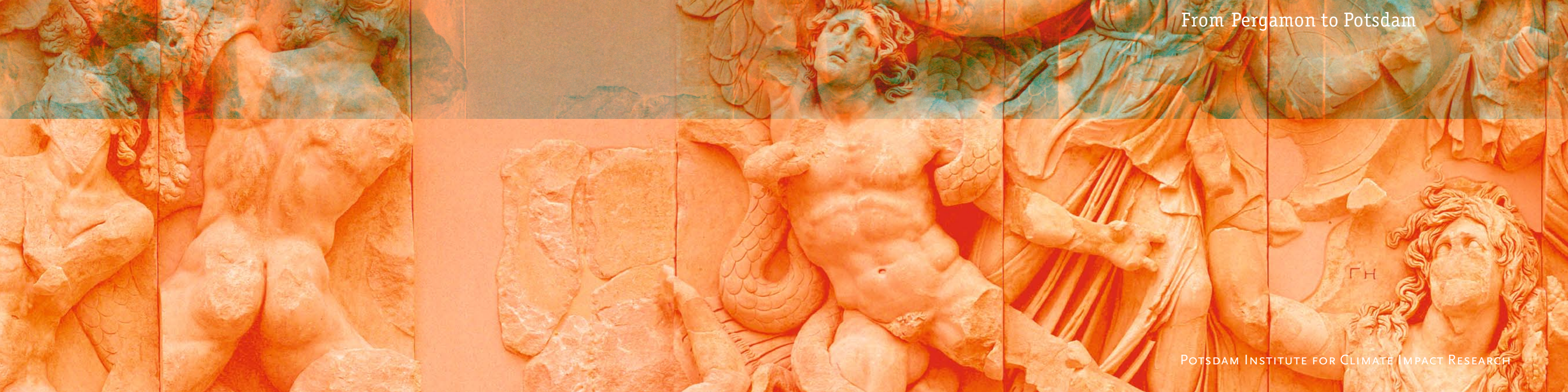




# HEAVEN AND EARTH

From Pergamon to Potsdam



*Imprint*

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### **The Pergamon Altar**

Sculpted around 170 BC in western Asia Minor and smashed to pieces several centuries later, the Pergamon Altar was rediscovered in the 19th century and reconstructed in Berlin with Turkey's permission. The Hellenic masterpiece depicts on a life-sized marble frieze more than 100 metres long the mythic tale of the victorious struggle of gods against chaos and the forces of nature – the Gigantomachy.

### **FROM PERGAMON TO POTSDAM**

The triumph of civilization over the volatile forces of nature, allegorized on the frieze of the Pergamon Altar as the battle between the Olympian gods and the sons of the Earth mother Gaia, today turns out to have been a Pyrrhic victory: The powerful tools of progress, forged during the Industrial Revolution 250 years ago, evoked forces which are beginning to slip out of control. In particular, the unbridled burning of fossil fuels and the so-induced global warming jeopardize the essential life-support systems of humanity.

In this way the giants – Gaia's offspring – are returning wilder and more irritable than ever, like monstrous hurricanes which can charge themselves with energy from heated ocean surfaces. Zeus, the champion of civilization, and the other Olympians, must act quickly to reach an agreement with Gaia, if the face of Earth is to be healed again.

In the ancient struggle, Athena – the goddess of science and wisdom – ignored Gaia as she pleaded for the lives of her sons. Today she knows that an ultimate victory is unattainable. A lasting, sustainable peace may be the best that can be achieved. Thus Athena cannot afford to balk; she must use her entire intelligence to establish a just world order – a place where the giants of nature can assume their proper place.

The Potsdam Institute for Climate Impact Research strives to aid the goddess of Science in this enormous task.



**Atlas** sided with his fellow giants in the war against the Olympians. In return Zeus condemned Atlas to stand at the western edge of the Earth and hold up the sky on his shoulders to separate the spheres. A popular misinterpretation is that Atlas had to hold up the Earth's globe.

