IL006 : The Challenges of Climate Change

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Motivation

The changes to global climate being brought about by human activity present one of the greatest challenges to confront humanity, and are likely to have a profound effect over the working lives of today's students. Preparing for them requires a comprehensive approach spanning multiple disciplines. The aim of this module is to equip students to face these challenges, by providing a grounding in the central scientific, economic and political issues surrounding climate change. The module will be taught by members of the Biology, Economics, Law, Mathematics, Physics and Politics Departments. It will be open to students from all disciplines, from across the university.
Principal themes of the module:

1. The underlying physical processes that govern global climate, the evidence for human-induced warming, and predictions for the future.
2. Ecological, economic and social consequences of climate change.
3. Difficulties in the way of reaching a political consensus for action to mitigate climate change; political strategies and technological mechanisms to overcome them, and to adapt to future changes.

Students taking this module should gain a solid understanding of the major challenges that climate change presents, together with knowledge enabling them to participate actively and constructively in the efforts to meet them.

Technical details

This course is aimed at undergraduate students across all disciplines in the University. Its base assumptions assume science and mathematics only to GCSE level. Since it may be some time since you did GCSE science we have tried to include brief explanations of scientific terms in the text.

A note on terminology

There are several different climate terms that are often used interchangeably in the press to describe ongoing changes to the climate. In practice, while they are related they are not identical, and so we identify them here.

- **Climate change:** can refer to any changes in the climate, on any length, time scale. They have happened over the history of the planet, as we will see. However. predominantly the challenges of climate change to which this course refers are those occurring now, and in the near to mid- term future.
- **Greenhouse effect:** This is the thermal blanket provided by the atmosphere, and is in fact essential to life. However, an **enhanced greenhouse effect** is something different, and a potential cause for concern.
- **Man made (anthropogenic) global warming:** This is really what this course is about. How has human activity impacted our climate, and how will these changes manifest themselves?

These notes

These notes currently only cover the ”Science base” element of the course (essentially the first two lectures). It is our intention to include later material as the course is delivered. However, there are two important things to remember about these notes.

1. The notes do not have the level of proofreading of a textbook, and errors are likely to be present. If you notice an error please let us know, if you spot a point where the details in these notes differ from a (reputable) textbook then the textbook may well be correct.
2. The level of detail in these notes is not necessarily that which will be expected in an exam. The exam is intended to test your level of understanding, but not necessarily your recall of all the details, although for completeness many of the details are given in the notes. You should consult the mock exam, your lecture notes, or your lecturers if you need more clarification.

Feedback

Finally, this is a new course, and one of the first at the University to cater to students across several different faculties. While we have given much thought to delivery and content this will evidently be imperfect, and we well any comments on constructive criticism that you may have. Please feel free to email this to A.J.Levan@warwick.ac.uk. If you wish it to be anonymous then we have set-up a form on website for the course which you may fill in.

Chapter 1

Understanding the past climate of the Earth

Learning objectives
From this lecture you should be able to:

- Outline how the broad properties of the Earth's climate have varied over its 4.5 billion year history.
- Describe different methods for measuring the past climate, and how they apply to different time frames in geological history.
- Appreciate the physical mechanisms thought to give rise to climate changes (in particular ice ages).
- Critique different climate measurement methods, and explain the difficulties in comparing them.
- Describe the time scales associated with these changes, and how recent climate change compares with these.

1.1 A very brief history of Earth

1.1.1 The early days

The Earth (and the solar system) are approximately 4.5 billion years old (1/3 of the age of the Universe at 13.7 billion years). The solar system was formed out of a collapsing ball of dust and gas. As this collapsed inwards the centre heated up, starting fusion reactions in the core of the sun (where hydrogen is turned into helium) and becoming the star we recognize today (with some differences). At the same time material further out formed what is known as a proto-planetary disc, essentially a disc full of dust particles. These particles gradually stuck together to build ever larger bodies, until eventually the individual planets were formed, and cleared their orbits of other material.

This epoch represents the earliest time that one may recognize the Earth as an entity. However, it was profoundly different to the Earth we see today. Firstly, it was excessively hot, with a near molten surface. Life, at least as we understand it, simply could not have survived in these conditions. Secondly, it has no water on the surface or in the atmosphere (again a vital element in the recipe for life). Finally, it also had an atmosphere rich in carbon dioxide, and in which there was very little oxygen.

From these beginnings the Earth has evolved into the planet we know today. It has gone from this burning beginning through phases in which the planet was almost entirely covered in ice (a so-called snowball Earth) and back again. It is clear that on these geological time scales the climate is anything but stable, and so the first challenge in understanding changing climate is to explain just how the Earth has varied through its history, and to develop a picture of what drives these changes. Through measurement and understanding of past climate we are much better able to comprehend and predict the human induced changes of today.

The first significant change to occur on the Earth arises from the arrival of water. While much of the surface of the Earth is covered with water today (and about 10 times as much as is in the oceans sits within the Earth's crust), there was little of this when it was first formed. Indeed, the water of the Earth is essentially all of extra-terrestrial origin, and was delivered approximately 4 billion years ago. The precise

