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Temperature

1.5 degrees Celsius.

That's the amount the Earth's surface has on average warmed since the start of the industrial revolution in the late 18th century and is linked with increased emissions of greenhouse gases from the combustion of fossil fuels.

That is an example of a deceptively simple statement that you might soon find in a newspaper article. But there is a lot to unpick.

The industrial revolution, starting in the second half of the 18th century, led to a massive increase in the combustion of fossil fuels such as coal, and later oil and gas, and the subsequent release of *greenhouse gases* to the atmosphere. These gases absorb some of the Earth's outgoing radiation and slow its escape to space, keeping the planet warmer. Consequently, the industrial revolution literally changed the world we live in now.

Changes in the Earth's global mean[1] surface temperature—literally the global average temperature increase of the Earth's

[1] I use the terms *mean* and *average* interchangeably throughout the book. Mean is the most commonly used *average* quantity. To avoid any doubt, the mean is calculated

surface—are synonymous with climate. What is the relationship between rising atmospheric greenhouse gases and surface warming? And why does it matter that the world has warmed by such a small amount? Hasn't the Earth been warmer than it is now? How do we even know the Earth's temperature is changing? And why are scientists so certain that human-driven emissions of greenhouse gases have played a major role in this warming? What about low and high-temperature extremes across the globe? Are they also harbingers of the impending climate? Where are surface temperatures headed in the future?

These are all reasonable questions that you *should* ask. Sadly, the quality of the answer to these questions can vary depending on where you search online and who you ask. In this chapter, I will briefly introduce and explain our planet's temperature record. To understand recent (100 year) changes in temperature, I will introduce you to some of the necessary science concepts.

Temperature naturally goes and up and down everywhere on the planet on varying timescales—from seconds to decades and longer. Weather is the state of the atmosphere at a particular location and point in time and generally includes meteorological quantities like temperature, sunshine, cloudiness, windiness, wetness, and, more recently, pollen and air quality. It is everything we expect to know from our daily weather forecast. It is this information that helps us make decisions about whether to wrap up warm or to expose our bare legs. And as we all know, the weather can change on timescales of minutes to days, and in the UK it often does. In other parts of the world, such as Ecuador, weather is less variable. As we discuss in Chapter 3, a lot of the weather we experience in the

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by adding all individual values and dividing by the number of values being added.

northern mid-latitudes is related to undulations of a ribbon of fast-moving air called the *jet stream*.

In contrast to weather, climate refers to changes in temperature (and other meteorological quantities) on longer timescales. The most noticeable example of climate is the seasons. If you live outside the tropics, you know that temperatures are generally higher in summer months and lower during winter months, and somewhere in between in spring and autumn months. These seasonal swings in temperature act as prompts for the natural world—for trees to grow leaves, flowers to bloom, and animals to hibernate. These swings are due to the way the Earth tilts relative to the Sun and the direction of that tilt as it makes its way around the Sun every 365-ish days. The impact of the Earth's tilt is more pronounced at higher latitudes, which is why there are more defined seasons in these parts of the globe. For example, during northern hemisphere summer months the Earth is tilted towards the Sun and the southern hemisphere is tilted away from the Sun (during their winter months). Climate also refers to changes on timescales much longer than the seasons.

Climate *change* describes shifts in the expected climate state over the longer term. These changes are not about whether January 2012 was warmer than January 1984. It is concerned about, for example, how the temperature at a particular location or averaged across the globe has changed between the 1980s and the 2010s. Why? Because, as we discuss later, there will always be odd years that are warmer or cooler than we expect. Climate change is about the frequency of those odd years and how they eventually become the new norm.

Let's think about what might cause an irregular year. This could be an isolated event like a large volcanic eruption, which could result in a global-scale change in temperature.

In 1991, Mount Pinatubo in the Philippines erupted with great ferocity. The energy of the eruption was so large it lofted huge amounts of debris (dust and gases) straight into the stratosphere, an atmospheric layer that starts at 10–15 km above the Earth's surface. This blanket of debris high up in the atmosphere (20–30 km) blocked a significant fraction of incoming sunlight. This reduced the amount of sunlight reaching the Earth's surface over large parts of the globe, leading to a drop in global surface temperature of 0.6°C. This blanket also scattered the remaining sunlight in a way that led it to reach deeper into thick forests. Surprisingly, this helped many plants photosynthesize more effectively, even with less direct sunlight. The dust and ash that had blanketed the atmosphere dispersed and washed out after 15 months, or so, and the global mean temperature quickly recovered. Thankfully, such volcanic eruptions are rare (and are not caused by or affected by changes in climate) but they serve as an example of how the Earth's global mean temperature can occasionally drop in a way that is not related to the overall climate trend. The long-term climate change trend (right now, at least) is warming.

At this point, it is also worth mentioning that global mean surface temperature hides a lot. There are places around the world that have cooled but there are more places that have warmed more rapidly. Some regions are experiencing more frequent and intense heatwaves, with temperatures regularly exceeding 50°C. This makes it increasingly challenging for people to live and work in these areas. While there are regional variations, the global mean temperature gives the overall picture of what's going on.

That's the big picture. To gain a deeper understanding of the Earth's climate we need to understand a bit more about the meaning of temperature, which involves us thinking about molecules.

