Netherlands Journal of Geosciences — Geologie en Mijnbouw | **87 – 3** | **231 - 239** | **2008**

Can you step twice into the same river? Climate change through time

Abridged text of the inaugural address as professor in Climate Modelling and Analysis at the Faculty of Geosciences of Utrecht University held on 29 February 2008

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Manuscript received: June 2008; accepted: September 2008

Introduction

Is it possible to step twice into the same river? That is the question I would like to put to you. At first glance, there is no reason to assume that a river will not look exactly the same tomorrow as it does today. And we tend to forget whether it was different yesterday or the day before. 'Will the weather ever get any better?' we tend to say to each other after a couple of rainy days. Will we ever see a cold winter again with an Elfstedentocht[1]? Fortunately, some people keep records of the weather, or keep track of rivers flooding or falling dry. That makes it possible to know for sure what stays the same and what changes.

Nowadays, the climate is a hot topic. Does it actually change or doesn't it? To answer this question we usually look at the globally averaged temperature. People in, for example, the Netherlands do not really notice when the world gets slightly warmer or colder on average, but the global temperature is a good yardstick for the forcings that affect climate and that is why we look at it. The global temperature is calculated on the basis of a great many local temperature records, which, in some places, go back a very long time. The Royal Netherlands Meteorological Institute (KNMI), for instance, has temperature records that begin in 1706. That is an exception, most records started much later. Only since 1880, records cover a sufficient number of places around the world to yield a reliable picture of the global temperature (Fig. 1). From this we know that the climate is not constant, but fluctuates, and that the Earth is actually getting warmer. Many institutes that are involved in this type of climate accounting, issue monthly, seasonal or annual press releases. The annual-mean temperature usually makes the papers or the TV news. The past year has been warmer than usual again, just like most other years since 1990. Newsrooms rightly consider this newsworthy.

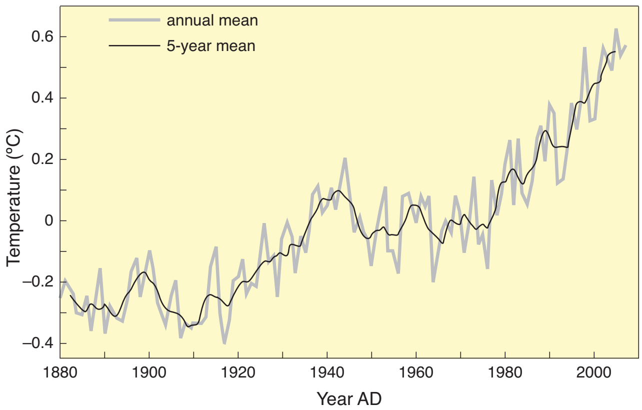

Fig. 1. The globally averaged temperature (yearly and five-yearly averages), calculated on the basis of local measurements at meteorological stations, ship records and satellite data. Shown are anomalies with respect to the mean over the 1951-1980 period. After: Hansen et al. (2006) with most recent temperature data obtained directly from NASA Goddard Institute for Space Studies (Jan. 2008).

It is very likely that the recent string of warm years can be attributed to an increased atmospheric concentration of carbon dioxide (CO_2) and the other greenhouse gases: methane and nitrous oxide. These gases are naturally present in the atmosphere and in combination with water vapour they cause the atmosphere to emit long-wave radiation. As a result, the surface of the Earth is warmer than it would be without this so-called greenhouse effect. The increase in CO_2 is due to the large-scale burning of fossil fuels by Mankind, which started during the Industrial Revolution. The increased levels of methane and nitrous oxide are also due to human activity. The increase of these greenhouse gas concentrations causes what is commonly called the anthropogenic greenhouse effect: an intensified warming of the surface of the Earth.

1 The most famous ice skating event in the Netherlands, the 'Elfstedentocht' ['Eleven Cities Tour'], is a 200 km skating tour on natural ice in the Dutch province of Friesland. As it requires a period of sustained, severe frost for the canals to solidly freeze over, the Elfstedentocht is - on average – only held once a decade.

