Unpredictable ice ages?

Ice and sediment cores store excellent records of the Earth's history and the isotopes within let geoscientists pin down how global temperature has changed over time. These records show the Earth has alternated between periods of intense cold and warming. But while there are clear patterns in the climate record, the frequency of ice ages is not always constant. Scientists are working to find out why.

The Earth's climate is controlled by astronomical phenomena that operate on timescales tens to hundreds of thousands of years long. One of these phenomena is the variation in the Earth's obliquity – the angle the Earth tilts on its axis. The inclination of the Earth's axis varies from approximately 22 to 24.5 degrees over the course of 41,000 years and the greater the tilt, the stronger the difference between seasons. Thus, when the winter is warmer, there is more moisture available for snowfall, and when the summer is cooler, the winter ice persists longer into the season, stimulating the start of a glacial period.

The other phenomenon is climatic precession, also known as precession index. It combines variations in eccentricity – how elliptical the Earth's orbit is and how that changes over thousands of years – with a parameter known as the longitude of perihelion. The longitude of perihelion controls the time of year at which the Earth is at its closest point to the Sun. At present, the Earth reaches this point in January, but when the closest approach happens in June (as it did 11,000 years ago), the Earth and the Sun are significantly closer. This close proximity causes the Earth to receive more energy, negatively affecting glacier mass balance and preventing glaciation. The changes in the longitude of perihelion occur over timescales of about 23,000 years. Changes in eccentricity, on the other hand, occur over much longer periods and every 100,000 years the Earth's orbit is almost circular.

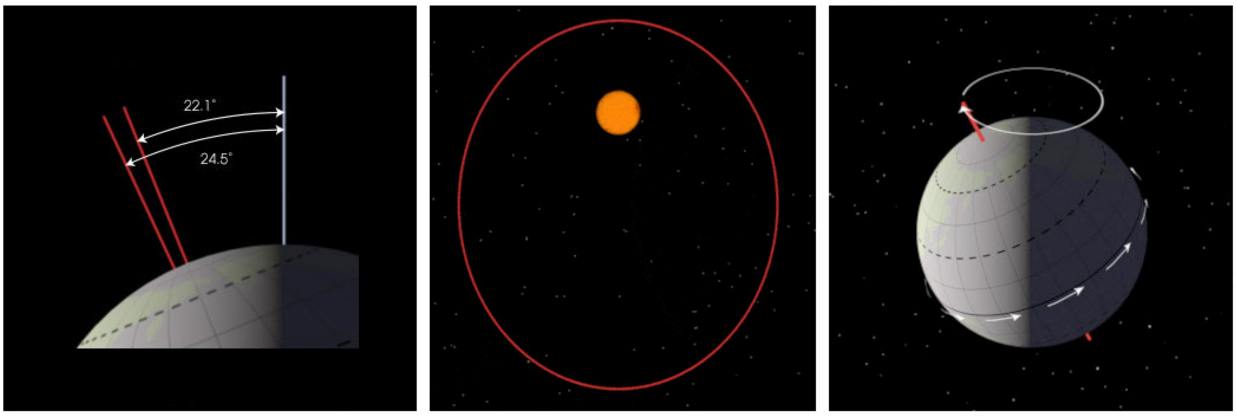
Combined, these changes in orbital parameters and obliquity are known as 'the astronomical pacemaker', a well-known control on the timing of glacial-interglacial cycles. However, the pulse of the Earth's climate is barely regular – in fact, we don't yet know how tightly these astronomical phenomena control the Earth's climate.

Recently, researchers have begun investigating what could cause delays in deglaciation and shifts in the sequences of ice ages in an effort to assess the strength of the astronomical pacemaker. One such scientist is Michel Crucifix, from the Georges Lemaître Centre for Climate Research in Belgium.

Using seven published models, Crucifix set out to see what could disrupt the ice age sequence from the pace set by the Earth's orbit and obliquity, and found that small changes in the amount of solar radiation the Earth receives, or the amount of heat it retains, could cause big shifts in the occurrence of ice ages. "I started playing with simple models of ice ages and it became pretty clear to me that the sequence of ice ages in these models was quite sensitive to parameters…I took this sensitivity issue as a starting point: what are the mathematical mechanisms at work; is this an artefact or does this sensitivity actually tell us about the real world?"