Moving molecules keep us warm

Let me begin by reminding you that we are all sitting on top of a small rock, albeit with an important molten core of iron and nickel that plays an important role in maintaining our protective magnetic shield. Our rock has a radius of about 6,371 km—this is the distance from the centre of the rock to its surface. Everyone and everything that has ever lived has been on this rock that has a total surface area of 510 million km^2 of which about 71% is currently covered by liquid water. At last count, it is currently home to over 8 billion people and 10 quintillion (10 followed by 21 zeros) insects, and a lot fewer other animals.

Our primary source of energy is a star, the Sun, which has a radius of 700,000 km and is almost 150 million km away from us. To put that into perspective, if the Sun were the size of a tennis ball, the Earth would be 7 metres away and a millimetre across (approximately the thickness of a credit card).

The Sun has a surface temperature of some 5,700°C. But here we all are on a planet with a global mean temperature of about 15°C that harbours a myriad of flora and fauna, capable of being self-sufficient on a planetary scale. How is this possible?

Before I begin to answer that question, I need to explain temperature for you. Yes, it seems daft because you will be familiar with temperature and use it in your daily life, but we need to discuss it in terms of moving molecules.

In our everyday lives, if we want to *describe* temperature, we use degrees Celsius or degrees Fahrenheit, depending on your age and where you live. But these values are only a metric for human understanding. For example, Celsius is intentionally defined by the state of water: at 0°C liquid water freezes and at 100°C liquid water boils transforming into its gas phase. And you will already have an intuitive sense of temperature, built up over time and with experience, enabling you to use the weather forecast to guide your choice of warm or cool clothing.

Temperature is a *measure* of the average energy associated with the motion of molecules within a thing—*kinetic energy*. The hotter the thing (e.g. the Earth, a wooden table, you, a hydrogen atom) the faster the constituent molecules are moving. The same is true for the atmosphere.

Rather than Celsius or Fahrenheit, physical scientists tend to use kelvin (denoted as K) to describe temperature because of the way this metric of temperature is defined from absolute zero. Absolute zero kelvin is a theoretical idea that corresponds to a complete absence of any molecular motion; in practice this temperature is impossible to achieve although experimental scientists have been able to get extremely close, to just under a billionth of a kelvin above absolute zero. The difference between Celsius and kelvin is an offset so that 0°C is equivalent to 273.15 K or absolute zero kelvin is equivalent to negative 273.15°C.

To relate the kinetic energy of a molecule, E (described by the joule and abbreviated J, see footnote[2]), to its temperature, T (in kelvin), we can use a simple formula $E = 3/2\, k_B T$, assuming the constituent molecules can move in all three dimensions, where k_B is the *Boltzmann constant*.[3] Essentially, this little formula relates the temperature of a thing to the amount

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[2] For completeness, I have included the units for various quantities throughout the book, such as seconds (s) for time. Don't worry if some units are unfamiliar—they aren't essential for understanding the text.

[3] This constant has an approximate value of 1.38×10^{-23} J/K.

of kinetic energy it possesses. It is kinetic energy that helps to determine whether our thing is in the solid, liquid, or gaseous phase. As kinetic energy increases, molecules can overcome the intermolecular bonds holding them together. When their kinetic energy exceeds the energy of these bonds, molecules are free to move relative to one another, causing the substance to transition from a solid to a liquid, or from a liquid to a gas.

As you move through the book, we will also discuss the concept of heat. Heat describes the *transfer* of energy from a hotter object to a cooler one. When a hotter object (with faster-moving molecules) comes into contact with a cooler object (with slower-moving molecules), the faster molecules collide with the slower molecules. With each collision, energy is transferred so that the faster molecules slow down, and the slow molecules speed up. This process continues until the molecules in both objects have the same average speed—at this point, the two objects will have the same temperature and *thermal equilibrium* is reached.

There are two types of heat relevant to our climate discussion: *sensible heat* and *latent heat*. Sensible heat is the heat you can sense with a traditional thermometer. Latent heat refers to heat that is released or absorbed as a substance changes its phase (e.g. ice to liquid water, and liquid water to water vapour), which does not result in a temperature change (more about that in Chapter 4). As mentioned earlier, higher temperatures result in molecules in the air moving more quickly, so that they bump into each other more often. Every time one of these molecules collides with the side of the thermometer, some energy is transferred to the molecules of liquid in the thermometer. As a result, the molecules in the liquid increase their kinetic energy, moving more vigorously and thereby expanding the liquid. This phenomenon is what causes the liquid in a thermometer to rise inside its little tube when the air temperature warms.

The importance of our Sun in the Earth's temperature

The Sun generates its energy from the fusion of hydrogen nuclei to form helium near the core, where temperatures exceed 15 million K and the pressure is nearly 250 billion times the Earth's pressure at sea level. At these enormous values of temperature and pressure, the subatomic structure of atoms is reorganized, allowing hydrogen nuclei to fuse and form helium. During this fusion process, a small amount of mass (m) is converted to energy (E) (via the famous relationship that relates mass to energy, $E = mc^2$, where c represents the speed of light) in the form of heat and light. The temperature of the visible surface of the Sun is much lower at only 5,700 K. This massive drop in temperature is associated with the density and movement of solar material in its upper layers.

Understanding how objects emit and absorb electromagnetic radiation is fundamental to understanding temperature. To explore this, I need to introduce the concept of a *black body*. This is an idealized object that absorbs all types of radiation in the *electromagnetic spectrum*, including (higher energy) gamma rays, visible light wavelengths, and (lower energy) radio waves.