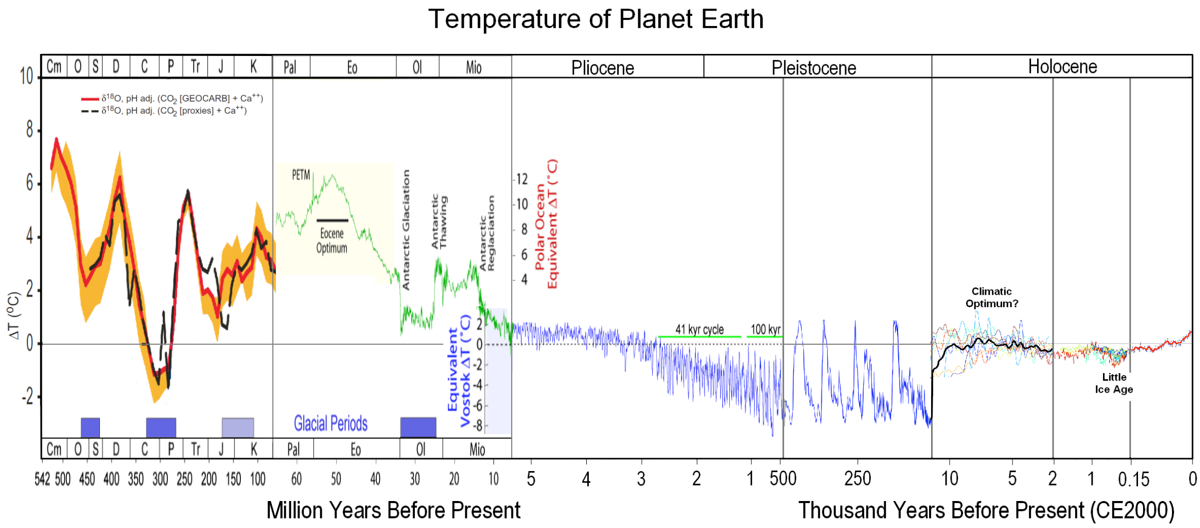

Figure 1.1: The temperature history of the Earth for the last 500 million years, as determined primarily from oxygen isotope analysis (see text). The x-axis has been stretched so that time is compressed on the left hand side relative to the right. A relatively stable climate in the past 10000 years is visible, with prior periods of extreme oscillation between ice-age and interglacial. Prior to this time other large excursions are visible, although their timescales are longer (partly due to the poor time resolution in the data). The temperature is plotted relative to today, which can be seen to be a relatively cool period in the context of Earth history. *Image Credit, Wikipedia, Paleoclimatology, retrieved 24/9/2013*

details of how water is deposited remain unclear, although it likely arrived via impacts of the young Earth with asteroids and comets during a period known as late heavy bombardment, when the rate of impacts was much higher than today. Indeed, most of the craters on the moon were formed at this time, although the moon is insufficiently massive to hold on to the water these impacts deposited.

This water is the key to life on Earth, as it is the solvent in which complex molecules can begin to form and evolve. Indeed, when looking for signs of life on other planets and moons around the Galaxy, it is the presence of liquid water that is thought to be a vital ingredient. Despite the arrival of water, the planet itself was still very different to that we see today .The oceans were highly acidic, and the atmosphere was dominated by carbon dioxide and methane. This is an extreme greenhouse climate, that kept the planet much warmer than it really should have been (we will see later how to work out just how hot the planet should be). However, despite these conditions life was able to begin, and to thrive, to the extent that it began to impact its own environment. The first significant life (from a climate perspective) were the algae which formed in the early oceans. These were extremely successful and formed large scale matts that covered much of the surface water of the planet, and are clearly visible in the fossil record today. They were so successful because of a combination of sunlight, and plentiful carbon dioxide. As plants they produced their energy from photosynthesis, taking in excess carbon, and in the process producing oxygen. Indeed, as time went by they changed the atmosphere of the planet from one which was dominated by carbon dioxide, to the nitrogen, oxygen mix we see today. It should at this stage be remembered that at the time this was no good thing. Most of the life that had gained a foothold on the early Earth had done so precisely because it could use the carbon rich atmosphere. The release of the large amount of oxygen had a profound impact. Firstly, the loss of the greenhouse gases caused a major climatic shift, and secondly many of the early life forms essentially found themselves poisoned.

This change gives an important lesson for today. It is clear that while the planet is undeniably huge and robust, it is possible for lifeforms on it to dramatically change the climate. As we learn from looking back into distant history. The first life-forms to inhabit the planet were so "successful" that they ended up wiping themselves out. This was the first mass extinction in the history of our planet, and is often known as the Oxygen Apocalypse.

1.1.2 Mass extinction

While the Oxygen Apocalypse marked the first mass extinction event, it was by no means the last. The definition of a mass extinction is vague at best, but it essentially relates to a significant loss in biodiversity via the extinction of a significant fraction of the species on the planet. There have been many mass extinctions over the life of the Earth, and the details of each one don't matter dramatically for this course. Some have been wrought by life on this planet, while for many others the life has been a innocent victim of the results. Major extinctions have likely been caused by volcanic eruptions, asteroid impacts and Galactic supernovae and gamma-ray bursts to name but a few. However, it is an interesting exercise to examine how these disasters actually translate into a mass extinction event.

The case of volcanic eruptions and asteroid impacts is actually rather similar. In both cases is it is not the event itself that results in the extinction, though it was of course catastrophic for anybody nearby. Volcanoes, even the most extreme ones will only wipe out life within a few hundred miles of their location, and a similar case is true for large asteroids (i.e. those greater than 100 metres or so across). The reason they result in mass extinction is because of the large amount of material they expel into the atmosphere. Volcanoes can have two effects, they outgas large quantities of greenhouse gas which can have a warming influence, but on the shorter term they also expel large quantities of particulate matter into the atmosphere (think of the chaos created by the geologically rather minor eruption of the Icelandic volcano Eyjafjallajökull in 2010). This blocks light from reaching the Earth, and results in a major cooling. The same is true of asteroid impacts. They kick large quantities of material into the atmosphere, blocking sunlight and resulting in a dramatic cooling of the planet beneath. Those species which are not well adapted to such conditions (or do not have the ability to adapt) are frequently forced to extinction.