## THE POTSDAM INSTITUTE FOR CLIMATE IMPACT RESEARCH (PIK)

From the outset, the aim of those working on Potsdam's Telegrafenberg hilltop was to reveal and explore the invisible, the unseen. In 1879, the world's first astrophysical observatory was established here in what is now the headquarters of the Potsdam Institute for Climate Impact Research (PIK). The beautiful building's three domes were studded with powerful telescopes capable of detecting even the most distant stars in the depths of the night sky. Yet even then, the scientists who worked here were not only concerned with the heavenly firmament; the sun and its relationship to the global climate were also a keen focus of their interest.

The research undertaken by the Potsdam Institute for Climate Impact Research continues this tradition of scientific exploration. But today, it is not the stars which are the subject of the researchers' scientific curiosity: the problem has moved much closer to home. Human-induced global warming poses one of the greatest challenges to humankind in the 21st century. The climatic change projected for industrial business-as-usual can disrupt our planet's natural and social habitats and even has the potential to change the overall dynamics and character of the Earth System. The challenges facing us are more complex, diverse and inter-

dependent than any of the problems which humankind has already *failed* to address.

The climate problem can only be solved through a general transition to global sustainability. In order to identify and address all its key aspects, the Potsdam Institute's scientific activities are organized into four main research domains:

*Earth System Analysis* is the prerequisite for a better understanding of the climate machinery. *Climate Impacts and Vulnerabilities* are crucial topics in assessing the susceptibility of nature and human society to the impacts of climate change. *Sustainable Solutions* need to demonstrate how global warming can be limited to a manageable scale and how social adaptation can be promoted, while *Transdisciplinary Concepts and Methods* unite specialized fields of study, knowledge and practice for the advancement of outcome-oriented approaches.

It is no exaggeration to say that the genuine cooperation between natural and social scientists at the Potsdam Institute is viewed as a model to be emulated worldwide. This is both an incentive and a burden. The fact is that if we are to master the challenges of climate change, dozens of institutes like PIK need to be established around the world.

As every modern child knows, it is not Atlas who bears the celestial or terrestrial spheres, but physics. There is no Greek demigod holding up the Earth; the Earth holds us. But humankind must start to shape nature in a way which sustains its essence. Why should an apparently slight global temperature increase of just 1–2°C have such significant implications for our planet, and why would it be fatal to allow the Earth's temperatures to climb even higher? These and other questions are answered in this brochure. Solving the problem of climate change may well require efforts worthy of Atlas himself – and will certainly require us to think on that scale. The Potsdam Institute, with just 150 staff, is striving to make a cognitive contribution to the solution of this planetary task.

CHRIS RAPLEY

*Director of the British Antarctic Survey*

## AN OUTSIDE VIEW

Unfortunately, the small-scale and increasingly urban perspective of our daily lives makes it hard for us to appreciate that we are, collectively, hurting the planet. We do so through what Samuel Butler observed is the “ineluctable desire of every organism to live beyond its means”. In this endeavour we have not yet reached the limits of our needs for material resources, but we are reaching the environmental limits of our waste products.

This is not the first time that humans have confronted such a problem. In the mid-nineteenth century, when London was the world’s largest metropolis, the discharge of sewage into the river Thames resulted in such an intolerable smell that Government action became necessary. Institutional impediments were overcome to achieve a technological solution – the construction of the Victorian unified sewage system.

Similarly, when it became apparent in the mid-1980s that the release of industrial chemicals, mainly in the northern hemisphere, had created the Antarctic ozone hole, with an associated skin cancer threat to animals and humans alike, a combination of technology and internationally agreed curbs on behaviour provided the solution.

It is a pity, then, that carbon dioxide is an odourless gas that has no link with ionizing radiation. Had it been otherwise, humans might have been more circumspect about releasing some 1000 billion tons of carbon dioxide into the atmosphere through the burning of fossil fuels. The consequence is increasingly evident: climatic change on a scale which threatens to transform the planet, damaging human society and the global economy – unless strong international measures are taken to reduce emissions quickly.