In thermal equilibrium (in other words, at constant temperature) the *Stefan–Boltzmann law* describes the power radiated from a black body as a function of the fourth power of temperature (temperature multiplied by itself four times): σT^4, where σ denotes the *Stefan–Boltzmann constant* (approximately 5.67×10^{-8} J/s/m^2/K^4), where s denotes seconds and m denotes metres. This is equivalent to the total energy radiated (across all wavelengths) per unit surface area of that object per second. The amount of energy radiated by an object varies with wavelength, with a peak related to the temperature of the radiating object (Chapter 2). At human temperatures (skin temperature of 33°C) our peak power is associated with thermal radiation wavelengths. Generally, higher temperatures result in radiation peaking at shorter (more energetic) wavelengths.

At the Sun's temperature, electromagnetic radiation is emitted across a wide range of energies with a peak at the green part of the visible spectrum, but also (at smaller amounts) at much higher energy X-rays and much lower energy radio waves. The Sun is our source of light for the Earth, essential for establishing and sustaining life. Light describes the visible part of the electromagnetic spectrum that ranges from 390 (violet) to 700 (red) billionths of a metre.

The energy released by the Sun is huge and is given by the black body calculation $\sigma T^4 \approx 63{,}200{,}000$ J/s/m^2 for an area of one square metre. The power of the Sun is the energy multiplied by its surface area described by its radius R ($4\pi R^2 \approx 6 \times 10^{18}$ m^2) resulting in 4×10^{26} J/s or 400 yotta J/s in scientific jargon.

The energy emitted by the Sun, including visible light, radiates outwards in all directions. Think of the Sun's energy as a bubble you blow from some soapy mixture. As the size of the radiating bubble increases, the Sun's radiating power emanating from its surface is spread across a larger surface area: the bigger the bubble the less power per unit area. The surface area of a sphere is $4\pi r^2$ so it is proportional to the square of its radius r, i.e. $r \times r$. So, the power per unit area on the radiating bubble moving outward from the Sun reduces by $1/r^2$—also known as the *inverse square relationship*. A relatable analogy is a torch being shone in the dark. The light from the torch becomes less intense (less bright) the farther you are from the source because the same amount of light is spread over a larger area.

This inverse square relationship saves the Earth from being fried by the Sun. Between us and the Sun we have about 150,000,000 km of near vacuum, so that in the eight minutes it takes light to travel from the Sun to the Earth the Sun's power per unit area is reduced by a factor of 22,500,000,000,000,000. The Sun's radiating bubble intercepts the Earth where the power[4] per unit area is now 1,367 W/m^2. We call this the *solar constant*, although its value varies slightly due to the Earth's non-circular orbit around the Sun and to regular changes in the Sun's energy output (see next paragraph). It is our free energy supply and has driven much of the Earth's climate history. That incident solar energy intercepts the daylight disc of the Earth, which has area of πr^2, where r denotes the Earth's radius. This energy eventually spreads out over the whole surface area of the Earth including the nightside, which has a larger surface area, given by $4\pi r^2$. Consequently, the energy received by the Earth every square metre and every second is on average $1{,}367/4 = 342\ W/m^2$.

The Sun's output is not strictly constant. There is a solar cycle with a period of approximately 11 years due to changes in the magnetic fields on the Sun that impede the convection of material below the Sun's radiating surface (*photosphere*). This results in lower temperatures at the Sun's photosphere. These cooler spots appear as dark blotches on the Sun's surface and are known as *sunspots*. These sunspots emerge at mid-latitudes

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[4] Power describes how fast energy is transferred or used. It has a unit of a watt, abbreviated to W, which is equivalent to one joule of energy per second. In other words, $W = J/s$. Power per unit area (W/m^2 or $J/s/m^2$) is what scientists call an energy *flux*—how much energy passes through an area every second—and is a quantity used widely in climate science to describe energy transfer.

on the Sun and propagate to the equator. Differences in the extremes of this solar cycle represent only 0.1% of the solar constant. While this solar cycle has been linked with changes in weather, measurements do not show trends that would go anywhere near explaining changes in the Earth's climate.

Changes in *solar weather* are also important because the radiation is accompanied by a stream of charged particles released by the upper atmosphere of the Sun, the *solar wind*. The rotating molten iron and nickel core of the Earth is central in maintaining a magnetic field that deflects most of these charged particles from reaching the upper atmosphere. Some of these particles get trapped and accelerated along magnetic lines into the upper atmosphere where they collide with atoms and molecules (e.g. predominantly oxygen and nitrogen) that subsequently radiate light in mesmerizing patterns that we call *auroras* or—as they are more commonly known—the northern lights (aurora borealis) and the southern lights (aurora australis). Without that molten iron and nickel core that maintains our magnetic field, the solar wind would have stripped away our atmosphere long ago, leaving the Earth a barren chunk of rock.

Our warming atmosphere

Let's for the moment assume the Earth's atmosphere is absent. In our thought experiment, the Earth is a bare rock in space. What happens to it? Solar radiation will begin to heat the rock, but some of the incoming radiation will be reflected to space. The fraction of incoming solar radiation reflected to space is called the *albedo*. For the Earth, the albedo is about 0.3, which means 30% of what we get from the Sun is sent back to space and 70% of incoming solar radiation (342 W/m^2) is absorbed (239 W/m^2). The amount of energy absorbed by the Earth's surface is approximately balanced by the energy it radiates back to space. We can calculate the corresponding temperature of the Earth's surface by balancing the incoming solar radiation with the radiation emitted by the Earth: $\sigma T^4 = 239\ W/m^2$. After using a little algebra, we get a temperature (T) of 255 K. That number is the *equilibrium temperature* of the Earth—the temperature at which our bare rock is in thermal equilibrium with its space surroundings. That is a bona fide climate calculation.

