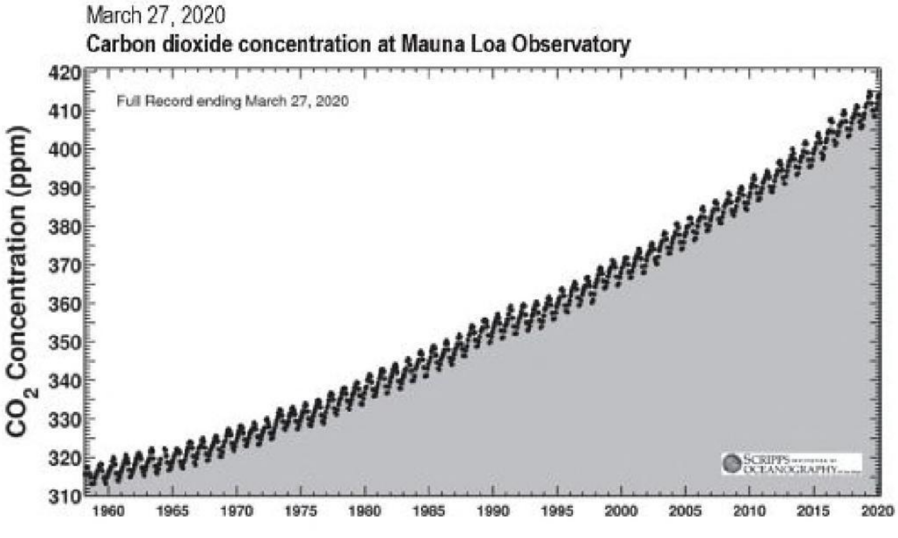


Figure 2.1[5]

Note, however, that global annual CO_2 emissions have increased by a factor of five since 1960, while the slope of the Keeling curve has not increased by a similar factor. Should this give us pause? Perhaps, except Keeling himself pointed out a very plausible reason why one might expect that not all the CO_2 being produced by humanity would be reflected directly by a concomitant rise in atmospheric CO_2 content. CO_2 can dissolve in water, creating carbonic acid, so one would expect some CO_2 to be taken up by the oceans. So, the rough quantitative correlation between the observed rise and our human contribution is, at the very least, suggestive.

Perspective is everything, however, and we must always remember a key warning in science: correlation does *not* imply causation. So, it is possible, without some underlying physical explanation and without more data, that the comparable rates of CO_2 in the atmosphere and human-generated CO_2 is just a coincidence.

To get a better idea of whether the observed CO_2 increase is correlated to human industrial activity, we can hope to explore longer-term variations to see if the current fossil fuel-generating era is anomalous or not. But Charles Keeling wasn't making direct measurements before 1958, and before his time the few direct measurements that were made were scattershot and discordant.

Fortunately, however, nature has given us a time capsule. In places that remain frozen all year long, ice builds up as snow falls. It is for this reason that places like Greenland and Antarctica have ice sheets over a mile thick. Like the growth of tree rings or sedimentary layers of rock, as one drills deeper into ice, one encounters ice layers that were deposited at ever-earlier times. And like growth rings, ice deposition is different in summer than in winter, so a regular pattern allows one to literally count years. Many cores are extracted from each area so better estimates can be obtained.

Figure 2.2 shows examples of core sites from a recent US International Trans-Antarctic Scientific Expedition study in Antarctica.

In the ice there are bubbles. Air gets trapped in the snow as it is compressed, and the bubbles therefore reflect the atmosphere at the time and place when the ice first formed. Measure the gas composition of the bubbles and you know the gas composition at that time and place. Since Greenland and Antarctica have the deepest, largest, and historically the most stable ice conglomerations, most ice cores come from these two locations, and at their upper layers, can be compared with the direct measurements going back to 1958 to calibrate the ice core estimates. Because each location gets a lot of snow each year, ice from successive years can be visually separated relatively easily so good time resolution is possible as well. It is also fortunate that Greenland and Antarctica are in opposite hemispheres, so in some sense comparing values from ice cores in both locations gives us both a global consistency check as well as a global average for each period.