Climate and Mankind

Contrary to what you might think, the scientists' fascination for the anthropogenic greenhouse effect is not a new-fangled idea. Swedish scientist Arrhenius already studied it in the early 1900s. He was the first to calculate the effect on the global temperature of a doubling or halving of the CO_2 concentration and arrived at a warming or cooling in the order of 5° C. He primarily considered natural fluctuations in CO_2, which might explain the greenhouse climates and ice ages of the past, but he also speculated on the possibility of anthropogenic CO_2 emissions becoming sufficiently large to change the climate (Arrhenius, 1907). Some thirty years later, the Briton Callendar published the first crude estimates of the actual increase in atmospheric CO_2 levels and showed that this increase matches the estimates of CO_2 production by burning fossil fuels (Callendar, 1938). Callendar also made some predictions for the future: he expected a warming of 0.6° C in the 22nd century if the CO_2 level would increase by 30% in comparison to pre-industrial values. Very precise and continuous measurements of CO_2 levels in the free atmosphere are available since 1958, and these show a steady increase. This result, and the advent of powerful computers, has greatly boosted research into anthropogenic climate change.

Figure 2 shows one of the first calculations (Hansen et al., 1988) of the evolution of the global temperature due to the measured increase in CO_2 and other greenhouse gases. The type of model used was very sophisticated for the early Eighties. It took many different processes into account: the concentration of greenhouse gases but also cloud formation, precipitation and snowfall, transport of heat by air currents and interaction with the land surface. The oceans are still modelled very simply: as a huge mass of standing water. The authors designed three different scenarios for the future period from 1984 to 2019. Scenario A assumed an exponential growth in forcings, for instance as a result of greatly increased CO_2 emissions. Scenario B assumed linear growth and scenario C kept the forcings constant from the year 2000 onwards. The authors also included volcanic eruptions in the forcings. The figure shows the global average calculated by the model for the period until 1983, together with measured temperatures, and predictions on the basis of each of the three scenarios. And what do we see? In the first place: considerable fluctuations in temperature from one year to another. Some of these fluctuations are due to external factors, such as the cooling that followed the eruption of the Agung volcano in 1963. In that case, the model faithfully followed the actual measurements. Some climate fluctuations are caused by internal processes, e.g. by El Niños, which happen every couple of years as a result of the interaction between the atmosphere and the tropical Pacific and which cause global warming such as took place in 1983. The model does not include El Niños, because it lacks an active ocean. The figure also shows a rising temperature trend: it gradually increases and this is particularly obvious from 1990 onwards.

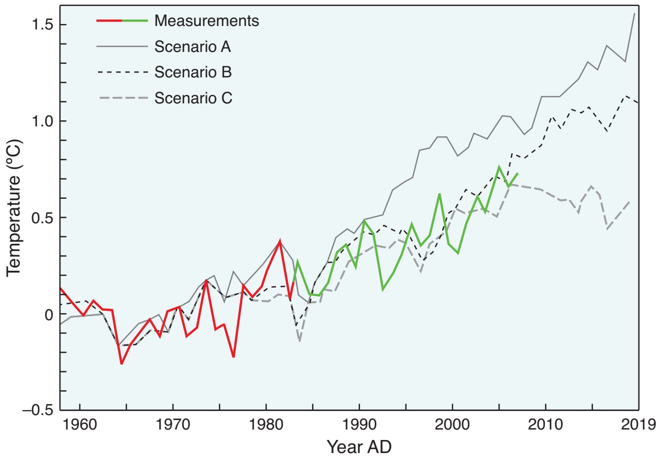

Fig. 2. The globally average temperature calculated by the climate model according to the observed forcing for the 1958 - 1983 period, and according to the three scenarios, A, B and C, for the 1984 - 2019 period. The temperature measured at the time the calculations were made is indicated by a red line. After: Hansen et al. (1988). The temperature measured for the 1984 - 2007 period has been added later (green line); see also Hansen et al. (2006).

The interesting thing about these model predictions is that it is now some twenty-five years later and we can compare the 'future' predicted in the Eighties with the measurements taken over the past twenty-five years. The important thing is the trend. After all, we cannot assume that the model predictions will be accurate for each individual year, because the internal processes that cause climate fluctuations cannot be predicted very long in advance and the timing of a volcanic eruption is not known at all beforehand. At the time, scenario B was considered the most probable and, in retrospect, this has proven to be right. As you can see, there is a close match between the trend in the measurements and in the calculations following scenario B (Hansen et al., 2006).

So it seems a forgone conclusion that Mankind had a hand in the recent warming. However, climate researchers prefer a more careful conclusion. The reason being that the current trend does not yet exceed the bandwidth of previous fluctuations much. If the model slightly overestimated the trend and at the same time underestimated long-term temperature variability, the overall picture may look quite different. That is why the IPCC, the United Nations' climate panel, only speaks of it being 'very likely' that the recent string of warm years can be attributed to the anthropogenic greenhouse effect. In another ten or twenty year' time, we will know for certain, but that is still some time off.