What you might notice is that 255 K is not that warm. It's a chilly 18°C below zero. That is close to the temperature in your freezer. The observed global annual mean surface temperature is closer to 15°C above zero, a discrepancy of 33°C. What are we missing? What we intentionally left out of our calculation is, of course, the atmosphere. The atmosphere acts as an insulating layer that keeps the Earth's surface warm.

The Earth's atmosphere is a thin, protective, gaseous layer. It stretches from the Earth's surface to about 600 km in altitude, where it merges seamlessly into outer space. At an altitude of 100 km, the atmosphere is already too thin for conventional aircraft to fly and is a commonly accepted definition of the boundary of outer space. However, for all intents and purposes, the atmosphere is mostly below 32 km—about 99% of the mass of the atmosphere above your head is within the lowest 32 km, with the remaining 1% spread over hundreds of kilometres. The Earth's atmosphere is comprised mostly of molecular nitrogen or N_2 (a shade higher than 78%) and molecular oxygen or O_2 (a fraction smaller than 21%). Most of the remaining percent is taken up by argon. What's left is just 0.04% of the Earth's atmosphere, including everything we rely on for survival and everything that is challenging our existence on the Earth. Our very survival on the Earth literally relies on just a few physical and chemical properties of the atmosphere.

So, let's now add an atmosphere to our climate calculation above. About 29% of incoming sunlight is reflected to space and about 23% is absorbed by the Earth's atmosphere, mainly due to water vapour, ozone, and dust. As a result, about 47% of incoming sunlight passes right through the atmosphere.[5] That energy is what is available to directly heat the Earth's surface. The energy budget of the Earth is discussed in more detail in Chapter 2.

Not all gases interact with radiation in the same way. Gases absorb and emit radiation at very specific energies. At just the right energy, gas molecules become excited and start to bend and stretch and vibrate in very particular ways. The ability of these molecules to dance around and redistribute their electronic charge is key to their ability to absorb infrared radiation. We will return to this in Chapter 3. At the energies emitted by the Earth's surface (and to a much lesser extent by the Sun), gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapour (H_2O) are among the key absorbers in the atmosphere. These gases are prominent examples of greenhouse gases. These excited gases eventually emit infrared radiation, also at very specific energies, in all directions: upwards to the overlying atmosphere where there may be greenhouse gases ready to absorb the radiation (and ultimately out to cold space) and downwards to the Earth's surface. So some of the energy that was radiated from the Earth's surface is returned by the gases that reside in the Earth's atmosphere. The true global mean surface temperature on the Earth is close to 288 K, and far higher than the frigid 255 K we calculated without the atmosphere being present.

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5. This breakdown adds up to 99%. The remaining 1% is associated with rounding these numbers to the nearest whole number.

The magnitude of the atmospheric *greenhouse effect* on the Earth is some 33 K. This additional 33 K, gifted to us by our atmosphere, is quite literally the difference between life and death. What we are witnessing now is a rapid increase in atmospheric greenhouse gases.

Our knowledge of these atmospheric gases and their role in the Earth's climate is nothing very new. Joseph Fourier in the early 19th century was the first to recognize that the atmosphere could intercept thermal energy. Later that century, other such as Eunice Foote, John Tyndall, and Svante Arrhenius, began to understand the ability of CO_2 and water vapour to absorb infrared radiation.

As an aside, describing the ability of these gases to absorb infrared radiation as a "greenhouse" is a misnomer, resulting from a throwaway comment made by one professor in a short scientific communication in which they tersely dismiss another professor's calculations about planetary temperature! In a garden greenhouse, sunlight passes through the glass and heats up the ground, which eventually radiates energy. Warm air near the ground rises and is replaced by cooler sinking air. The dominant warming process is associated with the glass roof and walls inhibiting the rising warm air from leaving the greenhouse. This is a very different and unrelated process to the warming effect of the infrared absorbing gases in our atmosphere.

A brief cycling tour through the Earth's atmosphere to space

If we could somehow bicycle upwards through the atmosphere, we would reach the beginnings of space at 100 km within a day or so. While we can think of our atmosphere as a thin gaseous layer enveloping the rock we call the Earth, the atmosphere has its own layers, each with its own thermal structure.

Assuming you can cycle about 15 km upwards in the atmosphere every hour, you will have already cycled right through the *troposphere* within the first hour. The troposphere is the lowest part of the Earth's atmosphere, stretching from the surface to 10 km (at polar latitudes) to 15 km (at tropical latitudes). This is where we will spend most (if not all) of our lives, aside from occasional aircraft travel. Incoming solar radiation heats up the Earth's surface, generating upwelling thermal radiation (Chapter 2). The upward vertical motion of warm air results in the higher temperatures found at the surface falling off by 6.5°C every kilometre of altitude. By the time you reach the *tropopause*, the top of the troposphere, temperatures are -40°C. The freezing temperatures in the upper troposphere act as a cold trap for atmospheric water. This layer turns water vapour directly into ice crystals, forming thin, wispy cirrus clouds, and prevents water from making it to the stratosphere.