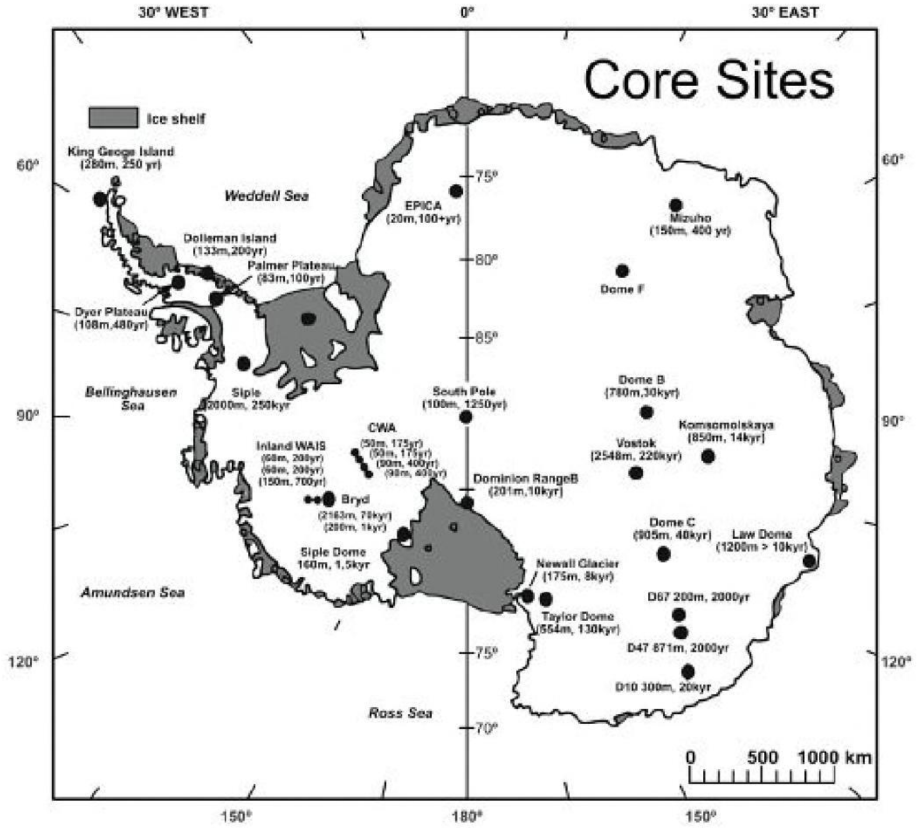


Figure 2.2[6]

Let’s take a walk back in time using the ice core data. Scripps Institution provides graphical examples of the data before 1958, matched to their own measurements from 1958 onward (where the black line thickens). Figure 2.3 shows the data going back to 1700, before the advent of the modern industrial era.

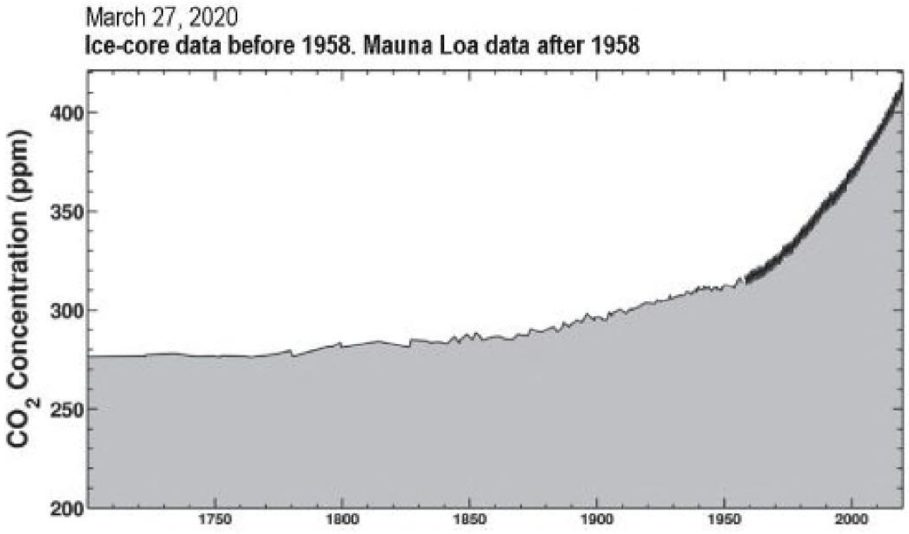


Figure 2.3[7]

Alternatively, one can go back to the dawn of human recorded history, about ten thousand years (Figure 2.4).