As is often the case, the devil is in the detail and it is random events that affect the climate on short timescales that are responsible for this irregularity. "I really like this idea of a system that is being intermediate between 'chaotic' and 'fully predictable'," Crucifix says. He considered the climate record from the 3.2-km-long ice core at Dome Concordia in Antarctica, which records 800,000 years of climate history: "there is regularity, but there are also a many rapid and not-so-well organised variations that seem to be incompatible with the presence of a nice, solid, pacemaker."

So what could cause the Earth to 'skip a beat' in a glacial cycle? Possible causes are volcanic eruptions and interactions between the ocean and atmosphere that are capable of perturbing the Earth's climate. Volcanic eruptions, for example, emit large quantities of sulphate aerosol into the upper atmosphere – particles that are a starting point for clouds. Clouds reflect solar radiation back



Components of the astronomical pacemaker: the Earth's obliquity (tilt on its axis), eccentricity (elliptical character of the Earth's orbit) and precession (the wobble of the Earth's axis that controls the time of year the Earth is closest to the Sun). (Credit: modified from NASA)

BACK TO CONTENTS

into space and cause the Earth to cool – such a change could be enough to stimulate the start of an ice age.

Records of what caused these climate perturbations, as well as what their effect on climate was, are recorded in ice cores. In the case of a volcanic eruption, you might find a layer of ash or sulphate that indicates a large volcanic event in an ice core, and can correlate this with changes in temperature on short – and possibly longer – timescales when looking at isotope data.

But the factors that cause these shifts are not yet known. "My intuition is that very small perturbations could do the job (as small as atmospheric perturbations), but which magnitude is needed and when they actually matter is not yet quantified," says Crucifix.

Indeed, Crucifix's findings show just that: small perturbations can alter the rhythm of glacial cycles. This lends support to a theory put forward by Eric Wolff known as 'the proximal cause of terminations': that the timing of the end of a glacial period can be influenced by the occurrence of abrupt climate events in the thousands of years that precede its termination. The research also builds on the findings of pioneers in climate theory such as Barry Saltzman and Ed Lorenz, who first considered the role of chaos in climate modelling. Crucifix shares his enthusiasm for his work: "I really feel like I am standing on the shoulders of giants…being able to borrow concepts introduced by these great scientists and extract an idea that was latent in their work but not explicitly formulated is thrilling."

Even small variations of climate model parameters can mean the difference between an ice age and an interglacial period, what we need to know now is when in the astronomical cycle can small changes in solar radiation lead to big changes in climate.

Sara Mynott
EGU Communications Officer

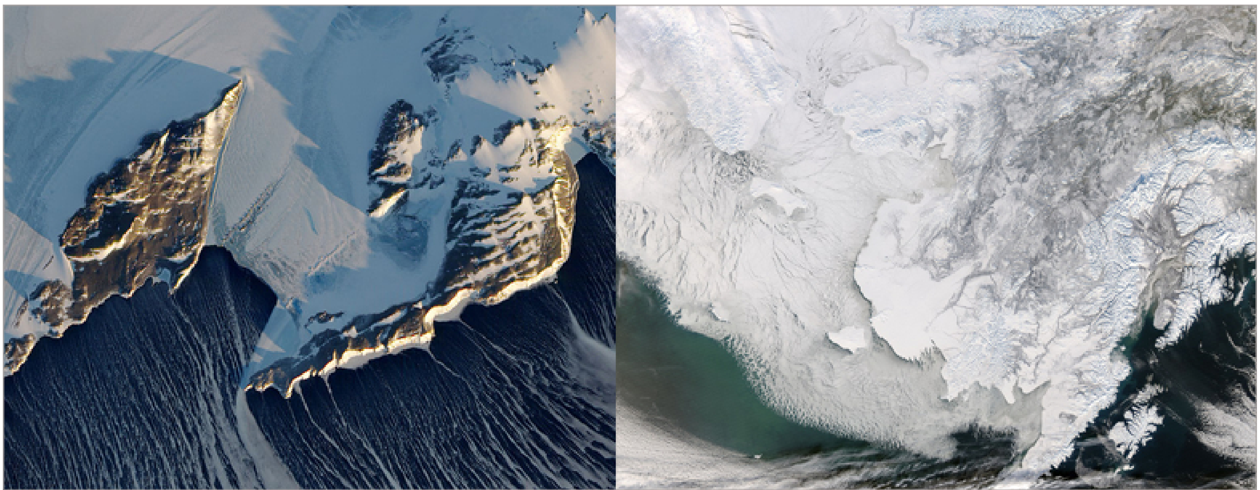
Acknowledgement
Michel Crucifix's research was funded by the European Research Council.