In the meantime, we can follow two different courses. On the one hand, it is important to establish whether the past few decades were indeed too warm, climatologically speaking. On the other hand, we should test how well our models can predict a climate change, such as we are expecting in the coming century. I will now briefly address the first point.

The recent decades in the light of the past millennium

How unusual are the recent warm years? To answer this question it is useful to extend the instrumental data to a longer period on the basis of historical sources or natural archives such as tree rings, ice cores or oceanic sediments. These indirect climate data are commonly referred to as proxy data. On the basis of this kind of information, various research groups have reconstructed temperature variations for the past millennium. Figure 3 shows some of their results. Each group calculated the average temperature for the northern hemisphere on the basis of another set of local proxy data; this is why the temperature curves differ from each other (Juckes et al., 2007). If we combine these curves we get a reasonable impression of the temperature trend. The differences also give us a good idea of the uncertainty in these types of reconstructions. The figure shows anomalies in the annual-mean temperature with respect to the average over the first hundred years of the instrumental data. Anomalies are small, some tenths of degrees, and we see that the temperature was usually around or just below the instrumental average.

Most reconstructions show a distinct cold period from the 15th to the 19th century, commonly called the Little Ice Age. Both the 11th and 20th centuries were relatively warm. Early climate historians, such as Briton Hubert Lamb, called the former warm period the Medieval Warm Period (Lamb, 1982). Those were the days when the Vikings colonised Greenland and wine was grown in England. In the early Eighties, Lamb based his conclusions mainly on European historic records. Much more information has become available since then. We now know, for instance, that different regions in the northern hemisphere experienced a climate optimum at different times (Crowley and Lowery, 2000). For this reason, the 11th century does not stand out in the record of the northern hemisphere average and the term 'Medieval Warm Period' became obsolete. This period, however, remains invariably popular among climate sceptics, who like to refer to the early climate historians and view the Medieval Warm Period as evidence that the current climate change cannot be attributed to Mankind. The early 20th century is indeed comparable to the 11th century but the late 20th century is a different cup of tea altogether. Measured temperatures in the past few years are far higher than what was normal during the past millennium. This still holds true if we take the uncertainties of the temperature reconstructions into account.

In addition to temperature reconstructions, there are reconstructions of the main forcing factors: volcanic eruptions, fluctuations in the Sun's intensity, as well as anthropogenic factors such as air pollution, land use and greenhouse gas levels. Modelling experiments have shown that volcanic eruptions and the Sun, together with internal processes of the climate system, can explain the pre-industrial temperature fluctuations (Weber, 2005). The same factors still play a role later, but in the second half of the 20th century human influences became increasingly important (Hegerl et al., 2003).

You probably realise by now that the warm years we have experienced since 1990 are truly unusual. Not only in comparison with the instrumental data of the past 150 years, but also in comparison with reconstructions for the past millennium. It is not certain that Mankind is responsible, but it is very likely indeed. What does the future hold in store? That greatly depends on the scenario we assume for the concentration in greenhouse-gases: how fast will that concentration rise, and to what level? In 1938, Callendar expected a 30% rise in CO_2 concentration by the 22nd century. That value was exceeded