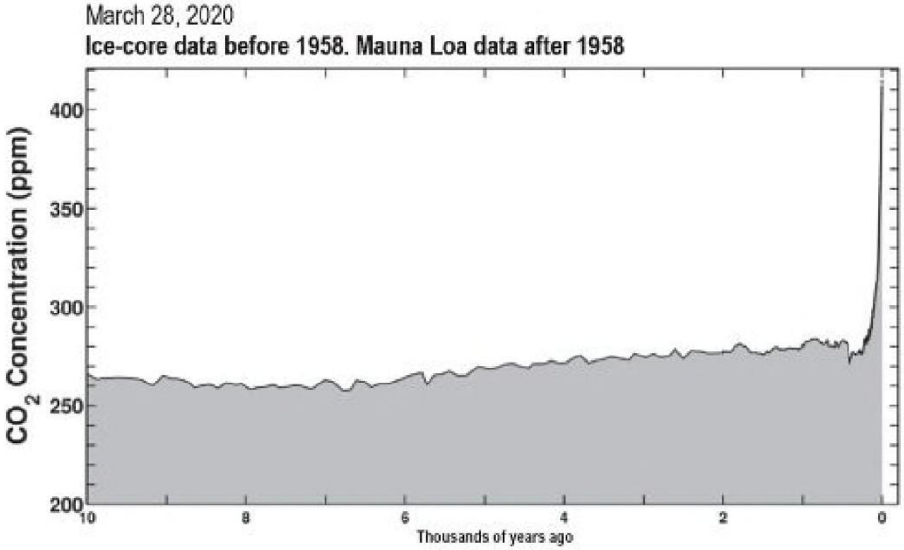


Figure 2.4[8]

The ice core record actually goes back about eight hundred thousand years. Here is the full record (Figure 2.5).

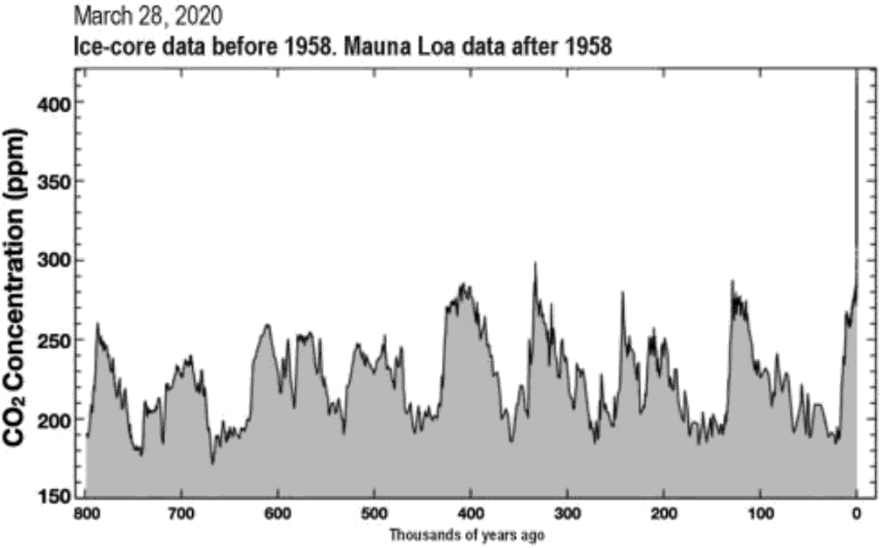


Figure 2.5[2]

Because this last figure spans so much time, it is useful to point out some markers to guide you. Of some relevance is the correlation between ice age and interglacial period, caused by periodic variations in the orbit of the Earth around the sun, with low and high CO_2 concentrations, respectively. Also, an important overall baseline number for comparison is the highest concentration of CO_2 previous to the present era, which was at 300 ppm, about 350,000 years ago (Figure 2.6).

Returning to the original Keeling curve, we can compare it to the global CO_2 emission from human activity, as taken from a figure prepared by the Global Carbon Project (Figure 2.7).

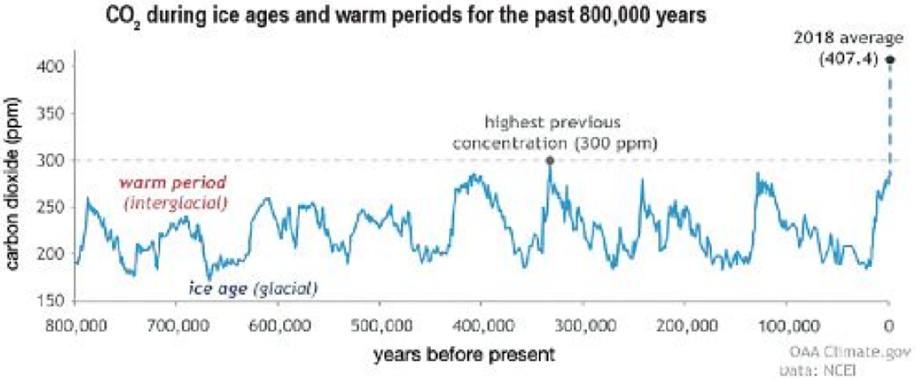


Figure 2.6[10]