References

Crucifix, M.: Why could ice ages be unpredictable?, Clim. Past, 9, 2253–2267, 2013

De Saedeleer, B., Crucifix, M. and Wieczorek, S.: Is the astronomical forcing a reliable and unique pacemaker for climate? A conceptual model study, Clim. Dyn., 40, 273–294, 2013

European Project for Ice Coring in Antarctica (EPICA): Eight glacial cycles from an Antarctic ice core, Nature, 429, 623–628, 2010



Left. The Nansen Ice Sheet, shortly before the onset of the Southern Hemisphere spring. (Credit: NASA) Right. Sea Ice in the Bering Strait. (Credit: J. Schmaltz/NASA)

Misunderstood? Soil organic carbon and climate change

Soils are essential to global development. They are the sustaining force that keeps communities alive globally and locally; without soil we would not have the ability to grow crops that feed the majority of the world's population. But soil also has another crucial role related to the Earth and its present and future populations: the storage of organic carbon. The importance of this, in relation to climate and development, has only recently been recognised.

Up until 2010, most climate models attributed the majority of carbon storage during glacial periods to the oceans. However, there has been no success in finding sinks of 'old radiocarbon' in the oceans to support this widely accepted hypothesis. In 2011, Roland Zech and his team investigated a key question that this idea raised: can the change in carbon pools over glacial-interglacial periods be quantified more accurately across the marine and terrestrial realms? Zech noticed that terrestrial estimates for carbon assumed that there was a decrease in stored organic carbon on the continents during glacial periods, meaning that the oceans take up somewhere in the region of 300–800 Pg C (petagrams of carbon, where 1 Pg is equal to 10^{12}

kg of carbon) from terrestrial sources in addition to the 200 Pg C from the atmosphere during glacial periods.

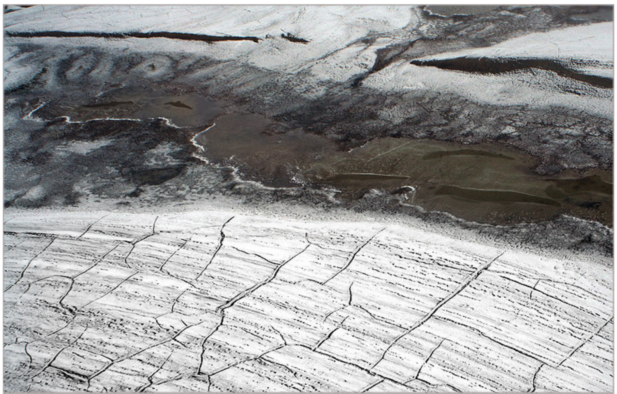
Yet Zech noticed that something had been overlooked: permafrost. Permafrost is soil and sediment that remains, and has remained, frozen for more than two years. In the Northern Hemisphere alone, permafrost occupies around 22.79 million square kilometres of exposed land surface. Zech noted that current organic carbon estimates do not explicitly consider the organic carbon stored below ice sheets in permafrost and new estimates suggest that soil organic carbon (SOC) in the Northern Hemisphere may exceed 1670 Pg C. Zech's research shows that this carbon is repeatedly stored in permafrost during glacial periods and, if not taken into account, it could significantly affect the reliability of climate models.

As permafrost provides an excellent environment for long term carbon storage during glacial periods, there have been increasing concerns about the effects of thawing of permafrost on climate. In a separate study undertaken in 2011, Charles Koven found results in contention with the IPCC 4th Assessment Report. Using a terrestrial ecosystem model of permafrost carbon dynamics, Koven found that Arctic ecosystems warming could shift from being a carbon sink to a carbon source by the end of the 21st century.

