Feature

The climate of the future: clues from three million years ago

In the eighteenth century, James Hutton came up with a theory that revolutionized the science of geology, ‘The present is a key to the past’. But could the past also be a guide to our future? The world three million years ago was warmer than present. What might it tell us about global climate change in the near future?

James Hutton is generally regarded as the father of modern geology. In the eighteenth century he came up with a theory that revolutionized the science of geology: uniformitarianism, expressed by Charles Lyell as ‘The present is a key to the past’. This has enabled generations of geologists to interpret information gleaned from rocks and sediments by reference to examples existing in the modern environment. Although this remains a cornerstone of geology, could the past also be a guide to our future? Certainly this would not surprise an historian; consider the old saying ‘history always repeats itself’. Nonetheless, in geology it is an idea that is only now being fully explored. The driving force behind this new adventure is the changing climate of our planet and our desire to understand, predict and mitigate the effects of future climate change.

According to the latest report produced by the Intergovernmental Panel on Climate Change, our planet is running a temperature. Within the next 150 to 350 years, Earth will warm by an extent not seen for millions of years. This warming is a result of the emission of greenhouse gases such as carbon dioxide (CO₂) and methane (CH₄) into the atmosphere. Rapid climate change has become the disaster scenario for the twenty-first century. Be it cities deluged by giant waves, paradise islands sinking into the oceans, or the corals of the Great Barrier Reef heated-up to extinction, everyone is aware that climate change can have a dramatic effect on the world we live in. In the recent Hollywood movie The Day After Tomorrow, New York was frozen solid as the climate of the Northern Hemisphere took a dramatic turn for the worse. But what evidence do we have for climate change in the past, and how can we use the information stored in the geological record to help us predict what our climate and environment might be like in the future? One of the best places to look is the world of the mid-Pliocene, three million years ago. The mid-Pliocene is the last time in geological history when our planet’s climate was significantly warmer, for a prolonged period, than it is today. So what was the mid Pliocene world like?

A window on the Pliocene world

Although the geography of our planet looked very similar to that of today three million years ago, the world was undergoing momentous changes everywhere, from the Americas to Tibet. At about this time, animals from South America first started to colonize North America, indicating that the Isthmus of Panama had finally risen above sea level. Along this trans-continental highway of migration, the armadillo was amongst the animals that migrated north, whilst dogs, cats, bears and many other animals headed south. In Africa, the spread of Savannah vegetation and retreat of forest habitats may have encouraged our primate ancestors to come down from the trees, colonizing the open plains of the rift valleys of east Africa and undergoing an evolutionary radiation into a number of ‘graceful’ and ‘robust’ australopithecines. Their fossil remains are found in modern Ethiopia and Tanzania. In Asia, the continued collision of India with the Eurasian land mass pushed the Himalayas still higher, intensifying the Asian monsoon. From the Americas, ancestral horses about the size of ponies migrated west along the Aleutian archipelago into Asia and Europe. In the Antarctic, the ice sheets and glaciers were not static, but fluctuated in size, influencing the global climate and sea level. In the oceans too, there
were changes. The emerging Isthmus of Panama finally cut off the exit route for Atlantic water into the Pacific, and this contributed to a saltier Atlantic Ocean which may have encouraged the warm water current known as the ‘Gulf Stream’ in the North Atlantic to flow vigorously.

For much of the past three million years our planet’s global climate has been cooler than today, particularly during the ice ages of the Pleistocene. However, during the mid-Pliocene there is strong evidence for a period lasting 300 000 years, when the global climate was warmer than it is today. On Antarctica, along the Transantarctic Mountains, rocks of probable mid-Pliocene age yield fossils of southern beech plants (Figs 1, 2), suggesting that parts of Antarctica were ice free. The question is, what caused this globally warmer climate and what relevance does it have to our understanding of current global warming? There are two key questions. Did higher levels of greenhouse gases in the atmosphere cause Pliocene warmth? Or was this aided and abetted by other factors such as more intense ocean circulation transporting heat from the tropics to the higher latitudes? Part of the evidence for this warm period comes from the fossil skeletons of marine plankton such as foraminifera, and from chemical evidence locked-up in marine rocks.