How can this be achieved? Without Olympian omniscience and authority to guide human actions, we must rely on a political process underpinned by evidence from science.

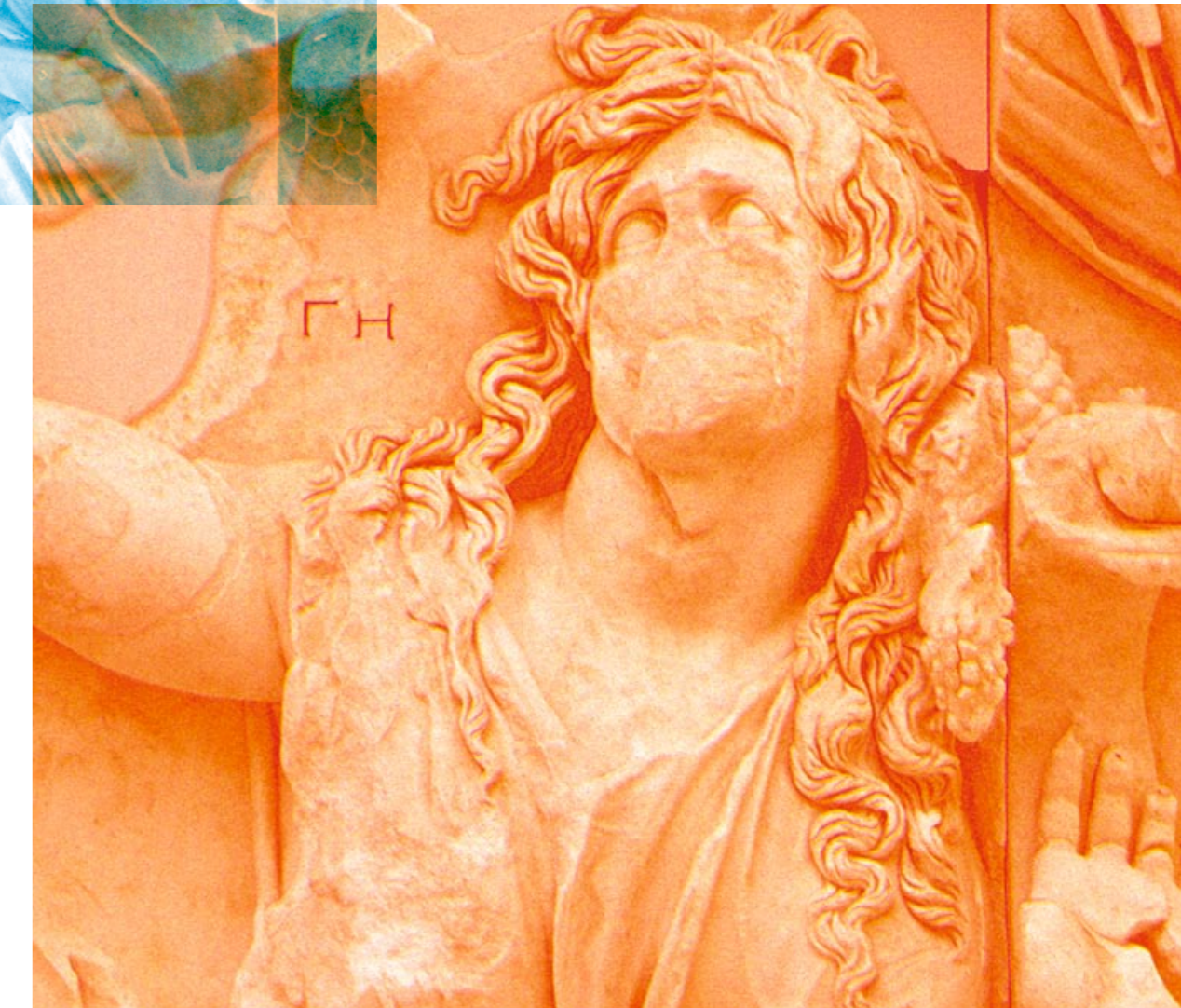
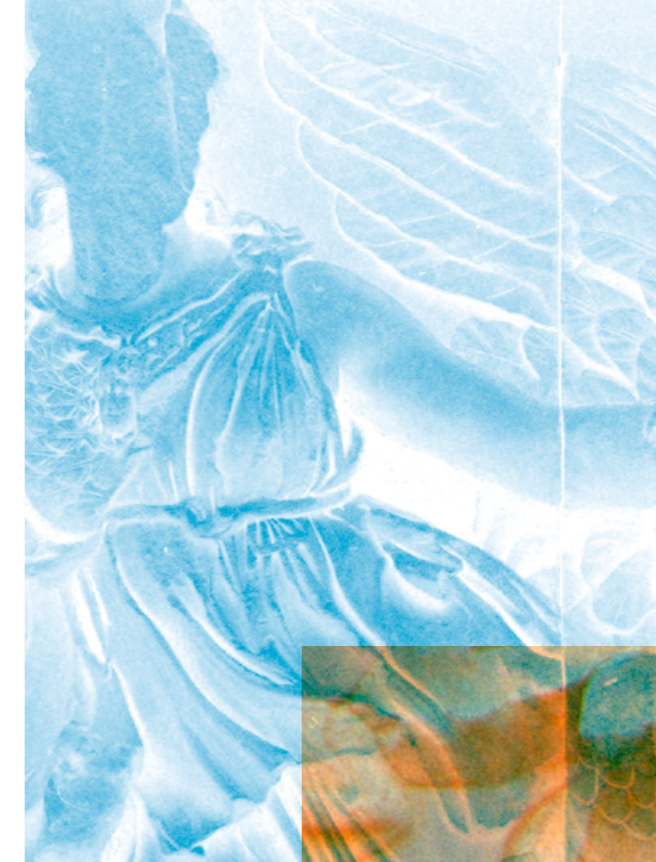
But the Earth is (as far as we are aware) the most complex object in the Universe, and understanding how it functions presents the science community with a daunting challenge. New approaches and practices are necessary, including the creation of interdisciplinary teams, an emphasis on synthesis, and a recognition that the practitioners of “Earth System Science” must interact at an unprecedented level with society at large.