This drop in temperature with altitude in the troposphere—the *lapse rate*—is a consequence of two things. First, the Earth's atmosphere is heated from below. The surface radiates heat and warms up the air near the surface. As this air heats up, it becomes less dense and rises, transferring heat to the atmosphere primarily through a process called *convection*. Second, as the warmer air rises in the atmosphere, it expands due to lower atmospheric pressures at higher altitudes. The rising air pushes against the surrounding air, and in doing so uses up its own internal energy, resulting in a drop in temperature. This behaviour is described by the *first law of thermodynamics* that says energy cannot be created or destroyed but it can be transformed from one form to another. This physical law appears again when I discuss how the atmosphere moves about on a planetary scale (Chapter 3). Eventually, the surface heat is transferred to the upper atmosphere and clouds, from which it then radiates out to cold space, driven by the large temperature difference between the warm atmosphere and cold space.

As you begin cycling through the next layer, the *stratosphere*, you'll notice that the thermometer strapped to your bike will register a temperature increase. Incoming solar radiation is being absorbed by ozone molecules (and to a lesser extent CO_2 and water vapour) that subsequently radiate energy. The result is that atmospheric temperature steadily increases to 0°C until you get to the *stratopause* at 50 km, some 3–4 hours after you started your upward journey.

The *mesosphere* lies above the stratosphere, stretching from 50 km to 100 km above the Earth's surface. There, temperature falls off precipitously with altitude, reaching -100°C at 100 km, 6–7 hours after you started your ride (8 if you include lunch and tea breaks). This is the coldest part of the atmosphere. Levels of incoming solar radiation are the same in the mesosphere as they are in the stratosphere, but there are fewer molecules to absorb the incoming radiation. In addition, atmospheric CO_2 present in the mesosphere absorbs radiation and eventually radiates in all directions, including to outer space. The *thermosphere* (100 km to 500–1,000 km) and *exosphere* (600 km to the near vacuum of outer space) are additional atmospheric layers that lie above the mesosphere.

We have now briefly introduced how the land and the atmosphere heat up due to changes in climate. The global oceans are incredibly efficient absorbers of incoming solar radiation and can retain energy more easily than gases in the atmosphere. Indeed, just the top few metres of the Earth's oceans contain the same amount of energy as our global atmosphere.

Ocean heat sponge

The efficiency of water at absorbing energy lies in the nature of the hydrogen bonds that link individual water molecules. Large amounts of energy are required to break those bonds between water molecules before they can lead to an increase in temperature, associated with the faster movement of the molecules. In short, water is one of the most difficult liquids to heat, or indeed cool. Without that resistance to abrupt temperature changes, the global oceans would be less hospitable to marine life. You and I also benefit from having a water content of 50–60%, which makes it easier for our metabolism to maintain a stable internal temperature and not be influenced more by daily fluctuations in our local environment.

The *ocean heat content*, calculated from measured changes in ocean temperature and density below the surface, describes the energy absorbed by the ocean. There are prominent examples of ocean temperature data being collected by ship crews as early as the 19th century during multi-year expeditions (e.g. HMS *Challenger*). The physical properties of the ocean have been measured routinely since the 1960s, initially by research ships and at various stations across the globe. Since the 2000s, a growing army of robotic floats have provided additional information. On a ten-day cycle, these floats dive down to 1 km below the ocean surface, drift about for nine days collecting data, then dive to 2 km below the surface before collecting data on their return ascent to the surface. At the surface, the floats broadcast the data they collected to overpassing satellites; the data are collated and analysed by scientists.

The ocean has absorbed more than 90% of the excess thermal energy trapped by rising levels of atmospheric greenhouse gases. Analysis of ocean heat content shows that since the late

1980s, this absorption has been steadily increasing and sometimes accelerating. Based on accumulated data, only about a third of this energy has made its way down to ocean depths below 700 metres.

Changes in ocean heat content are important because they affect marine ecosystems, contributing to the migration patterns of many species, like fish, towards cooler waters at higher latitudes; sadly, for life like coral that cannot move, these changes can lead to extinction. Higher values of ocean heat content can also lead to sea-level rise because water expands with higher temperatures, and this can in turn impact the stability of polar ice sheets (Chapter 4). We are already seeing islands in some parts of the globe being lost to sea-level rise.

Why do we care so much about 2°C warming?

We hear a lot about doing everything we can to avoid exceeding 1.5°C or even 2°C warming. But what does it mean? After all, even 2°C doesn't sound a lot, does it?

Frankly, we do not know with any certainty what will happen when we reach (and likely exceed) a global mean temperature that is two degrees higher than our pre-industrial value. It is certainly not a magic number beyond which we are doomed. Two degrees as a boundary was originally suggested by an economist back in the 1970s as a value that would push us past any temperature previously experienced by human civilization. The unprecedented speed at which global mean temperature is increasing means we are collectively sailing into uncharted territory and *that* is what we should be worried about.

While it will be a matter of global grief when we pass two degrees, it will not be the end of life. But it may very well be the end of our way of life as we know it. Analysis of huge volumes of data and massive-scale model calculations (Chapter 7) point consistently and unequivocally towards a change in our baseline climate (including sea-level rise, and an increased frequency of extreme weather events). It means that those once-a-century floods will occur every few years. Summer heatwaves that in the past occurred every few decades will become more commonplace.

Humans are a clever species (putting the current climate situation aside) and I am confident we can engineer and "science" our way out of many aspects of climate and the numerous impacts that it will have on our lives. But fighting against Mother Nature is a whole new ball game, and humankind does not have a great track record on this front. Increased temperatures may result in irreversible changes to the Earth, resulting in a cascade of consequences, some of which we can only guess. So-called tipping points (Chapter 7) could very well accelerate the rise in atmospheric temperature. The only effective lever to pull we have right now is to reduce emissions of greenhouse gases.