**Foraminifera: ancient oceanographers**

The oceanic circulation transports an enormous amount of heat around our planet, but the pattern of circulation has not always been the same. The present pattern may have been established as recently as the late Miocene (about six million years ago). The distribution of modern plankton is strongly influenced by sea temperature, salinity, food supply and light-penetration. These factors, in turn, reflect ocean circulation patterns, which are themselves a product of the prevailing geography and climate. As the geography of the world was very similar three million years ago, any major changes in the distribution patterns of plankton observed in the fossil record for that time should reflect changes in climate.

Foraminifera are single-celled, self-motile organisms that are part of the plankton. They produce a skeleton of calcite or silica cement called the ‘test’ (Fig. 3). Usually they are very small – you could easily fit a dozen of these on to the surface of a penny or cent, but sometimes they grow to over a centimetre long. Foraminifera species have a huge array of shapes, reflecting the range of ecologies in which they live. Some foraminifera live on the sea bottom, whilst others live up in the water column. It is the latter, planktonic forms, which give a good indication of the surface properties of the oceans.

Planktonic foraminifera have a fossil record extending back to the Cretaceous. In older rocks, many of the species belong to extinct lineages, and it is more difficult to determine their palaeoecology, as there are no modern analogues. This is less of a problem with the Pliocene, as many of the fossil species still exist today, meaning that they are reliable recorders for past ocean conditions. Modern species, such as *Neogloboquadrina pachyderma* (Fig. 4), *Globigerinoides sacculifer* and *Globigerina bulloides* (Fig. 5), are all found in Pliocene age marine sediments. These can be used to indicate cool high-latitude surface waters, warm nutrient-poor equatorial surface waters and cool, nutrient-rich, deep ocean waters welling up to the surface. It is the distribution of these warm and cool surface waters, and up-welling cool waters, that provide the tell-tale signs of ocean circulation.

During the 1990s a group of scientists from the United States Geological Survey reconstructed the distribution patterns of planktonic foraminifera in the
Pliocene oceans, using fossil material preserved in sea bottom sediments. Their data were sourced worldwide, but the majority came from the Atlantic Ocean, covering a range of latitudes from the tropics to the Arctic. The fossil assemblages of planktonic foraminifera preserved in the Pliocene sediments suggest that surface waters in mid to high latitudes, for example in the Atlantic Ocean to the west of Britain, were generally warmer than they are today. In tropical regions, however, sea temperatures appear to have been very similar to present. These global patterns of warmer ocean surface temperatures for the mid-Pliocene are also supported by evidence from diatoms – marine algae with a siliceous skeleton, and from ostracods – small crustaceans that live on the sea bottom.

The temperature difference from the present oceans suggests that Earth’s global climate was warmer during the mid-Pliocene. The observation that temperatures were only higher at mid to higher latitudes, and not in the tropics, suggests that an enhanced transfer of heat from the tropics to higher latitudes was occurring by ocean currents such as the Gulf Stream (Fig. 6). If it was only due to increased concentrations of greenhouse gases, then ocean temperatures should be warmer everywhere.

**Transporting heat in the oceans: the Gulf Stream**

The Gulf Stream in the North Atlantic is a good example of how oceans redistribute heat from the tropics to higher latitudes (Fig. 6). The Gulf Stream is a warm surface ocean current originating in the Gulf of Mexico, where, at only 80 kilometres wide it travels at 5 kilometres per hour (km/h), carrying water at about 25 °C. Further North, the current widens to several hundred kilometres, and slows to less than 2 km/h, dividing into several sub-currents, one of which is called the North Atlantic Drift. As they travel northwards, the warm waters of the Gulf Stream lose moisture through evaporation, making the sea particularly saline. In the North Atlantic, this saline water becomes cold enough to sink, mixing with cold water from the Arctic Ocean. This forms a deep ocean current called the North Atlantic Deep Water which acts as a pulling mechanism on the Gulf Stream, maintaining the direction and intensity of the current from the tropics. This circulation is driven by density contrasts in different water masses based on salinity and temperature (Fig. 7), and is called thermohaline circulation. In the North Atlantic, it is the Gulf Stream and the North Atlantic Drift, that bring warm saline waters from the tropics to the Northwest coast of Europe, and this warm water helps to keep the climate mild. The northern North Atlantic and Northwest Europe have annual temperatures that are about 9 °C above the average for their latitude. If you put this in context, without the Gulf Stream effect, London would have a climate similar to Norway.
Checks and balances: chemical evidence from algae