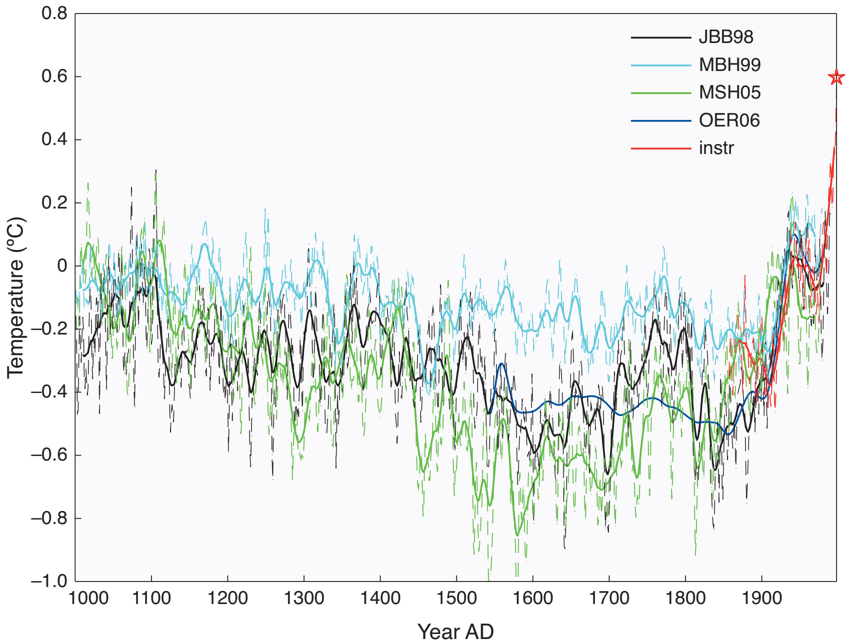

Fig. 3. The average temperature of the northern hemisphere for the 1000 - 1998 period, reconstructed on the basis of various proxy data: i.e. tree rings, documentary evidence and ice cores, all with a resolution of about a year (Jones et al., 1998 – black and Mann et al., 1999 – blue); marine cores, lake sediments and other low-resolution series, combined with tree-ring series (Moberg et al, 2005 – green); and glacier lengths (Oerlemans, 2005 – purple). The instrumental data are also included (red). The figure shows anomalies with respect to the 1866 - 1970 period as 3-year running averages (thin dotted line) and 21-year running averages (fat line). The red star marks the average for 2003 - 2005.

as early as 1996. The 0.6° C warming he predicted matches the actual rise in temperature during the past century fairly well. In 1907, Arrhenius assumed that the CO_2 concentration would double in 3000 years. We nowadays believe that this doubling will be reached in only a hundred years. So, predicting the effects of human behaviour turns out to be rather difficult, in particular if we wish to look further ahead than the next few decades. It is pretty well known by now what happens to the CO_2 that we are currently emitting into the atmosphere. Most of it will be absorbed into the oceans within a couple of hundred years, but a smaller proportion will remain in the atmosphere for a very long time. That little bit of extra CO_2 might be enough to ensure that present-day humanity is still affecting the climate in tens of thousands of years time (Archer, 2005).

Evaluating the climate models

Now I get to the second point: how good are the models that we use to predict the future climate? How good are the predictions for the climate in Europe, in the Polar Regions or the tropics? Will climate zones shift? What does a climate change mean for precipitation patterns, river discharges or soil moisture? Will storms get heavier, or more frequent? In short, how well do the models simulate all the aspects of the climate in case of a climate change?

Let me first explain what a climate model really is. It is a computer programme that calculates atmospheric and ocean currents on the basis of general principles. These are the laws of conservation of mass and momentum, while the temperature distribution follows from a heat equation. Currents and temperatures are linked, because currents transport heat and temperature differences generate pressure differences (the highs and lows on the daily weather maps) and this in turn creates currents. It takes a lot of calculating but is all fairly straightforward. What makes the whole thing so complicated are the countless number of small-scale processes involved, such as friction, evaporation and precipitation, chemical processes in the atmosphere and oceans, interactions with the land surface and the vegetation, the formation of land ice and sea ice, etc. Most descriptions for these processes are mixtures of empirical relationships and fundamental physical, chemical and biological knowledge. These descriptions have been extensively calibrated on the basis of actual measurements, but we cannot be completely sure that they will be as applicable in a changing climate. And especially these small-scale processes are important for the large-scale circulation and temperature distribution.

Climate models can be validated by simulating past climates and comparing these model simulations with reconstructed climate changes. Climate history goes back to hundreds of millions of years ago. The Earth has gone through many different climates, from extreme cold to extreme hot, slow and abrupt transitions as well as cyclic fluctuations. There were extreme greenhouse climates very long ago. But the Earth looked very different then from our present-day Earth: the continents were in other locations and the present-day mountain ranges did not yet exist. That makes it difficult to compare these past climates with the present-day or future climate. That is why we usually only study the period covering the past two to three million years, during which the Earth only changed marginally. This period is marked by alternating cold, glacial periods with large continental ice caps and warmer, interglacial periods. During glaciations the global temperature was some 5° C lower than it is now and every now and then there were rapid temperature shifts on top of that. During interglacial periods the climate is stable. Which climate of the past is most suited to validate our climate models? We are looking for a climate that closely resembles our future climate.

At the moment we are experiencing a warm period, which started some 10,000 years ago: the Holocene. In the early Holocene and during some earlier interglacial periods, the Earth was slightly warmer than it is now. That is due to small fluctuations in the Earth's orbit around the Sun and in the tilt of the Earth's axis. These affect the distribution of solar radiation around the Earth and also through the seasons. As a result the northern hemisphere had relatively warm summers. So it was a bit warmer in these interglacials than it is now, but not as warm as the temperatures we are expecting in the near future. And, moreover, the warmer weather had different causes. These climates did not heat up rapidly like we are expecting for the coming century. So, these periods are only partly relevant as analogues for our future climate.