Progress is possible through the efforts of geographically dispersed teams. Indeed, this is

essential given the distribution of key experts worldwide. However, a powerful adjunct is to assemble an appropriate mix of bright minds under a single roof, guided by a single purpose, and unfettered by distractions.

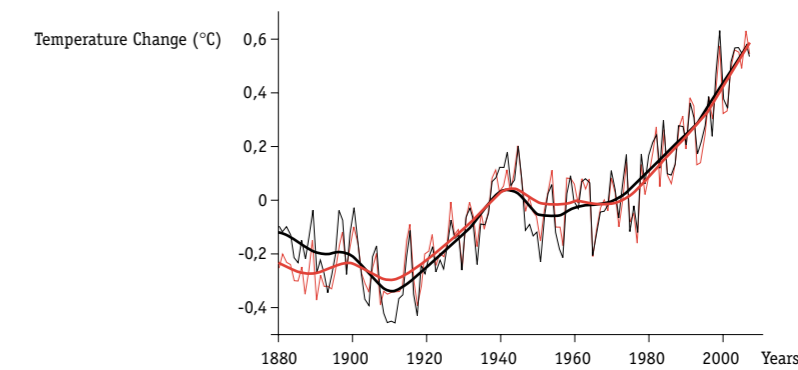
Such is the nature of the Potsdam Institute for Climate Impact Research. Only established 15 years ago, it is already pre-eminent in its field. The outcomes of its work are described in this document, which I commend to the reader, who, I assert, cannot fail to be impressed by PIK’s contributions to help humanity (in the words of its Director) “Avoid the Unmanageable and Manage the Unavoidable”.

**Gaia**, the peaceful Greek goddess, personified the Earth. She gave birth to the giants, also known as Titans. In the Titanomachy depicted at Pergamon, she implores Athena not to separate her from her son Alkyoneus, who is mortal without her.