The evidence from the planktonic fossil assemblages suggests that temperatures were warmer at mid to high latitudes during the mid-Pliocene, but were about the same in the tropics. But, as palaeoclimatologists often get different results from different sources, it is a good idea to try and verify this by looking at evidence independent of the fossil distribution patterns. For example, fossil assemblages can be disrupted on the sea bed by bioturbation, or the composition of the assemblages can be changed by selective dissolution. In both cases this could have an effect on the temperature signal of the fossils. One additional line of palaeotemperature evidence is from organic molecules called alkenones. These are made by marine algae that are found in the surface layers of the world’s oceans, from the tropics to the Arctic (Fig. 8). Like planktonic foraminifera, they record the properties of the sea surface.

Alkenones are preserved in sediments of mid-Pliocene age. There are some sites in the tropical Atlantic and Pacific that have alkenones of this age. Scientists at the University of California have reconstructed ancient sea temperatures from these alkenones. The sea temperatures suggested by the alkenones indicate warmer conditions in the equatorial regions (on average by about 5 °C warmer than present), as well as at higher latitudes, three million years ago. This is a very different picture from that painted by the planktonic foraminifera, which only suggest warming at higher latitudes. If the alkenones are right, then the transfer of heat from the tropics to higher latitudes via enhanced ocean circulation cannot wholly explain the increased temperatures in the tropics at that time.

Other evidence for Pliocene warmth: clues from fossil leaves

Stomata are small pores on a leaf surface that allow carbon dioxide to enter the leaf and oxygen to escape, thereby facilitating photosynthesis. In addition, water is lost through the stomata by transpiration. Stomatal densities change in response to changing atmospheric levels of carbon dioxide. Therefore, the number of stomata on the leaves of fossil plants can be used to estimate the levels of carbon dioxide in the ancient atmosphere. However, stomata may also vary in response to the local amount of annual rainfall, so fossil leaf material needs to be studied from geographically widespread sites in order to properly assess the level of carbon dioxide in the atmosphere during the past. When the stomata of fossil leaves of mid-Pliocene age are counted they suggest that carbon dioxide levels in the atmosphere ranged from 360 to 400 parts per million (p.p.m.v.). This represents an increase of 80 to 120 p.p.m.v. over mid-nineteenth century levels (i.e. before the start of the Industrial Revolution). The concentration of CO₂ in the Pliocene atmosphere appears to have been almost identical to atmospheric concentrations today that are a result of the emission of greenhouse gases into the atmosphere.
Making models of the Pliocene world

The pattern of sea surface temperatures produced by the alkenones is not like the pattern produced by the planktonic foraminifera. It is not characteristic of a sea temperature pattern produced by enhanced ocean heat transport or thermohaline circulation, which would redistribute heat away from the tropics to mid to higher latitudes. Instead, the pattern is similar to that which might be expected as a result of higher concentrations of atmospheric carbon dioxide, which would act to warm the oceans globally, and not just at mid to high latitudes. The possibility of higher levels of atmospheric carbon dioxide is supported by evidence from fossil leaves. This is important to the current debate over global climate change, and how far this is influenced by the emission of greenhouse gases. The best way to analyze all of the data from the fossils and alkenones is to build climate models that can simulate past climate change. In an effort to understand why our world was warmer at this time, scientists from the British Antarctic Survey, in collaboration with the University of Bristol, took the same model that the UK Meteorological Office uses to produce its daily weather forecasts and used it to generate estimates of what our planet’s climate was like three million years ago.