In the case of astronomical events such as supernovae or gamma-ray bursts, both of which are related to the collapse of stars much more massive than the sun, the effect is more subtle. However, the Earth is effectively bathed in an extremely high does of radiation (in the case of gamma-ray bursts the name is a bit of a giveaway). Luckily for us, the atmosphere is capable of absorbing much of this radiation, preventing a lethal dose from reaching the Earth surface. Indeed, even in cases where it does, only the part of the Earth facing the explosion gets the full blast. However, the atmosphere pays a price for blocking this radiation. Firstly, the ozone layer is almost completely destroyed, allowing damaging ultraviolet radiation to reach the surface of the Earth. Secondly, and more complexly, the reactions in the upper atmosphere trigger the production of nitrous oxides (remember the atmosphere is basically made up of nitrogen and oxygen). These effectively block optical light. Thus these is the double effect of an increase in damaging UV radiation and a decrease in optical light, resulting in a cooling of the planet. As is the case with impacts and volcanoes, this cooling is catastrophic to those life forms that cannot adapt.

The details of these mass extinctions, and which mechanism may be responsible for each of them are of course extremely important, but for the purpose of this course it is simply important to note that it was not the events themselves which caused the extinction, but the climate change that followed. We should not take the benign climate in which we live for granted. Manmade or not, it has the potential to be very different.

1.1.3 Up and down then calm, the last million years

Perhaps the most striking feature in the climate history of the last geological period (known as the Pleistocene, and lasting from 2.5 million years ago until about 12000 years ago) is the see-saw shape of the temperature record. With large scale (ten degree or more) swings between warm and cold. This is a period in which ice ages have been dominant. During these times the polar ice sheets reach down towards the tropics, and much of the polar regions sit below ice. The sea levels are much lower (simply because so much of the water is locked up in ice) and most of the habitable land sits in the tropics (see below for a description of how ice ages actually occur). Life during these periods has to be adaptable, since on timescales relevant to evolution the climate shifts are gigantic. Early humans were hunter gatherers, who were able to make large geographical shifts to the most productive hunting lands.

The last ice age was at its peak 25,000 years ago, and largely ended around 10,000 years ago. A feature which is clear looking at the temperature record over this geological period is that the temperature over the last 10,000 years has been more stable that any time in the previous 100,000 years. For most of that time temperature was oscillating rapidly, with significant climatic shifts on timescales of hundreds of years. It has been argued (e.g. Burroughs 2005) that it was this stability that ultimately enabled the building of the society that we see today. In particular, climate became stable enough that crop growing in a fixed location became a viable intergenerational option, when previously it had not been. In other words, climate stability may have played an important role in the development of agriculture and the modern society that we known today. It is a cautionary tale therefore that all of human history has been played out in this relatively calm environment, and not in a wildly one.

1.1.4 Recent history: The past 1000 years

While in general climate has been largely steady for the past ten thousand years, this does not mean that no climate changes have occurred. During the medieval period there was a pro-longed time known as the "little ice age", during which cold winters frequently froze the River Thames (indeed, there was a winter market on it each year). It is interesting to note that during this time period global average temperatures were actually only around 0.2 degrees lower than in the preceding period. While some of these effects were no doubt geography dependent (e.g. a cooling that was more pronounced in the well documented regions of north-western Europe) they are apparent in the several climate records. The origin of this cooling remains somewhat unclear. There may have been significant volcanic activity, reducing solar input. There was certainly a period of pro-longed solar inactivity, during which almost no sun spots were observed (known as the Maunder minimum) and there may also have been changes in ocean circulation due to previous climate change. It is interesting to note though that these changes arose due to globally modest changes in the temperature. This also offers an important lesson – the impacts of climate change is far from uniformly distributed across the planet.
The most striking feature of recent climate history is not the little ice age, but the rapid upturn in temperatures beginning at around 1900. This has resulting in something approaching one degree of temperature rise over the course of the last century. This is extremely rapid climate change on a geological timescale, and if it were to continue would doubtless pose major problems for civilisation – dealing with precisely these problems is the core aim of this course.

1.2 Measuring past climate

While we frequently hear about the changing climate around us today, this means little without some historical context. We have so far talked about climate over the past several billion years, but have yet to address the question of how we know how ancient climate behaved. This is far from a trivial question, and many of the controversies that have surrounded the climate change debate stem from the interpretation of the methodologies that are used. It is therefore we worth exploring exactly how we know the past climate of the Earth.
Clearly this is less problematic in recent history. For the past few decades we have excellent records of temperatures measured at multiple sites around the globe. This is supplemented by weather balloons which provide detailed temperature profiles as a function of height, and Earth observation satellites that provided detailed maps of surface temperature across the globe. This highly complete data in principle allows for the construction of detailed climate records, but only for the relatively recent past. Since climate is by definition the weather averaged over long time periods (formally climate is often referred to as a 30 year average) it is difficult to use these data to discern historical climate.
Going further back, the thermometer has been in general use for several hundred years, and so we are able to use these records to probe further back still, albeit with larger issues of calibration (just how accurate is a thermometer?) and with sparse geographical coverage. We can also utilise other historical records such as shipping records of ice extent or sea level.
The difficulties of understanding the drivers of changing climate are then compounded by the ability to measure not only temperature but other properties of the Earth contemporaneously. In particular, since atmospheric composition plays a central role in the climate of the Earth, and in the ongoing discussions surrounding global warming it is desirable to obtain not only an accurate temperature record, but also a measurement of the atmosphere at the same time. Below we discuss how both temperature and atmospheric composition is obtained through geological history.

- *Ice cores:* Perhaps the best known and most useful long term tracer of temperatures are ice cores, where deep cores are drilled through polar ice. The ice at the poles is extremely ancient and can be several miles deep in places. A new layer of snow is set down each winter, but does not melt over the summer, gradually compressing and building up over the millennia. Since there is little snowfall over the summer time other particulate matter can settle on the surface of the ice, providing a dark line in the snow, and allowing individual years to be counted. The width of the line for each year provides an immediate estimate of precipitation in a given year (allowing for the compression from the weight of snow above it). This in itself can be used as a temperature proxy, since warmer winters tend to allow for more precipitation. However, the real wonder of ice cores comes from their ability to provide atmosphere and temperature measurements at the same time. Firstly, small holes that form within the ice preserve the ancient atmosphere at the time the snow fell, these bubbles can be extracted from the ice and tested to measure oxygen and carbon dioxide levels at the time for several hundred metres, until the ice becomes so compressed that all the bubbles are crushed.