A common question about our planet's history is whether today's global mean temperatures are truly unprecedented, or if the Earth has seen even greater extremes in its ancient past. There are several periods of time during the Earth's history when temperatures were hotter than today. One of the hottest periods of the Earth's climate is called the Cretaceous, which describes a period 145 to 66 million years ago, particularly during the *Cretaceous Thermal Maximum* about 90 million years ago. The world was then a very different place. You would recognize most of today's continents on a map of the globe during the Cretaceous, but some of the major continents look squished together, although in fact they were splitting apart from each other: North America from Eurasia, South America from Africa. India was floating around the Indian Ocean, and Australia was connected to Antarctica. The climate was warmer and more humid, with atmospheric CO_2 levels more than treble today's values, which was most likely due to emissions from volcanism, driven by plate tectonics. Global mean temperatures were somewhere between 10°C and 15°C higher than today and sea levels at their peak were 100 to 250 metres higher than today. As a result, forests flourished on polar continents where we would expect ice sheets. And, yes, there were dinosaurs wandering around, at least for some of this geological period (Chapter 6). These conditions are more extreme than any current climate prediction we have for the year 2100.

It would be remiss of me not to also highlight the *Paleocene–Eocene Thermal Maximum* (PETM) which occurred more recently at about 56 million years ago. The PETM is arguably more relevant to our climate today because it represents a comparatively short period of about 200,000 years when the global temperature increased by 5–8°C. It was triggered by a massive release of carbon, the source of which is still being debated by scientists. The primary trigger for the PETM is widely hypothesized to be massive volcanic activity from the *North Atlantic Igneous Province*, which released CO_2 and methane by heating carbon-rich sediments over thousands of years. This trigger was then amplified by positive feedbacks; for example, warming led to thawing of permafrost that subsequently led to the release of methane to the atmosphere.

So, if the Earth has been a lot warmer in the past and life still managed to thrive, why all the fuss about today's warming climate?

Well, for most of the Earth's history, CO_2 levels and temperatures have been going up and down, but this was due to slowly varying "drivers" (Chapter 6). Changes were happening on million-year timescales, so that fauna and flora that existed had a chance to adapt and continue to flourish. What we are witnessing now are large changes in the Earth's global mean temperature that are occurring at an unprecedented pace—on the scale of decades to centuries rather than millions of years. This is much faster than most of the natural world can react and adapt.

Another key point is that human civilization has flourished over the last 10,000 or years when temperatures were a degree or cooler than they are today. That means that where we live, where we farm for food, and our trade routes are based on a past climate and not on the climate we are currently experiencing or on the climate we expect in the future. Adaptation to our changing climate will demand massive-scale investment that will no doubt represent a large fraction of global gross domestic product.

But how do we know about past and present temperature changes?

For present-day changes, the answer is simple: thermometers. Sure, they're (probably) fancier than the ones you stick in your ear (or elsewhere) or the one you use(d) in school science laboratories, but they are still thermometers. The instrument temperature record, quite literally the advent of temperature data being recorded by instruments, started in England in the 17th century. Continuous records of global data started in 1850. Back then, measurement coverage was biased towards heavily populated land regions of the world, with little or no coverage of polar regions, the tropics, and the deserts. Nowadays, we rely on an array of instruments and measure changes in temperature throughout the atmosphere, not just at the surface, across the globe. These include instruments on ships and planes, on balloons that rise through the atmosphere collecting data, and Earth-orbiting satellites (since the 1950s). These measurements, taken from many independent sources, show consistently that the global mean surface temperature has risen by about 1.5°C since the late 19th century. This rate of change is higher than any other time in the past 2,000 years. As I discuss in Chapter 7 there is an uncertainty on that number, but the uncertainty is comparatively small compared to the reported value. As we will also discuss in that chapter, open and transparent estimates of uncertainties is part and parcel of scientific inquiry—it engenders a level of trust that is crucial for the acceptance and advancement of scientific knowledge.

If we want to study temperature changes further back in time, before there were thermometers and the people to use them, we must change our strategy. We must seek help from Mother Nature. Instead of using direct temperature measurements, we can use measurements that are *proxies* to temperature, i.e. quantities that change predictably with temperature. Examples of proxies include tree and coral rings, and ice cores. The underlying ideas are quite simple but extracting the proxies and translating changes in the proxies to estimates of temperature involve careful scientific analyses. Calibration of these proxies is achieved by the continued comparison of proxy and instrument records alongside each other.

For example, a tree grows every year, with new growth occurring close to the bark. This means that the closer you go to the centre of the tree trunk, the further back in time you are measuring. The growth rate changes somewhat predictably with changes in climate, which results in growth rings of varying widths. These rings are only visible when you take a core sample to look at a cross section of the main trunk. The distance between the consecutive growth rings tells us something about the climate for a particular year. At temperate latitudes, tree growth is faster during spring and early summer (less dense and lighter wood) and slower during later summer months (more dense and darker wood). Generally, the ring widths are fatter during warmer and wetter years and thinner during cooler and dryer years. If you're lucky you might even spot evidence of other notable events in the tree's life, like burn scars from a forest fire.