Black carbon rich soils on an Icelandic farm. (Credit: Ragnar Sigurdsson/www.arctic-images.com)

Now recognised as an active and crucial component of the carbon system, it is important to map SOC pools accurately. Although researchers have attempted to map SOC behaviour before, they have had little success in producing detailed, high resolution maps until recently. In 2012 Jeroen Meersmans undertook a national soil survey across France, analysing over 2000 soil samples in an effort to measure soil properties and factors controlling SOC and went on to develop a model for predicting spatial and temporal distribution of SOC across France. The resulting model allowed detailed projections of land that will be characterised by a gain or loss in SOC, as well as the possible outcomes of land management decisions – such as whether to farm the land and what should be grown there. This type of tool is extremely important in managing SOC as it allows people to optimise carbon storage in soils and minimise soil-related CO_2 fluxes (that could cause increased global warming).

Understanding SOC storage is also the basis for sustainable agriculture. SOC is an important component of the three main aspects of soil fertility: helping release nutrients such as nitrogen and phosphorous, binding soil mineral particles together for increased water holding and infiltration capacity, and providing a key food source for flora and fauna. Increasing and retaining SOC content is therefore an important mechanism for improving soil 'health' as well as mitigating climate change.



Arctic permafrost. (Credit: Wikimedia Commons user Broken Inaglory)

Earlier this year Kathryn Page investigated the effectiveness of agricultural techniques in retaining SOC and found that 'no-till' management (planting crops without disturbing the soil through digging and overturning) is more effective than conventional methods. Research has also shown that other techniques including improved crop residue management, crop rotations and conversion of marginal cropland to native vegetation or permanent grassland can increase SOC content.

It is important to transfer land management research to decision making tools for land use. Tools such as the Global Biosphere Management Model (GLOBIOM) are a step towards this goal. GLOBIOM tracks effects of land use change and trade, going beyond traditional land management tools by modelling both changes in demand for land use, and changes in land profitability – key determinants of real world land use change.

Despite the breadth of research going on in this area, there remains much to be understood about the nature of SOC, such as how it binds to other minerals inside the soil and how this will affect the stability of SOC as the climate changes.

Jane Robb
EGU Educational Fellow

Reference

Koven, C.D. et al.: Permafrost carbon-climate feedbacks accelerate global warming, Proc. Natl. Acad. Sci. USA, 108, 14769–14774, 2011

Page, K.L. et al.: Organic carbon stocks in cropping soils of Queensland, Australia, as affected by tillage management, climate, and soil characteristics, Soil Research, 2013

Zech, R. et al.: High carbon sequestration in Siberian permafrost loess-paleosols during glacials, Clim. Past, 7, 501–509, 2011

Atlantic meridional overturning circulation during the Holocene

Implications for understanding modern climate

Over the past 25 years scientists have drawn on a variety of sources to identify periods and forcers of change in global climate. In the 2013 study 'Long-term variations in Iceland–Scotland overflow strength during the Holocene', David Thornalley and his team added another significant piece to the puzzle of deep water formation, a system that is crucial to the transport of heat around the globe.

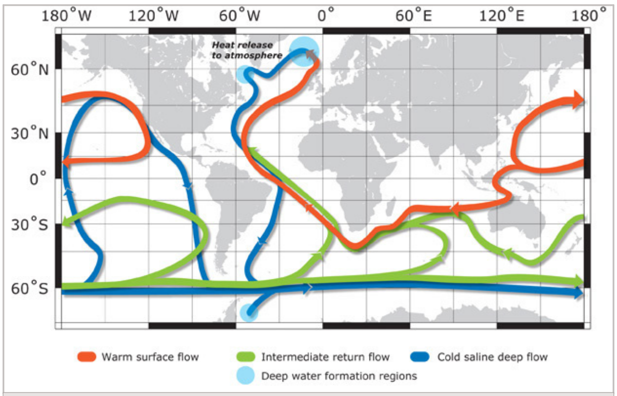
By assessing the grain size of 13 sediment cores, Thornalley and collaborators were able to reconstruct the overflow of dense bottom waters from Nordic seas across the Iceland–Scotland undersea slope to the North Atlantic during the Holocene. Overflow strength is determined by ocean bathymetry (the topography of the ocean floor) and the difference in density between the Nordic and North Atlantic waters. Factors influencing seawater density include temperature and salinity, and as high winds blow across Nordic waters, more water is evaporated, leaving denser, more saline water behind. Winds also contribute to the effects of ocean bathymetry, forcing waters across undersea barriers.