The second technique is to measure the temperature, and this is less straightforward, although a first order guess can be obtained by the level of precipitation, this is a crude approximation. The technique that is most often used is to measure the ratio of different isotopes[1] of oxygen. Water naturally contains both of these isotopes so one can have $H_2{}^{16}O$ (most normal water) and $H_2{}^{18}O$. Because of the different isotopes these molecules of water have different masses. This means they behave differently. In particular, the heavier ^{18}O tends to evaporate more slowly in hot weather, and precipitate out more rapidly in cooler weather. What this means in practice is that the ration of $^{18}O/^{16}O$ goes down as temperature drops. Hence by measuring this ratio, and calibrating against recent history it is possible to use ice cores to track temperature back for hundreds of thousands of years. In practice one can use not only the oxygen isotopes but also those of hydrogen (hydrogen can contain just a proton, or a proton and a neutron in an isotope known as deuterium). The effect of using heavier hydrogen is essentially identical to that for Oxygen.

- Sea floor: Sediments on the sea floor can also be tested for isotope ratios. These sediments potentially allow us to track back even further into climate history. Unlike the ice caps they are not subject to melting (or never forming) in the hot conditions in early Earth, or due to continental drift. They are records of some of the earliest life on Earth, which formed in the sea, and as sedimentary rock can be found with ages of billions of years, are essentially the age of the oldest fossils. The sea floor sediment in places is made up of the shells of crustaceans (much as the sandy beaches are). These shells are mainly made from Calcium Carbonate (chemically $CaCO_3$). This contains, calcium, carbon and oxygen. This opens up isotopic temperature measurements in the same way as is possible for ice cores, from measurements of oxygen isotope ratios. In practice one can also use the $^{13}C/^{12}C$ ratio as well, which provides a different temperature proxy. In particular, plants preferentially take up ^{12}C and not ^{13}C, so that a highly productive biosphere (which is normally the case for higher temperatures) will enrich the atmosphere in ^{13}C. This is incorporated into the shells of sea creatures equally well as ^{12}C (this has been tested) and so the ratio of ^{13}C to ^{12}C provides a separate measure of temperatures.

  Of course, sea floor measurements are not necessarily taken from the sea floor today. Over the course of billions of years tectonic activity has moved many of these feature above sea level, or at an angle to the ground (the jurassic coast is a good example). This means that while we can measure a good temperature record, we must be careful in interpreting the geography. The location of the sediment now, does not necessarily represent where it was when formed. None-the-less this technique is the primary method in which the oldest climates can be measured.

  A key problem with sediment analysis is that the age of the rock cannot come from counting sequential yearly deposits, and must be determined via dating of radioactive isotopes within them. These isotopes are produced in the cores of stars with known ratios, but the radioactive variants decay away with time, leaving a different ratio. For recent history radiocarbon dating is a good example, where the ratio of radioactive ^{14}C to stable ^{12}C provides an age measurement. For older events, and those not involving carbon, other elements and isotopes are used, most notably Rubidium and Strontium.

- Dendrochronology: This is simply the measurement of tree-rings, and perhaps surprisingly can go back tens of thousands of years. It is more accurate as a dating technique than radiocarbon dating, since as with ice cores one can count the rings. The principle is to match the ring patten (i.e. the sizes of the rings) with a sample of known age, building a ladder from the current time back as far as possible with overlapping ring systems. The rings provide a record of the conditions when the tree was alive, since the width of a ring is a proxy for the local temperature and availability of water. However, they are limited because of the decay of wood, meaning unless unusual conditions

[1] Isotopes are atoms of a given element that have a different mass. In the case of an oxygen atom, most contain 8 protons and 8 neutrons and are denoted chemically as ^{16}O. All isotopes of an element will have the same number of protons, but can have differing numbers of neutrons. Oxygen also comes in a variant with 10 neutrons ^{18}O.

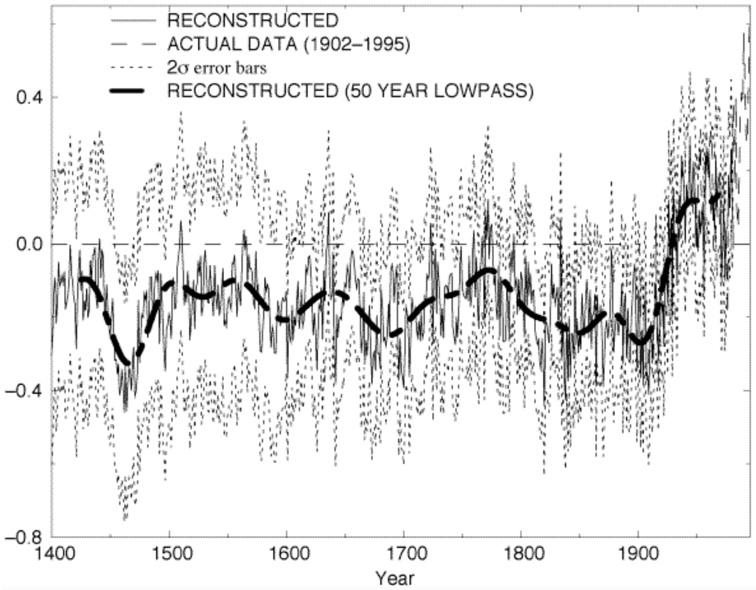

Figure 1.2: The now famous (or infamous) hockey stick diagram, showing changes in temperature over the past 600 years, based on a combination of dendrochronology and satellite data. They show are broadly constant temperature for the first 500 years, with a rapid upward trend in the past 100 years. This rapid change in temperature is seen as a hallmark of anthropogenic global warming, beginning around the time of the industrial revolution. However, this plot has also been highly controversial, and much of the debate around global warming has hinged on the data used to create it, and its interpretation. *Image credit: Mann, Bradley & Hughes, 1998, Nature 392 779*

exist they can only be used for temperatures going back several thousand years. They also record information which is very geography dependent, and many different samples must be used to gauge a more complete picture of temperatures. Interestingly, a similar method, applied to coral can also be used to measure sea temperatures.