**Prometheus**, one of the giants, was a friendly trickster and was also considered a god of fire. He stole it from Zeus, who had hidden the flames from man. The Greek poet Hesiod relates in his tale that Zeus had him chained in revenge. The giant shown here gazes up at Zeus, who has struck him down with a bolt of lightning.



Progression of globally averaged surface temperatures based on data sets from NASA (red) and the Hadley Centre (black). The figure shows annual values and the overall trend.

## GLOBAL WARMING

Our planet is in the initial stages of dramatic climate change. Records show that since 1900, globally averaged surface temperatures have increased by 0.8°C (see figure). Around the globe, mountain glaciers are retreating, and Arctic sea ice cover has shrunk by 20 per cent in recent decades. The margins of the Greenland and Antarctic continental ice sheets now show signs of disintegration. Global sea levels have already risen by 20 cm in the 20th century, and satellite altimetry shows that they are currently soaring by 3 cm per decade.

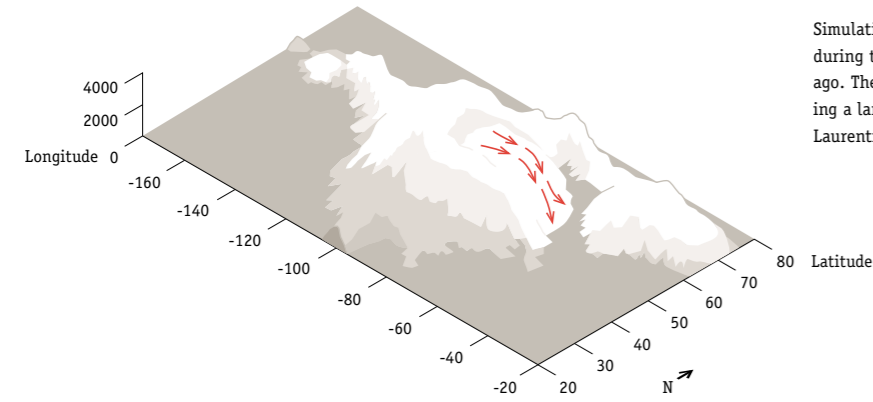
There has been a broad consensus within the international research community for many years that the observed global warming is predominantly due to human activity. The primary cause is the rise in atmospheric CO<sub>2</sub> concentration to its current level of 380 ppm. Today's atmospheric CO<sub>2</sub> levels are the highest for millions of years – before the Industrial Revolution, the level was just 270 ppm! These CO<sub>2</sub> emissions are caused by the burning of fossil fuels such as coal, oil and gas, and by agriculture and deforestation. 56 per cent of the CO<sub>2</sub> emitted by human activities is still present in the atmosphere.

Carbon dioxide has always played an important role in the Earth's climatic processes,

as environmental history shows. The Potsdam Institute is a major player in tracing this history, producing numerous publications to international acclaim. Carbon dioxide traps solar radiation which would otherwise escape into space and directs some of it back towards the Earth's surface. Thus in combination with several other gases, it forms a warming cocoon around our planet which, without this greenhouse effect, would be too cold to sustain life. In climate history, CO<sub>2</sub> concentration has generally changed only gradually over the course of many millennia, following geological cycles. But like Prometheus who stole fire from the hearth of Zeus, humankind has seized control of this carbon cycle, with the result that every year, we are currently extracting the same quantity of fossil fuels from the Earth as were formed over a period of around one million years.

The latest climate trends offer a bitter foretaste of the future: the last ten years were the warmest decade for many centuries and subjected us to new types of extreme weather conditions. If we adopt a "business as usual" approach and take no action to curb greenhouse gas emissions, the temperature of the Earth's atmosphere could increase by another 5°C by 2100. This is equivalent to the

temperature difference between an ice age and an interglacial episode. However, as we are already in a natural period of interglacial warming at present, we should really call the human-induced era ahead of us the "fire age" or "hot period". According to current scientific thinking, this dangerous climate change must be avoided at all costs, and global warming must be limited to a maximum of 2°C relative to the pre-industrial value. This will ultimately require a transition to a carbon-free society worldwide before the end of this century. The Potsdam Institute is developing detailed strategies for the implementation of this transition (see p. 25).