The model runs on very fast supercomputers that have the processing power of hundreds of desktop PCs. These powerful computers are needed to perform the trillions of calculations required to simulate what the Pliocene climate was like. The model divides the Earth up into a series of grid boxes. In the atmosphere these grid boxes are approximately 200 km wide by 400 km long. The size of individual grid boxes in the oceans is even smaller. Within each of these grid boxes variables important for the prediction of climate are calculated, based upon the laws of thermodynamics and Newton’s laws of motion. Then, at progressive time steps of the model, the reaction between the individual grid boxes is calculated. Very quickly millions of calculations are occurring at every time step of the model. However, before the computer simulation can be started, the model needs to be set up for the Pliocene world. This is where all the knowledge about what the world was like during the Pliocene from rocks and fossils becomes invaluable. The model set-up involves reconfiguring the positions of the continents to compensate for continental drift, reconfiguring the height of the land, prescribing carbon dioxide levels and initializing the oceans in a Pliocene state.

The results from the model indicate that three million years ago global annual average temperatures were up to 3 °C warmer than today. This had major effects on regional climates. For example, in Western Europe the UK climate was warmer during winter and summer (Fig. 9), but there was also more rainfall (Fig. 10). Warming occurs almost everywhere over the planet three million years ago, but is most intense at high latitudes. Why is this so? The answer can be found by examining the link between ice and climate. The ice-sheets of Greenland and Antarctica act as gigantic mirrors reflecting back part of the energy received by the Earth from the sun. Antarctica alone acts as a mirror that is over one-and-a-half times the size of the USA. But, during the Pliocene, the Greenland ice-sheet did not exist and the Antarctic ice-sheet may have been reduced in size by one-third. So, the reflecting mirrors of the Earth were smaller than they are today, which allowed more of the sun’s energy to be retained, and hence global temperatures were warmer.

What does the model say about the role of carbon dioxide? Although smaller ice-sheets were important, increased levels of carbon dioxide in the atmosphere made a significant contribution towards the warmth of that time, particularly at the tropics and low latitudes.

So what does the model say about the role of ocean currents and what sea surface temperatures were like? The model results indicate that the oceans did not transfer significantly more heat away from the tropics to the high latitudes during the Pliocene. Furthermore, the model predictions of sea surface...
temperatures more closely match those produced using alkenone estimates than those derived from the planktonic foraminifera.

What might the mid-Pliocene tell us about the future?

Studying warm climates of the past and identifying model/data inconsistencies provides a tough test for the primary tool currently used to study future climate change, namely global climate models. Our results suggest that mid-Pliocene warming was caused by more carbon dioxide in the atmosphere combined with climate feedbacks associated with smaller ice-sheets. Since the pattern of sea temperature change reconstructed from alkenones, and predicted by our climate model, is not consistent with that produced through changes in ocean circulation/ocean heat transport, we also conclude that there was no major change in thermohaline circulation at that time. This gives us more confidence in the stability of modern ocean circulation in the face of global warming, and suggests that the scenario of climatic catastrophe pictured in the film *The Day After Tomorrow* is, fortunately for us, an unlikely one.

The other lesson to learn from the mid-Pliocene is that increased carbon dioxide levels in the atmosphere can have a dramatic effect on global temperatures and ice-volumes. Indeed, the analogue of the Pliocene suggests that if carbon dioxide concentrations remain at their current levels, or increase further, then we can expect to see significant reductions in global ice volume and higher sea levels. Considering the proportion of the world’s population who live adjacent to the coast this is a serious threat. Some island nations might disappear.

The concept of studying the past as a guide to our future is relatively new. Therefore, we should continue to question whether it is possible that an as-yet unknown climate feedback or forcing has the potential to dramatically change our appreciation of the mid-Pliocene world, what made it warm and what significance it has for our future.

Suggestions for further reading


Web links

Climate change, the global environment and fossils: British Antarctic Survey: [http://www.antarctica.ac.uk](http://www.antarctica.ac.uk)

Bristol University ‘Bridge Group’: [http://www.ggy.bris.ac.uk/research/bridge](http://www.ggy.bris.ac.uk/research/bridge)

*Palaeontologia Electronica*: [http://palaeo-electronica.org](http://palaeo-electronica.org)