Putting all this together can give us a temperature record which goes back many millions of years. Over this time period we see the earth's climate has been highly variable, and in particular has consisted of ice ages, punctuated by milder periods in between. The punchline from these measurements is that **Climate change does happen**. The question we need to address in this course is if this climate change is driven by human (anthropogenic) or natural force.

One notable thing about current warming is that it is occurring at a rapid rate. This is certainly unusual within climate history, since most changes occur on timescales of centuries to millennia (if not even slower). This could be an immediate hallmark that the current warming has been caused by human activity. However, in practice, there are examples, albeit rare, of rapid climate shifts in geological history.

1.3 Past evidence for rapid climate impacts

1.3.1 The younger dryas

At the end of the last ice age, as the Earth began to warm. However, this was not a simple warming as might be expected. Around 12000 years ago the Earth, and in particular the North Atlantic region suffered a rapid fall in temperature, plunging it back into an ice age that lasted for another 300 years. The transition from a warming to a cooling trend was significant (about 3 degrees), and occurred on a timescale of less than a decade. It is postulated that it occurred due to the collapse of ice sheets in the North Atlantic (not that different to the Greenland ice sheet today) that disrupted ocean circulations. We will return to this idea later in the course.

1.3.2 Doggerland

At the end of the last ice age the UK was connected to Europe by a bridge of land occupying much of what is now the north sea. This bank of land is still visible underneath the sea, and is known as Dogger bank, giving the now inundated land the title “Doggerland”. This land is now submerged largely due to rising sea levels since the last ice age. However, it appears likely that the final inundation was rapid, rather than a gradual change. Two changes around 8000 years ago are likely to have triggered its final submersion. Firstly it was likely devastated by the Storegga Tsumani, evidence for which can be found across large areas of northern Britain. However, the final submersion likely happened by a rise of sea level of a few metres on a timescale of a few years. This probably arose due to the melting of an ice wall surrounding a massive glacial lake (known as Lake Agassiz) in Greenland. A large quantify of freshwater was held behind ice walls in this lake, and their eventual melting released sufficient water into the oceans to raise sea levels rapidly by 1-2 m, sufficient to flood Doggerland. Any similar sea level rise today could have major impacts of people living in low lying areas such as the Nile or Ganges delta.

1.4 Ice Ages

As we have already seen, it is generally acknowledged that the Earth has undergone numerous ice-ages over the course of its history. These mass climate shifts occur as the Earth cools and the ice is able to move from the poles towards the equatorial regions. The definition of an ice-age is vague, and is generally defined as being due to the presence of significant ice sheets below the arctic circles.

During ice ages the global mean temperatures can be 10 or more degrees lower than we observe today, although it interglacial periods they have also been significantly hotter than we observe today. Given these large scale shifts in temperature, which have occurred over geological history long before mankind had a significant impact on the atmospheric composition, it is relevant to ask if we understand the origins of this, apparently natural climate variation, this is particularly important if we wish to claim an understanding of the climate we observe today.

Our main model for understanding ice ages arises from the orbit of the Earth around the sun. There are various periodic changes in this orbit, and these in turn impact both the level and distribution of light that we obtain from the sun. In particular, there are three periods of importance.

1. Eccentricity: The Earth’s orbit is not a perfect circle, it is slightly elliptical, with an average distance of 93 million miles, but a range of between 91-95 million. When the Earth is further away it gets less energy, when it is closer it gets more. At present the Earth is at its largest distance from the Sun during the northern summer, and closest during the Northern winter (yes, this is the right way around). The distance has only a very small impact on the temperature, but averaged over a long time period can be significant. In particular, the eccentricity is not a constant in time, but varies slightly over a time period of about 100,000 years. When the eccentricity is low the orbit is nearly circular and the amount of light received is constant throughout the year. When the eccentricity is high the changes between nearest and farthest approach are significant and temperature changes can occur.

2. Obliquity: The axis of the Earth is tilted relative to the plane of the orbit. This means that the angle the suns light makes with the axis of the Earth varies, and is not just highest at the equator and lowest at the poles, but varies with time. The different angles that sunlight makes with the ground are the primary drivers of the seasons. In the northern hemisphere, the sun remains low in the sky in winter, even at midday. This means its light is spread out over a larger area, and so it is cooler. The opposite is true in summer. Again, long term changes in the precession angle with time have important consequences for the way sunlight is distributed over the Earth.

3. Precession: This is the angle of the Earth axis of rotation, and is similar to obliquity, but measured relative to fixed stars. Precession is best sort of as the wobbling of a gyroscope. The period of this precession of 26,000 years, also impacts the way that sunlight is distributed onto the surface of the Earth.

These three different periods interact with each other in complex ways. Sometimes their effects add together, while at other times they cancel out. However, they can be calculated analytically, and therefore it is possible to compare forewords and backwards models of the way solar energy is distributed around the globe with actual temperature records. These generally (but not perfectly) show a good correlation, indicating that incoming sunlight, and its distribution around the Earth are the primary drivers of large scale climatic shifts such as ice ages.