Similarly, corals are sensitive to changes in ocean temperature and generate annual rings so their cross sections can also provide us with information about temperature, sunlight, and environmental nutrients. Unfortunately, due to ocean warming, corals are dying. Living corals are normally resplendent in colour due to a symbiotic relationship between the coral polyps, which build the white exoskeleton, and photosynthetic algae (zooxanthellae) living within them. When oceans warm, this partnership breaks down and the coral loses these algae and its main energy source, revealing the white skeleton beneath. This is called "bleaching". If the ocean warming is persistent, this results in the death of the coral.

Collectively, these data from trees and corals can take our record of temperature back in time to 2,000 years from present day.

To go even further back in time, we need to turn to ice cores. Ice cores are cylinders of ice extracted from ice sheets or glaciers. The longest ice cores (close to 3 km in length) take us back 800,000 years from the present day. They are an incredibly valuable resource for climate science, providing a high-resolution measurement record. The climate data they contain lies within bubbles of ancient air that was trapped in the growing ice sheets as they formed and grew. These bubbles contain information about historical levels of atmospheric greenhouse gases (Chapter 6), and a range of oxygen isotopes that can be linked with changes in temperature. Before I explain how to determine temperature from oxygen, let me explain atomic isotopes—you can skip the next paragraph if you know what they are.

Atoms are the smallest unit of a chemical element, such as carbon, oxygen, sulphur. Their atomic structure is important for how they interact with other atoms. They are comprised of a nucleus, which is home to protons and neutrons, and a bunch of electrons that travel around the nucleus in concentric orbits. Protons, neutrons, and electrons are examples of subatomic particles. Neutrons don't hold charge, but they have mass; protons are positively charged and have mass; and electrons are negatively charged and have comparatively no mass. The mass of the atom is approximately the combined mass of the protons and neutrons residing in the nucleus. The atomic number of an atom is defined by the number of protons in its nucleus. An atom with the same number of protons (same chemical properties) but a different number of neutrons (different mass and physical properties) is called an isotope of that atom. Atoms typically have a preferred isotope in the natural world, with alternative isotopes representing only a small fraction of the total number of that atom on the Earth. For example, almost 99% of natural carbon exists on the Earth in a stable form with six neutrons (carbon-12). But there is a small percentage of stable carbon with seven neutrons (carbon-13, almost 1%), and there is an unstable form of carbon that is subject to radioactive decay that has eight neutrons (carbon-14, only minute amounts). These are all carbon isotopes, and they all have an atomic number of six. I shall explain later in Chapter 3 how these carbon isotopes give us additional clues to humans' influence on climate.

Back to oxygen isotopes in ice cores. Unlike gas, bubbles trapped in ice cores cannot give us information directly about temperature. Instead, scientists melt small portions of the ice core and use that water for their analysis. As you know, water (H_2O) is comprised of two hydrogen atoms bonded to one oxygen atom. There are several isotopologues[6] of water—both oxygen and hydrogen each have isotopes that can bond to form different isotopic combinations. In this case, we are particularly interested in a combination of two isotopes of oxygen with two isotopes of hydrogen. The two oxygen isotopes include oxygen-16 (with eight protons and eight neutrons), which makes up almost all (99.76%) oxygen, and oxygen-18 (with eight protons and ten neutrons). The two hydrogen isotopes include hydrogen-1 (with one proton and no neutrons), which makes up almost all (99.99%) hydrogen, and hydrogen-2 that is also known as deuterium (with one proton and two neutrons). Scientists use sensitive instruments to compare the isotopes of oxygen and hydrogen in the melted water from the ice core samples against the standard isotopic ratio of ocean water. Generally, there are fewer of the heavier oxygen-18 and hydrogen-2 isotopes to be found during cooler time periods. That's because it takes more energy (in other words, higher temperatures) to evaporate the heavier isotopes from water than the lighter (more prevalent) isotopes. Water that evaporates due to higher temperatures incorporates the heavier isotopes. As the water vapour is transported poleward, by the global movement of air (Chapter 3), it begins to cool and precipitates preferentially the heavier isotopes. Changes in the rates of evaporation and precipitation of these isotopes are examples of

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[6] An isotopologue is a molecule in which at least one of the constituent atoms has been replaced by a different isotope.

temperature-dependent fractionation. Relating these changes to temperature is achieved by comparing measurements of isotopic fractionation in snowfall from recent years and changes in polar mean annual temperature. The heavier isotope data reveal seasonal oscillations that are used to count the years going back in time. While the ice core record from Antarctica takes us back 800,000 years from present day, shorter ice cores collected in other regions around the globe provide consistent information over periods of 100,000 years before present day.

The Antarctic ice core reveals a cyclical temperature change, with cycles occurring on scales of 10,000–100,000 years. These are called glacial-interglacial cycles and are driven by well-understood periodic drivers, which I describe in Chapter 6. Lower temperatures occur during glacial periods that mark the advance of glaciers across a large fraction of the Earth. The last glacial period was some 15,000 years ago. We live in an interglacial period called the Holocene (Chapter 6).

Now we have put recent changes in the Earth's temperature in a broader historical context, it's time to ask about who is to blame for this recent upward tick in temperatures? Are humans *really* to blame?

Are we responsible for recent global warming?

This is a contentious issue for progressively fewer and fewer people, but the short answer is a resounding yes! There are several, consistent lines of evidence to back up this answer.