What about the cold periods? During the glaciations, the greenhouse-gas levels were much lower. That is due to natural feedback loops in the climate. A low greenhouse-gas level makes the temperature fall even more and so the cooling can in part be attributed to a reduced greenhouse effect. We could view the glacial climate therefore as a sort of mirror image of our future climate. Glacial climates also exhibit rapid changes. However, it was cold -not warm- and we cannot simply assume that the climate responds in a symmetrical manner.

Trying to find climate 'analogues' was a popular pastime for quite some time. Scientists hoped to find out more about regional climate responses in a changing climate by studying, for example, the early Holocene. We have now abandoned this idea. Greek philosopher Heraclitus already said: 'You cannot step twice into the same river, for other waters and yet others go ever flowing on. They go forward and back again'. That seems obvious to me. The climate changes continuously and identical climates never return. Unfortunately, climate researchers often claim that is why they do not need to look to the past at all, and that is not correct. Even though there were no exact analogues in the past, past climates can serve as practice material. Do we understand why the climate changes and which mechanisms are involved?

Two palaeoclimates are widely used to validate our models. The one is the cold period of 21,000 years ago, the Last Glacial Maximum. The other climate is a warm period of 6000 years ago, the middle Holocene. Both periods have been selected by the Palaeoclimate Modelling Intercomparison Project – PMIP (Joussaume et al., 1999), an informal joint project of climate researchers who are studying past climates using models as well as proxy data. The scientists involved in this international project agreed on forcing factors for these two periods, enabling all modelling groups to carry out identical experiments and making a meaningful model intercomparison possible. The climates during these two periods have been described in detail by combining many different proxy data.

The Last Glacial Maximum

As the name implies, the Last Glacial Maximum was the coldest period of the last glacial. Glacial inception is due to small changes in insolation, caused by changes in the Earth's orbit. This first triggers cooling followed by the ice caps growing and a decrease in greenhouse gases. Unfortunately, existing climate models are not yet capable of simulating all these coupled processes at the same time. We therefore slightly simplify the test simulation for the Last Glacial Maximum: we impose glacial insolation, greenhouse-gas levels and ice caps and then calculate how the atmosphere and the oceans respond to these forcings. Figure 4, from the 2007 IPCC Report (Jansen et al., 2007), shows the forcing factors summarised in the top graph. The remarkable thing is that during the glacial maximum itself insolation only plays a minor role, while the lower greenhouse-gas levels and the ice caps are about equally important. Other factors involved are atmospheric dust and vegetation. In the centre picture you can see the ice caps, reconstructed on the basis of geological data, and calculated changes in sea surface temperatures. The temperature drops all around the world, but with major regional differences. The bottom picture is the most important. This simulation was carried out by six different climate models, including KNMI's model. The regional temperature changes calculated by the six models have been plotted against the global change for three different regions. The grey bars indicate the actual cooling, estimated on the basis of proxy data. For the Antarctic region the calculated temperature changes were either too high or too low, but for the North-Atlantic region and the tropical Indian Ocean the calculations were spot on.