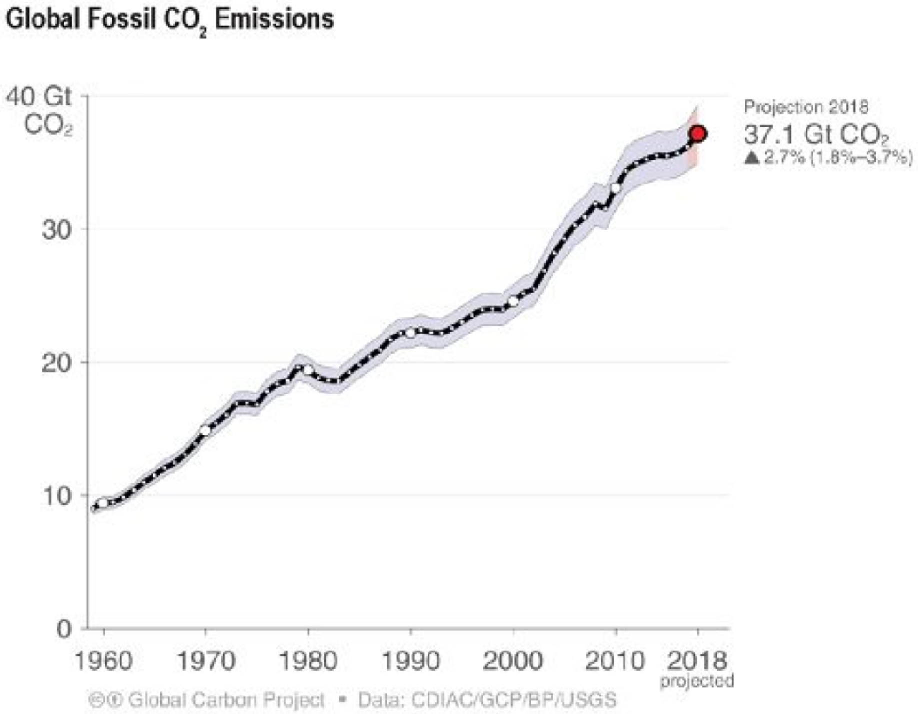


Figure 2.7[11]

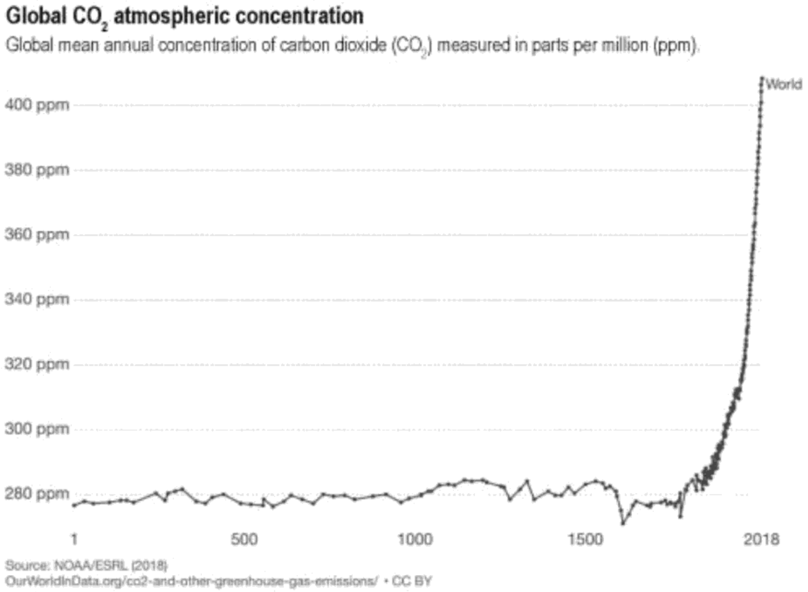
The monotonic rise in CO$_2$ production is compatible with the Keeling data, and the dip in slope visible after 1990, when the first IPCC report was followed by the Kyoto Protocol, is also reflected in the Keeling curve. Marginally visible is the increase in slope in the

1970s preceding 1974, followed by a dip at that time due to the first oil crisis.