Based on fundamental physical principles we understand the relationship between gases that absorb radiation at infrared wavelengths and emit radiation at similar wavelengths and the resulting warming of the Earth's atmosphere and surface. We have known this for over a century. We also know that this effect is not instantaneous, because it involves the absorption of energy over different timescales (Chapter 2). In addition, we know from historical (proxy) data that, except for rare meteoric strikes and mega volcanic eruptions, slow changes in atmospheric greenhouse gases due to natural causes are related to slow changes in atmospheric temperature—and that recent changes are much, much faster than can ever be explained by the natural world. Quite the opposite is true: the natural world is struggling to catch up to rapid changes in temperature. The last piece of evidence that points to humans being responsible for recent changes in climate comes from computer models. These models act as our virtual laboratories to study the Earth's climate, allowing scientists to simulate the various effects of natural processes and human activities. By comparing these simulations with observations, scientists have concluded that human activity is the primary cause of recent climate change.

A computer model of the Earth's climate represents millions of lines of computer code, built up over decades and drawing on a massive amount of scientific research. These millions of lines of computer code include detailed descriptions of the physics and (some) chemistry of the Earth and their interactions. These climate models range in size and scope, but the larger ones, typically used as a basis of proclamations from the Intergovernmental Panel on Climate Change (IPCC), take a long time to run on some of the fastest computers on the planet. To test the ability of these models to reproduce real-world changes in climate, they are compared exhaustively against measurement records.

There are two broad types of model calculations used by climate scientists: nature model runs that include only natural influences on the Earth's climate, and model runs that also include human influences. Natural influences include volcanic activity and changes in solar output. Natural variability of the Earth's climate—phenomena like El Niño—plays a small additional role. Volcanoes slowly release a variety of trace gases but predominantly water vapour and CO_2. Large volcanic eruptions associated with massive amounts of destruction and often loss of life are thankfully rare, but can they eject large amounts of reflective particles into the upper troposphere and lower stratosphere. These particles act as a shield for incoming sunlight, reflecting it back to space, resulting in observable periods of global mean temperature cooling. Notable volcanic eruptions include Santa María (1902), Mount Agung (1963), El Chichón (1982), and Mount Pinatubo (1991). These sorts of eruptions typically cool global mean temperatures by less than 0.1°C, offsetting some of the expected warming due to increased atmospheric greenhouse gases. But this cooling is typically short-lived as the lofted particles begin to disperse and eventually (and slowly) drop out of the sky. I have discussed earlier in this chapter the changes in solar output due to sunspot cycles, which affect solar output by 0.1% and reduce levels of incoming radiation—but not to the extent that would explain a trend in global surface temperature such as we have observed. Model runs that also include human influence consider changes in greenhouse gas emissions from human activity.

Results from nature model runs from 1900 onwards show that they can more or less reproduce observed global mean changes in temperature until about 1960—and then, when real-world observations show a sharp upward increase, the nature model continues to meander around small negative global annual mean changes. The nature model run also reproduces the rapid periods of cooling that correspond to the large volcanic eruptions. In other words, the observed post-1960 increase in global mean temperature we observe is not consistent with *just* natural climate variations. That is our *detection* of a signal of human influence on the Earth's climate.

To *attribute* that mismatch—between the nature model run and observations of global mean temperature—to human influence, we must show there is only one plausible explanation. With our nature run, we have already shown that volcanic eruptions and changes in solar output are not responsible for the increase in global mean temperature. But when we include the human influence of greenhouse gas emissions, the new model shows better agreement with observed warming throughout the 20th century, including the sharp increase after 1960. In other words, rising emissions of greenhouse gases due to human activity is a plausible explanation that is consistent with the measurement record.

In practice, this detection and attribution analysis is carried out with multiple, independent models and rigorous statistics that help to strengthen the certainty of any result being reported.

Measured changes in global mean surface temperature sometimes feature short periods when there is no discernible increase in warming, a reduction in the annual warming change relative to previous years, or when there is even a cooling. These so-called periods of hiatus spark flurries of conspiracy theories suggesting that global warming is a hoax (it is not), which is met with consternation from climate scientists. In the past century, there have been two hiatuses: 1) 1941–1973, when there appeared to be a temporary cooling; and 2) 1998–2013, when warming appeared to slow down. The 1998–2013 event caused the biggest kerfuffle, mainly because climate has moved up the political agenda since the second half of the 20th century.

There are two things to remember with hiatuses. First, real climate data are complicated. There are year-to-year variations in global mean temperature due to natural variability of the whole system. For the most part, the annual increase in warming is smaller than natural variations, but not always. And that's why it's important to collect long datasets so that short-term changes do not overly influence our interpretation and understanding of the data. And it's worth noting that this is generally true for all data, whether you're examining global mean temperature, currency exchange rates, or house prices. Indeed, many scientific articles that have reported unexpected environmental trends (or their absence) have been overturned when put into context of longer measurement records. Measurements of global mean temperature show a clear and unequivocal upward trend since human records of temperature began, with the hiatuses representing only short blips. An accessible analogy is climbing Mount Everest. The overall direction is upwards but there are regular places where it flattens off—the locations of base camps where climbers can acclimatize to the lower oxygen levels found at higher altitudes. With real environmental data, sometimes the steps go down for a bit before going up again. But hopefully you get the general idea.

Second, computational models of the Earth's climate provide a way to test our understanding of these observed changes in warming. Current models can reproduce the hiatus during 1941–1973, with studies suggesting an important role for natural variability in the climate system. The observed slowdown in warming during 1998–2013 represents a more complicated picture. However, the evidence suggests that the slowdown was due to combination of natural variability of the climate system and changes in volcanic emissions and solar output that sit atop

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