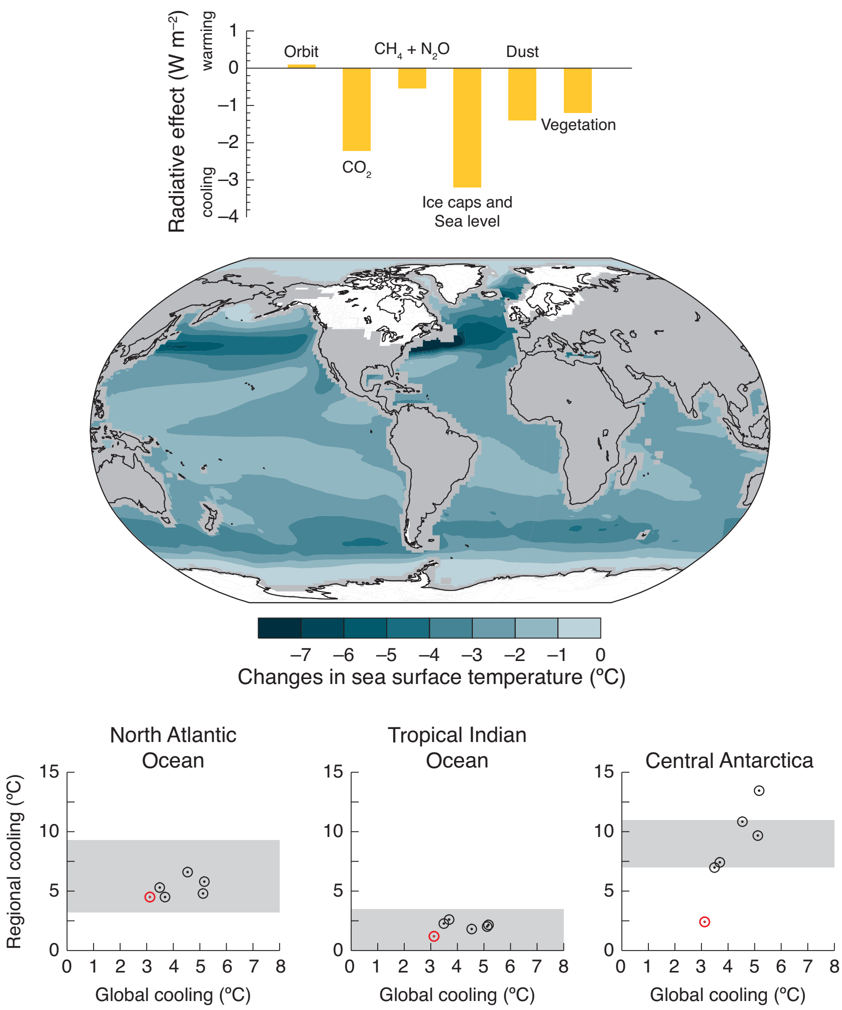

Fig. 4. The Last Glacial Maximum; at the top: the forcing factors, converted to show their effect on the radiation balance. These forcing factors are: insolation (due to changes in the Earth's orbit), greenhouse gases (CO_2, CH_4 and N_2O), albedo changes resulting from the ice caps and the larger land surface related to a lowered sea level, atmospheric dust and changes in vegetation. In the centre: reconstructed ice caps and calculated changes in sea surface temperatures. At the bottom: calculated regional temperature changes plotted against changes in global temperature for three regions. The grey bars represent the temperature changes for each region estimated from proxy data. Each bullet represents a climate model, the red bullet is the KNMI model. After: Jansen et al. (2007).

If we consider the spatial pattern of temperature changes for, for instance, the Atlantic Ocean in more detail we observe major differences between models and between the models and the proxy data (Kageyama et al., 2006). This spatial pattern is determined by a number of different processes: cold air outbreaks from the American continent, the sea-ice cover, the heat exchange between the seawater and the air above it and the circulation in the Atlantic Ocean. Models are not yet capable of striking a proper balance between all these processes. Gulfstream and deep ocean circulation also differ greatly from one model to another. Only a few models reproduce the glacial circulation, which must have been weaker than the current one and also less stable (Weber and Drijfhout, 2007). On the contrary, many models show stronger ocean currents. In this case as well, the signal is based on a subtle balance between various factors and different models reach different conclusions (Weber et al., 2007). So the causes of the weakened circulation are by no means clear.

We may conclude that models generally represent the large-scale temperature response pretty well, but that they have a problem with simulating signals involving many different interconnected processes, such as changes in regional climate or in ocean currents.

The middle Holocene

We will now look at a more recent period, the middle Holocene. At that time, summers were warm and the northern hemisphere had an intense monsoon circulation. The underlying mechanism is simple. The monsoon circulation is driven by the temperature contrast between land and sea. In summer, the land is always warmer than the sea because the seasonal cycle of the seawater temperature lags a few months behind that of the land temperature. So if the summer is relatively hot, the temperature contrast between land and sea becomes more pronounced and this reinforces the monsoon circulation and the accompanying precipitation. Figure 5, which is taken from the previous IPCC Report (McAvaney et al., 2001), shows the distribution of different types of vegetation for North Africa. These days, this region is mainly covered in desert. Only in the tropics some vegetation is present in the form of steppes, savannahs and forests. During the middle Holocene, the vegetation zones shifted and expanded northward. The fact that the present-day desert was once a steppe is remarkable. We sometimes refer to this as the 'green Sahara', which extended from a line running from the present-day Sahel in the west to Sudan in the east, right up to the Mediterranean coast.