1.5 Summary

Here we have examined how historical climate can be measured and quantified, and looked at some of the different physical forces which are thought to drive it (we will look in more detail at these later in the course). It is clear that the climate has changed markedly over the history of the Earth.
Perhaps the most remarkable things about past climate are firstly that we are able to measure it with such precession, and secondly that we can broadly explain the pattern that it takes. In other words, our study of past climate gives us confidence that our understanding is complete enough to make our statements about current climate robust. In this sense it is interesting to note that if we input the same science that works so well for ancient climate into models and run them through the 20th century they fail to find a match – it looks as though something is happening in the 20th century for which we don't have a good explanation for in past climate – this of course is the impact of humans, and is the core subject of this module.

Chapter 2

Lecture 2: The basics of climate science

Learning objectives
From this lecture you should be able to:

- Describe how the temperature of the Earth is set.
- Understand how changes in greenhouse gas concentrations impact the energy balance of the Earth.
- Calculate changes in the temperature for changes in the physical conditions of the Earth.
- Appreciate how slightly different atmospheric balances have dramatically changed the climates of Mars and Venus.
- Understand how feedbacks act to enhance or dampen climate changes.

Key to understanding climate change is an appreciation of the basic science that drives the temperature and climate of our planet. At the simplest end it is these basic principles that allow us to determine the temperature of the Earth, while it is the same laws applied in highly advanced computer codes which allow us to build both weather and climate models that provide projections of future climate.

2.1 The Earth is heated from above

There are two natural sources to consider for driving the temperature of the Earth. The first is internal energy. The core of the Earth is at a temperature of around 6000 degrees, about the same as the surface of the Sun. The second, is the Sun itself, which bathes us continuously in its light.
The outward radiation from the centre of the Earth has many uses, it is the source of geothermal energy for example. This energy is largely created in the hot and dense core of the Earth, via the decay of radioactive species such as Uranium (^{238}U,^{235}U), Thorium (^{232}Th) and Potassium (^{40}K). These radioactive species are characterized by a half-life (simply put if you have 1 kg of one of these elements the half-life is the time it takes for half of it to decay). The half-life of these elements is of order billions of years, comparable to the age of the Earth, and so their energy input is becoming gradually less important with time (but was important early in the history of the Earth). Today, the total heat flow from these radioactive decays is of order 0.1 Watts per square metre (W m^{-2}).
This number can be compared with the energy input from the Sun. This is readily measurable, and comes in at 1370 W m^{-2} at the equator. It becomes less moving towards the north or south poles because the incoming energy is spread over a larger surface area[1], and at the poles the sunlight is just grazing the surface, leaving very little of the energy behind. Averaged over the surface of the Earth the solar flux is actually 1/4 of this or 343 W m^{-2}. This is clearly much larger than heating from the internal energy of the Earth, and so it is safe to conclude that it is the sun that is the driving force for the temperature of the Earth.

[1] Note that, as with seasons the changing temperature has almost nothing to do with the distance from the Sun

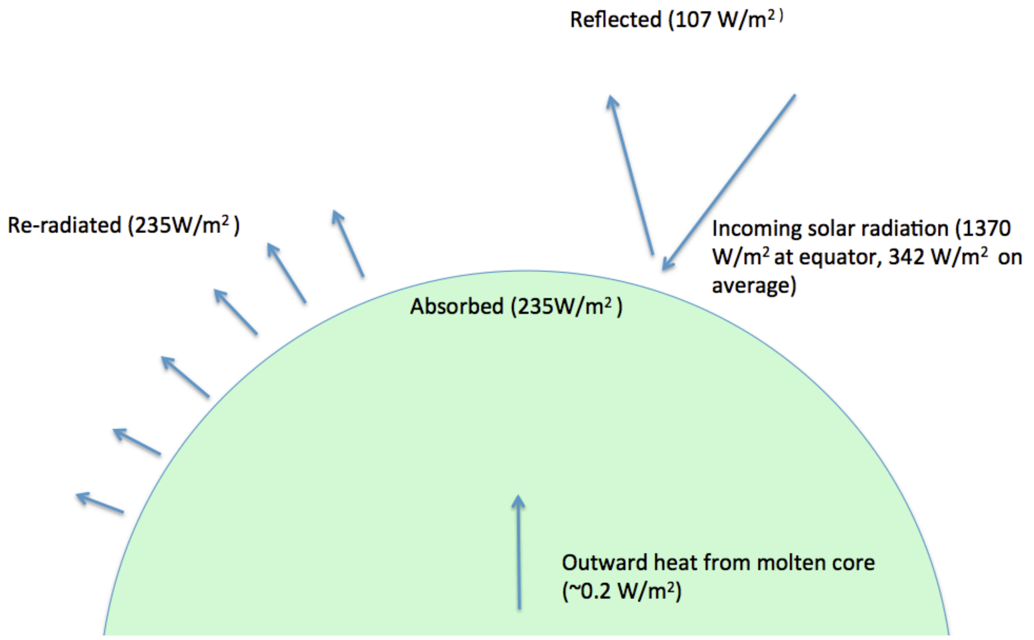

Figure 2.1: A simple model for heat transport on the Earth. Incoming energy from the sun is either reflected (about 30%) or absorbed. The reflected radiation has little impact on the temperature, while the absorbed radiation heats up the surface of the Earth. As the surface heats it re-radiates this energy to keep in equilibrium, and this sets the temperature of the planet.

2.2 Equilibrium temperature

Changes in the climate of the Earth are also relatively slow. The average temperature Earth is not dramatically rising or cooling on timescales of anything less than years, and so we can conclude that it is close to equilibrium. Simply put,

Energy in from Sun = Energy out from Earth.