Simulation of ice cover over North America during the last interglacial about 20,000 years ago. The figure shows a Heinrich Event, involving a large-scale surge of ice from the Great Laurentian Ice Sheet into the Atlantic Ocean.

## MODELLING THE PAST AND FUTURE CLIMATE

The Potsdam Institute develops and runs global and regional climate models. With its global models, it simulates the Earth's long-term climate, while its high-resolution models are primarily intended to show the implications of climate change for Europe and especially for vulnerable regions. The Potsdam Institute has established a worldwide reputation for testing its climate models against relevant phenomena in the Earth's history. This is possible because information about past epochs is contained in numerous natural "climate archives" – ice that is hundreds of thousands of years old, fossilized air bubbles, tree rings and deposits in the seabed. Among other things, the Potsdam Institute undertook the first-ever simulation of the climate of the last ice age (20,000 years ago) using an ocean-atmosphere model.

Climate models are algorithms which contain concentrated information about physical correlations in the form of equations. For example, they may contain equations which calculate temperatures, winds and ocean currents. Ideally, these models are run on parallel computers to enable the many different equations to be worked out simultaneously for many diverse points around the globe – calculations

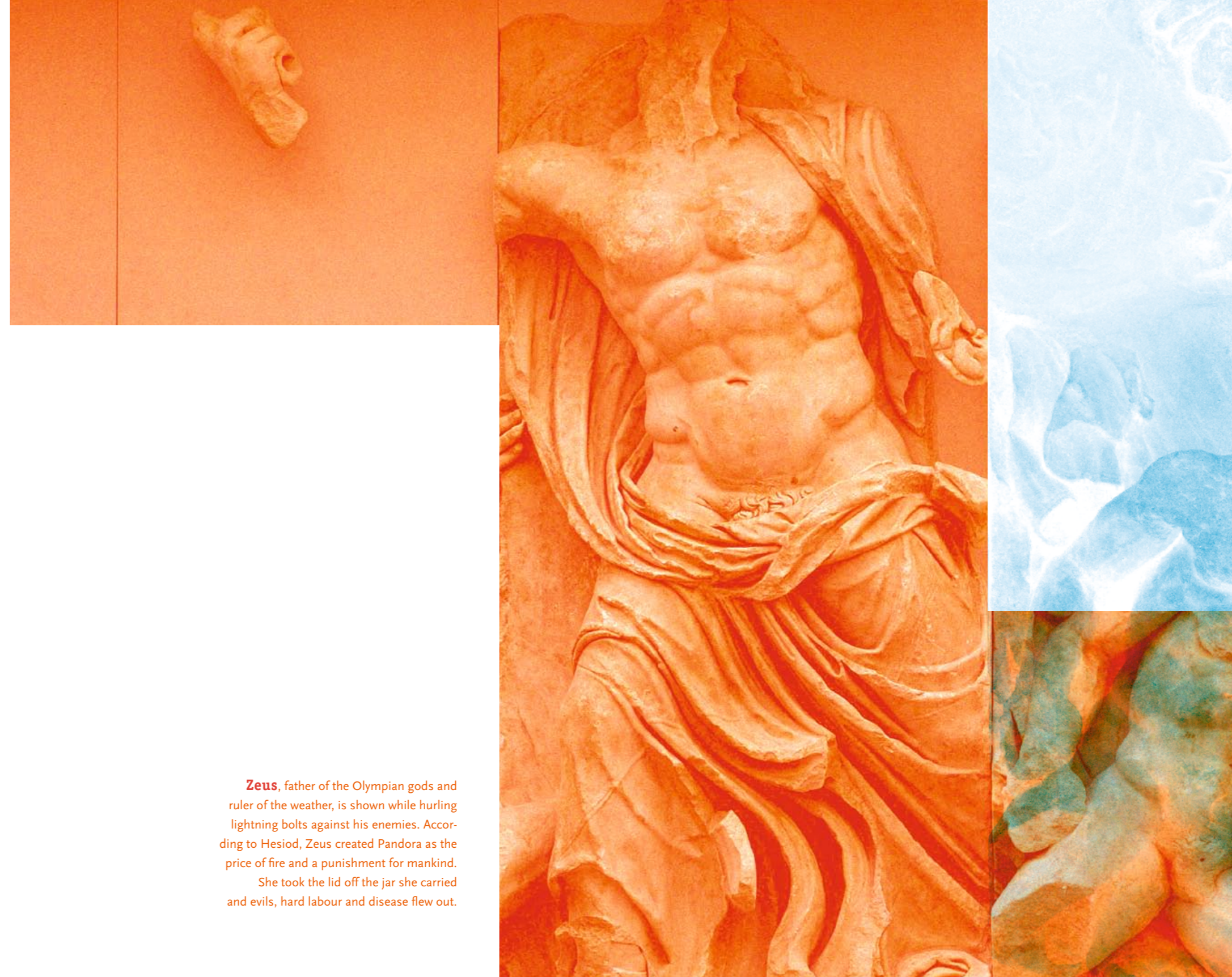
which cannot possibly be carried out using a pencil and paper.