The coloured lines in the middle picture of Fig. 5 indicate the difference in precipitation between the middle Holocene and the present day for a large number of atmosphere models. The models simulate more precipitation during the middle Holocene, especially in the tropics. The calculated increase in precipitation in this region agrees with the reconstructed increase in xerophytic (moisture-loving) vegetation. However, north of 20° N the models show hardly any increase in precipitation, whereas to grow a steppe vegetation in these

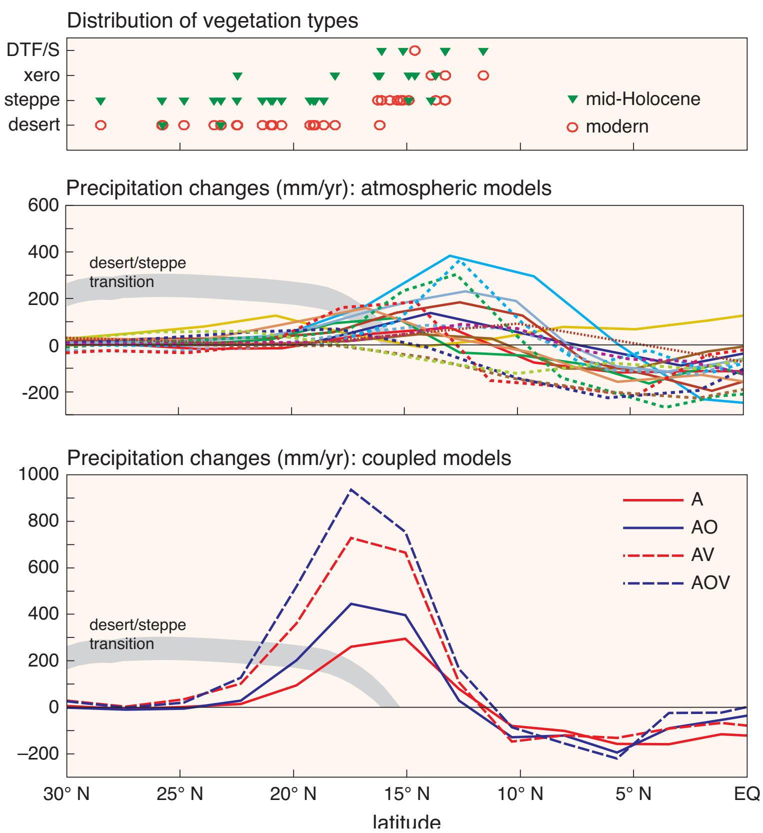

Fig. 5. The middle Holocene. At the top: the distribution of desert, steppe, xerophytes and dry-tropical forest with savannah (DTF/S) for North Africa (20° W - 30° E) for the mid-Holocene climate (green triangles) and the present-day climate (red circles). In the centre: calculated precipitation changes for the same region, the graph also shows how much precipitation is needed to establish a steppe landscape in a desert area. At the bottom: results for different model configurations: atmosphere only (A), atmosphere coupled to ocean (AO) or to vegetation (AV), or a complete atmosphere-ocean-vegetation model (AOV). After: McAvaney et al. (2001).

desert areas it is estimated that some 200 to 300 mm extra precipitation is needed each year. So the northward expansion of the vegetation zones is clearly underestimated by the models. The bottom picture shows what happens if we run the simulations with an atmosphere model coupled to a vegetation model or an ocean model, or to both. This clearly strengthens the signal. This is due to recycling of moisture by the vegetation and a better description of the temperature contrast between land and sea when we include an active ocean. However, even these coupled models cannot explain the green Sahara.

We also find a different precipitation pattern over Europe during the middle Holocene (Masson et al., 1999). The south-eastern part is wetter and the north-west is drier than at present. Some models reproduce this pattern, because higher water temperatures in the Mediterranean Sea lead to wetter winters. Other models show almost the opposite pattern. So we cannot be certain about the mechanism.

Also for the middle Holocene the dominant climate signal, a strong monsoon, is represented well. The models perform even better if they take vegetation and an active ocean into account. However, if we zoom in on spatial details, such as the northward expansion of the monsoon or the precipitation over Europe, the models do not perform so well and our knowledge is insufficient.