Thornalley's team was able to obtain a measure of the strength and depth of the Atlantic meridional overturning circulation (AMOC) – an essential component of the Earth's climate system that allows the formation of the North Atlantic Deep Water. Their results showed that overflow strength was weaker in the early and latter part of the Holocene and strongest due to a deepening of the overflow path around 7,000 years ago – coinciding with a period of regional high temperatures.

Deepening overflow of the Nordic waters contributes to a complementary strengthening in the inflow of North Atlantic waters northwards. This results in regional warming that helps to control the balance of ice sheets and overall climate of northwestern Europe. Large freshwater influxes from melting of ice sheets due to global warming are suspected to weaken the AMOC by raising the depth of overflow in the North Atlantic and decreasing both the regional warming and balancing effect of the North Atlantic waters on northwestern Europe.

Although current forcing factors of climate change are primarily anthropogenic rather than natural, and expected to remain so in the future (the projections by the International Panel on Climate Change look to the end of the current century), research on the past can help us understand the future.

In his paper, Thornalley also ran model simulations that showed a predicted reduction of around 40% in the maximum winter overflow depth by the end of the 21st century, broadly in line with the results from other studies reviewed in the IPCC Working Group I report. Previous palaeoclimate reconstructions have shown that reduction or cessation of Nordic overflow would have resulted in extreme



Warm water produces warmer air and increases atmospheric moisture. Therefore, regions affected by warm currents such as the Gulf Stream are characterised by milder, moister climates. (Credit: Thornalley et al., 2013)

widespread climate impacts, including increased instability of climate and ice sheets in the North Atlantic.

Although past events aren't directly analogous to present changes, Thornalley identifies in an interview two key benefits from a deeper understanding of pre-anthropogenic change. First, he says, it allows us to identify the range of climate impacts and build up our understanding of the past: "It's not until relatively recently that we knew that climate could change so abruptly", a statement mirrored in the IPCC's recent Working Group I report where they referred to 'unprecedented changes' in climate. And second, Thornalley believes that if we can use models to replicate past variation, we can gain confidence in the predictions made by the same models for future climate change.

Given the multiple feedbacks associated with the climate system, both positive and negative, the regional climate implications of a reduction in overflow depth in the North Atlantic are not obvious. What is clear is that current levels of anthropogenic CO_2 emissions are likely to have far-reaching changes that we don't yet fully understand. As Thornalley puts it: "There's a lot we still need to learn about the Atlantic meridional overturning circulation and the complexities of climate."

Jennifer Young
UK-based freelance science writer

References

Oppo, D. W. & Curry, W. B.: Deep atlantic circulation during the Last Glacial Maximum and deglaciation, Nat. Edu. Knowledge 3(10), 1, 2012

Thornalley, D. J. R. et al.: Long-term variations in Iceland–Scotland overflow strength during the Holocene, Clim. Past, 9, 2073–2084, 2013

Working Group I, IPCC 5th Assessment Report: Climate Change 2013: The Physical Science Basis – summary for policymakers, 2013

The slow discovery of human-induced climate change

"Few of those familiar with the natural heat exchanges of the atmosphere, which go into the making of our climates and weather, would be prepared to admit that the activities of man could have any influence upon phenomena of so vast a scale."

Weren't it for the old-fashioned language, climate sceptics, who believe there is no scientific consensus on human-made climate change, would readily place this sentence in a 2013 paper. However, the statement belongs to a landmark study published by Guy Stewart Callendar in 1938. He carries on with: "In the following paper, I hope to show that such influence is not only possible, but is actually occurring at the present time."

Seventy-five years later, the world's biggest carbon emitters are now taking action. China, who alone emits nearly a quarter of man-made emissions, agreed to implement emission caps earlier this year. The US, the second largest CO_2 emitter, followed suit with US President Obama issuing regulations to limit carbon-dioxide emissions from power plants in the country. The European Union also considers preventing dangerous climate change a strategic priority, and has recently committed to spend at least 20% of its 2014–2020 budget on climate action.