Both the energy in and the energy out come from sources that are thermal. This means that the relative amounts of light at different wavelengths are essential a property purely of the temperature of the source. The sun is hotter and so emits more blue light, while the Earth is cooler and emits light mainly at longer wavelengths in the infrared. Formally, both can be approximated as so called black-bodies (bodies which absorb and re-emit radiation) with characteristic temperatures of 6000 Kelvin (the Sun) and 300 Kelvin (the Earth). The surface of the earth is heated by the sun. At the distance of 1AU (1.5×10^{11}m) from the sun we can calculate the so called solar constant, which is the solar radiation hitting each m^2 at this distance from the sun. This is straightforwardly measured as is around 1370 W m^{-2}. Using just these numbers, the temperature of the Earth can be worked out from some simple physics. We will outline it here, but the steps are more important than the algebra.

1. The incoming energy from the Sun (S) is equal to the outgoing energy from the Earth.
2. A fraction of the energy is reflected, this is characterised by the albedo (A), so $(1-A)$ of the radiation is absorbed.
3. This radiation is spread over the surface of the Earth. In projection from the sun this just looks like a disc, so it is spread over an area of πR^2, where R is the radius of the Earth. In other words, the total energy in (E), is given by

$$E = (1-A)S\pi R^2 \tag{2.1}$$

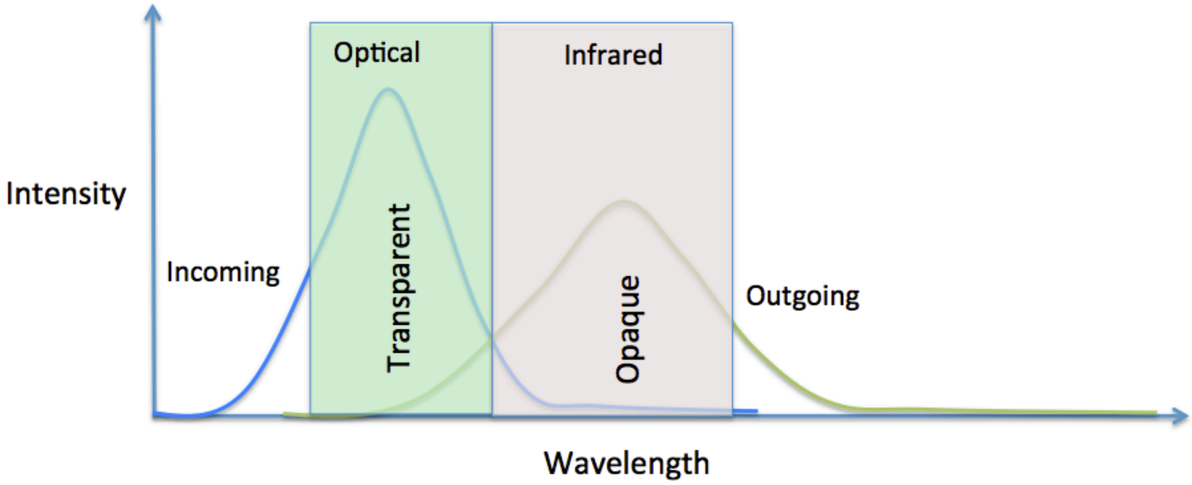

Figure 2.2: Why there is a greenhouse effect. The incoming solar radiation has a spectrum like the blue line. It peaks in the optical, where the atmosphere is mostly transparent. The outgoing Earth radiation, while equal in energy is characteristic of a much cooler object than the Sun. This means it is emitted primarily in the infrared. In the infrared the Earth's atmosphere is opaque. It absorbs much of the infrared light, trapping the energy on the Earth, and resulting in a much higher temperature.

4. The energy emitted obeys black-body laws, and in particular the Stefan Boltzman law $E = \text{Area} \times \sigma T^4$, were T is the temperature of the Earth and σ is a constant.

5. The Earth radiates energy from all of its surface, which has surface area $= 4\pi R^2$ (the surface area of a sphere). Equating the incoming and outgoing radiation we get

$$(1-A)S\pi R^2 = 4\pi R^2 \sigma T^4 \tag{2.2}$$

6. From this we can re-arrange for the temperature of the Earth and get

$$T^4 = \frac{S(1-A)}{4\sigma} \tag{2.3}$$

If you try putting the above numbers into your calculator you will find that the temperature of the Earth should be 255K (about -18 centigrade). This is often referred to as its *equilibrium temperature*. Of course, this doesn't actually represent the true average temperature of the Earth, which is of order 30 degrees hotter. The reason the Earth isn't in fact a ball of ice is almost entirely down to the *greenhouse effect*.

2.3 The greenhouse effect

The greenhouse effect is the insulating effect of the Earth's atmosphere that absorbs some of the outgoing radiation and re-radiates it back to the surface. This re-radiation effectively warms the planet, and stops it from being dominated by ice.

The key to the greenhouse effect lies in the properties of its atmosphere when bombarded with infrared light. The atmosphere in the optical is effectively transparent, and it is not surprising that our eyes have evolved to work at this wavelength. However, it is not equally transparent at all wavelengths, because gases within the atmosphere act to block that light. It turns out that much of the infrared is in fact blocked by a combination of water vapour, carbon dioxide and methane.