What are the immediate takeaways from this data? Some things stand out: (a) the present era is unprecedented in the recorded history of CO_2 in the atmosphere of the planet over almost the past million years; (b) geological variations in the CO_2 concentration have occurred, but at much smaller levels and over much longer timescales than the recently observed rise; (c) those times with higher levels of CO_2 in the atmosphere appear correlated with warming periods, and those times with lower levels with ice ages; (d) the rise began with the beginning of the modern industrial era, and the rate and overall magnitude of increase appears commensurate with global fossil fuel consumption by human industrial activity; and (e) the economic and political vicissitudes of the human condition appear to be reflected at some level in the recent undulations in directly measured atmospheric CO_2 concentrations.

The connection between CO_2 concentration in the atmosphere and the growth of human industrial production and fossil fuel appears unambiguous, making the current era qualitatively and quantitatively new in recorded human history. But is this quantitative change likely to be significant from the point of view of climate? That will require a discussion of the basic dynamics of CO_2 on Earth, which we shall turn to next.

Before completing this historical tour, however, there is one more curve of CO_2 concentration that I find personally compelling. I have shown plots over the recent era, over the industrial era, and over geological eras. The following is a plot over the last two thousand years. All of the modern dramas in human civilization took place over this time, from the rise of Christianity to the fall of Rome, the creation of Islam, the dynasties of China, the medieval era, imperial wars, and in the west, the Enlightenment, the Renaissance, and ultimately the modern technological world, including the atom bomb and two world wars. During this time the human population has grown from perhaps two hundred million to almost eight billion, a fortyfold increase. The energy use per human has increased by a far larger rate. During almost all of these remarkable developments of modern civilization, humans had little global physical impact on the planet—until today.



Global CO_2 atmospheric concentration

Global mean annual concentration of carbon dioxide (CO_2) measured in parts per million (ppm).

Source: NOAA/ESRL (2018)
OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY

[12]

CHAPTER 3

CYCLES AND CYCLES

I celebrate myself, and sing myself,
And what I assume you shall assume,
For every atom belonging to me as good belongs to you.

— Walt Whitman, "Song of Myself"

The history of Earth is a history of overlapping cycles, repeated with great regularity on ever-decreasing timescales. We are relative latecomers to that history, and while we often imagine ourselves as the Masters of the Universe, we are nevertheless the slaves of chemistry.

Every atom that makes up you and me has been recycled throughout the universe and throughout Earth on its cosmic journey. Yes, we are stardust, but we are also intimately connected to everything that has ever lived on Earth and to the very rocks we walk on, water we swim in, and air we breathe.

With the exception of hydrogen, every other element in Earth's atmosphere, and in our bodies, including carbon, oxygen, and nitrogen, was fabricated in the fiery cores of stars. Their explosive deaths in supernova explosions seeded the galaxy for the formation of new stars and the solar systems that formed around them. Hydrogen is the dominant element in the universe, but stars produce significant amounts of carbon, nitrogen, and oxygen, as well as silicon and iron, during their lifetimes. This accounts for the fact that iron and silicon make up much of the interior of rocky planets like Earth, as well as the interior of asteroids and meteoroids that orbit throughout the solar system. Equally important, planets large enough to have atmospheres and hold on to them for billions of years have lighter elements, like carbon, nitrogen, and oxygen, and compounds containing hydrogen, dominating their atmospheres.

From the dawn of terrestrial time, these elements have been recycled throughout the planet. The hellish period of the Earth shortly after the gigantic impact that created the moon and liquified much of the planet is called the Hadean period, after Hades, and for good reason. As the molten rock condensed after the impact within a few thousand years, a dense atmosphere was left behind containing mostly CO_2, hydrogen, and water vapor, with no free oxygen. Estimates are this early atmosphere was almost thirty times denser than our current atmosphere, and the dominant gas was CO_2. This means this initial concentration of CO_2 in the early atmosphere was well over ten thousand times greater than it is today.

CO_2 was reduced to its present abundance as a result of the first great carbon cycle on Earth, the geological cycle. Before the emergence of life, it was the only carbon cycle. The dense CO_2 layer began to decrease as the Earth cooled and liquid water oceans began to cover the Earth's surface. This first bit of chemistry is simple. Carbon dioxide dissolves in water and combines with it to form carbonic acid:

$$H_2O + CO_2 = H_2CO_3$$

The carbonic acid interacts in the ocean, or with the rock, forming substances called carbonates, where a CO_3^{2-} ion combines with things like calcium, magnesium, or iron. These tend to be insoluble in water and sink to the bottom of the ocean floor (like the buildup of scale inside pipes with hard water), effectively removing carbon from the atmosphere-ocean system.

This process could not continue indefinitely if that were the end of the story, as eventually some equilibrium between the