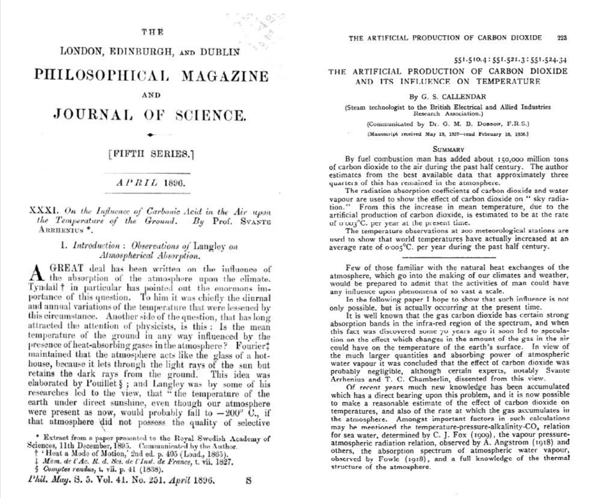
These measures follow a long-standing consensus by the climate-science community who now overwhelmingly agree that climate change is real and that greenhouse gases emitted by human activities are the main cause. The recently released report on the physical science basis of climate change by the Intergovernmental Panel on Climate Change (IPCC) summarises this agreement by stating: "It is *extremely likely* that human activities caused more than half of the observed increase in global average surface temperature from 1951 to 2010."

The consensus of the scientific community on climate change and its severe consequences is now clear, and is pushing policymakers to finally take action. But the history of climate change science tells us that wasn't always the case.

The deadly glaciers and the relation between CO_2 and temperature

Callendar's 1938 paper was ground-breaking: it was the first to demonstrate the warming of the Earth's surface and to suggest this warming was related to fossil-fuel burning. But it was not without errors. Fearing "the return of the deadly glaciers", Callendar believed that a human-generated temperature increase would be beneficial. The 'deadly glaciers' were a reference to the ice ages of the Earth's past, when glaciers had covered Europe and much of North America.

In the late 19th century, Svante Arrhenius calculated the influence of atmospheric carbon on ground temperatures in an attempt to explain the Earth's ice ages. Physicist John Tyndall had earlier found out that water vapour, methane and carbon dioxide strongly



THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* By Prof. SVANTE ARRHENIUS *.

I. *Introduction: Observations of* Langley *on Atmospherical Absorption.*

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall † in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this: Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier‡ maintained that the atmosphere acts like the glass of a hot-house, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet §; and Langley was by some of his researches led to the view, that "the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to −200° C., if that atmosphere did not possess the quality of selective

* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December, 1895. Communicated by the Author.
† 'Heat a Mode of Motion,' 2nd ed. p. 405 (Lond., 1865).
‡ *Mém. de l'Ac. R. d. Sci. de l'Inst. de France*, t. vii. 1827.
§ *Comptes rendus*, t. vii. p. 41 (1838).

Phil. Mag. S. 5. Vol. 41. No. 251. *April* 1896. S

THE ARTIFICIAL PRODUCTION OF CARBON DIOXIDE 223

551.510.4 : 551.521.3 : 551.524.34

THE ARTIFICIAL PRODUCTION OF CARBON DIOXIDE AND ITS INFLUENCE ON TEMPERATURE

By G. S. CALLENDAR

(Steam technologist to the British Electrical and Allied Industries Research Association.)

(Communicated by Dr. G. M. B. DOBSON, F.R.S.)

[Manuscript received May 19, 1937—read February 16, 1938.]

SUMMARY

By fuel combustion man has added about 150,000 million tons of carbon dioxide to the air during the past half century. The author estimates from the best available data that approximately three quarters of this has remained in the atmosphere.

The radiation absorption coefficients of carbon dioxide and water vapour are used to show the effect of carbon dioxide on "sky radiation." From this the increase in mean temperature, due to the artificial production of carbon dioxide, is estimated to be at the rate of 0·003°C. per year at the present time.

The temperature observations at 200 meteorological stations are used to show that world temperatures have actually increased at an average rate of 0·005°C. per year during the past half century.

Few of those familiar with the natural heat exchanges of the atmosphere, which go into the making of our climates and weather, would be prepared to admit that the activities of man could have any influence upon phenomena of so vast a scale.

In the following paper I hope to show that such influence is not only possible, but is actually occurring at the present time.

It is well known that the gas carbon dioxide has certain strong absorption bands in the infra-red region of the spectrum, and when this fact was discovered some 70 years ago it soon led to speculation on the effect which changes in the amount of the gas in the air could have on the temperature of the earth's surface. In view of the much larger quantities and absorbing power of atmospheric water vapour it was concluded that the effect of carbon dioxide was probably negligible, although certain experts, notably Svante Arrhenius and T. C. Chamberlin, dissented from this view.