Future research

You will probably realise by now that many questions remain as yet unanswered in palaeoclimatic research. I hope, however, that I have made clear to you that climate predictions for the near future are not credible without putting models to the test of past climates. That does not mean that validation is simple, because there are no good analogues and proxy data are often multi-interpretable and suffer from large uncertainty bands. Within PMIP a lot of discussion was needed about the two case studies I have presented to you, the Last Glacial Maximum and the middle Holocene. It is no easy matter to integrate different disciplines. Yet these case studies have yielded a clear picture of the things we understand about climate and what gaps still need to be resolved. Cooperation does not only yield understanding and knowledge for the modellers. Also there are benefits for the interpretation of proxy data, when model results are at hand. These make it possible to underpin the links between forcing and climate response and to understand spatial patterns. Moreover, experience shows that interdisciplinary studies, which combine model results and proxy data, greatly boost the willingness to achieve a quantitative interpretation of proxy data and a synthesis of different types of proxies.

The gaps in our knowledge represent as many future research opportunities, especially if different types of expertise are combined. This applies to the entire spectrum from modelling studies to empirical studies into proxy data for the past millennium all the way to very ancient greenhouse climates. Some research themes are obvious, and I will briefly describe three of these themes.

Of course I will remain interested in the past millennium. I am especially thinking of climate variations in Europe and the Atlantic region, such as the Medieval Warm Period and the Little Ice Age (Van de Plassche et al., 2003; Palastanga et al., 2008). Our knowledge about these periods is far from complete. There still is much uncertainty about the underlying mechanisms. Is it the Sun, volcanoes, or the atmospheric circulation? The stability of the ocean circulation (De Vries and Weber, 2005) is also very relevant for the climate in Europe.

The second theme regards the Holocene precipitation pattern I mentioned before with a wetter northern Africa and southern Europe, and at the same time a drier north-western Europe. Comparable changes in precipitation can be identified in proxy series that cover millions of years from the circum-Mediterranean region. These proxy series contain cyclic patterns that can be linked to fluctuations in insolation. It is hypothesized that this link is established through alternating wet and dry phases of the Mediterranean climate, which are comparable with the transition from the mid-Holocene climate to the present-day one. We have already been able to underpin part of this hypothesis (Tuenter et al., 2004). The proxy series mentioned consist of terrestrial and marine deposits that are frequently related to river discharges. In follow-up studies, I therefore want to combine climate, river-system and Mediterranean circulation models with different proxy data, i.e. long time series for a number of locations and detailed spatial patterns for the middle Holocene. That should elucidate possible interconnections between changes in monsoon patterns and other processes such as winter depressions in the mid-latitudes.

The third theme is the greenhouse climate of 55 million years ago, the Paleocene-Eocene Thermal Maximum (PETM). This was a very warm period, probably caused by a catastrophic emission of methane from the deep ocean. Methane converts into CO_2 in the atmosphere, so at the time there was a real greenhouse climate, comparable with our future climate. That makes this period so very interesting, even thought direct comparisons are difficult to make, because the Earth looked rather different from the present-day one. Proxy data indicate that the Polar Regions in particular were very warm, whereas climate models systematically underestimate this polar warming (Sluijs, 2008).

The Royal Netherlands Meteorological Institute (KNMI) recently took the initiative to develop a new climate model, EC-Earth, to which various Dutch and European research groups are contributing. One of the first tests to validate this model was a PETM simulation. EC-Earth seems to be performing fairly well for the summer temperatures of 55 million years ago, but we are not as satisfied with the winter results. This model will eventually offer us the possibility to study processes which cannot be explicitly described by older climate models. One could think of changes in the atmospheric chemistry in an extremely hot climate with high greenhouse-gas levels and the impact of this on the radiation balance and the temperature. In this theme also, I hope to make progress by clustering expertise, i.e. knowledge of the land surface and the hydrology, climate modelling and the aforementioned climate reconstructions.

Finally

I am now getting towards the end of my leap-day lecture and I would like to end this inaugural address with another quotation from Heraclitus (Fig. 6). This time he says: 'Into the same rivers we step and do not step. We exist and we do not exist'. The attention is now shifted from the river to Mankind. Mankind does not stay the same either, but is changing continually, and for this reason alone, our future climate must be unique and without any analogues in the past.

I have spoken.

Fig. 6. Stone arch in Utah (US), created by wind erosion. Similar arches, symbolising changes that are (mostly) invisible, can result also from erosion by rainwater and frost, rivers or marine currents.

Word of thanks

I owe a lot to PMIP for the inspiration and encouragement to take this research direction. Many thanks are also due to the Royal Netherlands Meteorological Institute – KNMI, which liberally allows me time to hold this chair, and to my new colleagues at Physical Geography, for their excellent initiative to establish this chair. Many thanks also go to many of my colleagues, relatives and friends for their support and friendship – without them I would not have been able to climb this chair.

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