This is important. Remember the incoming radiation from the sun peaks at optical wavelengths. It can pass freely through the atmosphere, but the outgoing radiation from the Earth is primarily in the the infrared. It can't pass back out and into space, and therefore is trapped. In other words, the equilibrium is

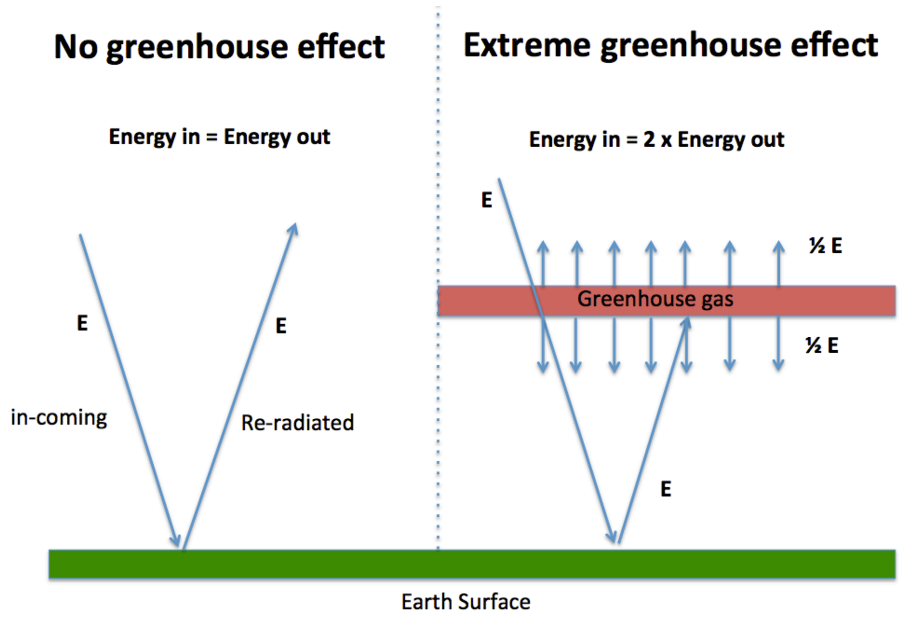

Figure 2.3: A simplistic model of the greenhouse effect. The left hand side shows a planet with no greenhouse effect. In this case the energy in is always equal to the energy out and equilibrium is preserved. In the right hand panel we have an effective greenhouse. It absorbs all incident IR light, and then heats up. It re-radiates half of this energy upward to space, and the other half back to the ground. In this case the energy in is equal to twice the energy out. The response of the planet is too warm up until equilibrium is restored.

broken and the planet begins to warm. The degree of warming is then governed by the composition of its atmosphere, and we can find very good examples of this does (or doesn't) work by looking at our nearest neighbours, Mars and Venus.
The equilibrium temperature of Venus is 232 Kelvin, the equilibrium temperature of Mars is 210 Kelvin. Interestingly both are lower than the Earth, even though Venus is closer to the sun, this is largely because of a very different albedo for Venus, which reflects a lot more light back into space. However, the *actual* temperatures of Venus and Mars are 735 and 214 Kelvin. Mars is actually very close to its theoretical number, Venus is much hotter that it should be. The reason for this is simple. Mars has a carbon dioxide atmosphere, but it is extremely tenuous and does little to insulate the planet. In contrast Venus has an extremely thick atmosphere, made up mostly of carbon dioxide. It has suffered a runaway greenhouse effect that has left it far too hot to support life.

2.3.1 Modelling the greenhouse

We can simply model the greenhouse effect by considering a "layer" in the atmosphere which allows all incident radiation in, but absorbs (and re-emits) all re-radiated emission from the earth's surface. In this model. The layer in the atmosphere absorbs and remits the radiation, however, it emits half of it downwards, and half of it upwards (see Figure **??**. This means that only half of the incident radiation is returned to space, and the rest of the "back radiation" is radiated to the ground. This creates what is known as a radiative forcing. Since we know that ultimately we need to balance this radiation the solution is for the temperature of the surface to warm up, such that σT^4 becomes large enough to balance the incoming radiation. It turns out (and is straightforward to show) that this simple version of the greenhouse effect would yield a warming of $\sim 20\%$.

2.4 Radiative Forcing

Changes to the Earth radiation balance can be expressed as by radiative forcing, and this is the standard nomenclature that will be found in many textbooks and reports. The radiative forcing is simply a measure of the imbalance between incoming and outgoing radiation. It can be due to many different physical processes, not just those occurring in the atmosphere. Simply put, a positive radiative forcing means that more energy comes in that goes out, and so the Earth warms, a negative forcing means the more energy goes out than comes in, and this results in a cooling Earth.

2.5 Greenhouse gases

It is clear from the above discussion that there is something in our atmosphere which is very effective at keeping heat from escaping. This is actually vital for life, we would not have liquid water if it wasn't for these greenhouse gases which insulate us.

Greenhouse gases can be of varying strengths, with some effectively blocking all IR light, while others only block a small fraction. A greenhouse gas is therefore simply defined as one which does block outgoing IR radiation. Not all gases do this. Oxygen and Nitrogen in their simple diatomic forms (O_2,N_2) are not greenhouse gases, and so the dominant gases in our atmosphere do not contribute to the natural greenhouse effect. In order to act as a greenhouse gas the molecules must create an asymmetry in their distribution of charge. Normal diatomic molecules (O_2,N_2) don't do this because they are symmetrical, but molecules containing three or more atoms do, especially when they are atoms of different elements. For this reasons CO_2 and CH_4 (methane) act as powerful greenhouse gases. The effect of a given greenhouse gas can be ascertained from its *global warming potential*, this is essentially the impact of a given gas, relative to carbon dioxide (which has a global warming potential of 1). There are many molecules that have much higher global warming potentials than carbon dioxide, although they also tend to be much rarer in the atmosphere, and so aren't considered strongly.

However, this discussion is actually slightly misleading. The most effective greenhouse gas in the atmosphere is not carbon dioxide, despite its prominence in most discussion. The reason the world is not freezing is not because of CO_2, but because of H_2O – water vapour. Because of the way water vapour behaves in the atmosphere (for example as a function of weather, or temperature) it doesn't have a calculated global warming potential, but it is water, and not CO_2 that absorbs most of the outgoing IR radiation. Equally, while water vapour is the explanation for the natural greenhouse effect, the reason that CO_2 is so widely discussed is because it is the major *anthropogenic* (man-made) greenhouse gas. It is the CO_2, and related gasses which are likely to result in an *enhanced greenhouse effect*, and are the suggested cause of most of the global warming that has been seen to date.