Of recent years much new knowledge has been accumulated which has a direct bearing upon this problem, and it is now possible to make a reasonable estimate of the effect of carbon dioxide on temperatures, and also of the rate at which the gas accumulates in the atmosphere. Amongst important factors in such calculations may be mentioned the temperature-pressure-alkalinity-CO_2 relation for sea water, determined by C. J. Fox (1909), the vapour pressure-atmospheric radiation relation, observed by A. Angstrom (1918) and others, the absorption spectrum of atmospheric water vapour, observed by Fowle (1918), and a full knowledge of the thermal structure of the atmosphere.

First pages of Arrhenius's 1896 (left) and Callendar's 1938 (right) seminal papers.

block radiation coming from the Sun. Inspired by this, Arrhenius calculated that cutting atmospheric carbon dioxide by about half would return the Earth to the ice ages. Using the same crude atmospheric model, he estimated that by doubling the CO_2 in the atmosphere, the global temperature would increase 5 to 6 °C. But at a time when the industry was burning fossil fuels at a negligible rate, he thought it would take thousands of years for that much CO_2 to be added to the atmosphere.

Early 20th century scientists criticised Arrhenius' calculations and ignored that variations in atmospheric CO_2 – those of human origin in particular – could alter the climate. Callendar's paper was met with similar scepticism. It took another few decades for consensus to start forming around the idea that human-made climate change was real.

The Keeling Curve and ice cores

Following the Second World War and well into the Cold War, there was a sharp increase in research funding from US military and other government agencies, giving many American scientists – including Charles David Keeling of Keeling Curve fame – the chance to make detailed measurements of carbon-dioxide levels in the atmosphere. These showed CO_2 concentrations were increasing steadily each year. Now, over 50 years later, the levels approach 400 parts per million (ppm), an increase of over 40% since the industrial revolution. While it was clear that atmospheric CO_2 was rising, it was still hard for some scientists to accept that the Earth's climate – a complex system influenced by many variables – could be dangerously warmed by this.

The 1980s brought fresh and critical discoveries from ice-core research, yielding information on local temperatures and atmospheric composition in the past few thousand years. Researchers, such as Hans Oeschger and Willi Dansgaard, discovered that the

Earth's temperature had abruptly changed various times in the past and that the changes in temperature and CO_2 had mostly moved in lockstep.

The scientific consensus had begun to form: the rapid concentration of atmospheric CO_2 prompted by fossil-fuel burning could drastically change the climate.

Climate change gets political

In the hot year of 1988 the consensus was strong enough for the discussion on human-induced climate change to enter the realm of politics. In June that year, climatologist James Hansen (then of the NASA Goddard Institute for Space Studies) testified before the US Congress, alerting decision-makers and the public to the dangers of climate change:

"I would like to draw three main conclusions. Number one, the earth is warmer in 1988 than at any time in the history of instrumental measurements. Number two, the global warming is now large enough that we can ascribe with a high degree of confidence a cause and effect relationship to the greenhouse effect. And number three, our computer climate simulations indicate that the greenhouse effect is already large enough to begin to [a]ffect the probability of extreme events such as summer heat waves."

In the same year, the World Meteorological Organization and the United Nations Environment Programme established the IPCC "to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts."

Twenty-five years, and five Assessment Reports later, the "[w]arming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased," as stated in the latest IPCC's report's summary for policymakers.

Climate change is in our hands. (Credit: Stephanie Flude)

If the discovery of human-induced climate change was slow, slower still – at a time of urgency – has been the implementation of concrete and efficient measures to fight it.

As University of East Anglia's Corinne Le Quéré wrote in The Guardian following the release of the IPCC summary for policymakers, "[the scientists'] job is done now and it is time to let the policymakers do theirs." The scientific community, and the world, waits to see how political leaders will respond.

Bárbara Ferreira
GeoQ Chief Editor & EGU Media and Communications Manager

References

Arrhenius, S.: On the influence of carbonic acid in the air upon the temperature of the ground, Phil. Mag. J. Sci., series 5, 41, 237–276, 1896

Callendar, G. S.: The artificial production of carbon dioxide and its influence on temperature, Q.J.R. Meteorol. Soc., 64, 223–240, 1938

Weart, S.: The Discovery of Global Warming, American Institute of Physics, 2013