Through computer simulations, experiments can be conducted which scientists cannot, or should not, perform in the real world. For example, they can model different scenarios to study the effects of various CO<sub>2</sub> concentrations in the atmosphere. This enables them to develop projections using the "if... then" principle: *if* humankind emits a certain amount of carbon dioxide (or other gases), *then* the following climatic changes (temperature increase, sea-level rise, etc.) are likely to occur.

The opposite question that we can ask is this: which volume of climate-relevant gases can we still allow ourselves to emit without jeopardizing the target which the European Union has set itself, namely to limit global warming to a maximum of 2°C relative to the pre-industrial value? The answer is that global greenhouse gas emissions must be reduced by at least 50 per cent by 2050.

Although a model can simulate the overall climate system very effectively, not all the feedback mechanisms between the various subsystems are properly understood yet. However, more and more components, such as the continental ice sheets, the biosphere and the

carbon cycle, are being integrated into the models. By comparing the results achieved from the application of the models with observed data, scientists can learn more about the natural mechanisms of climate change. This subjects the models to challenging tests. The Potsdam Institute recently undertook a systematic comparison of data from the last ice age with a large number of models in order to ascertain the climate's sensitivity to CO<sub>2</sub> forcing. The study confirms that the climate system can indeed be massively disrupted by human activity and that effective counter-measures must be taken within the next one or two decades.

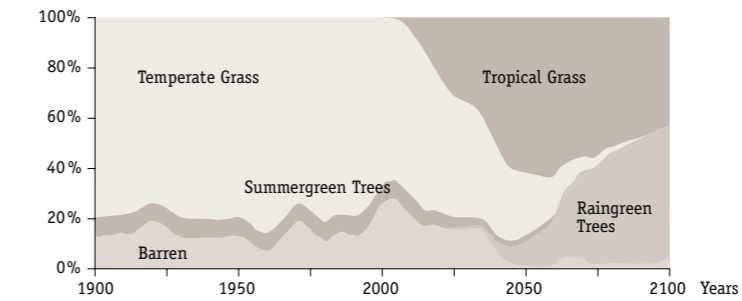


**Zeus**, father of the Olympian gods and ruler of the weather, is shown while hurling lightning bolts against his enemies. According to Hesiod, Zeus created Pandora as the price of fire and a punishment for mankind.

She took the lid off the jar she carried and evils, hard labour and disease flew out.



**Klotho**, one of the three Moirae (and goddesses of human fate), is hurling a snake-filled vase at her opponent, a violent son of the Earth. Even Zeus was unable to interfere with the Moirae.



Shifts in the vegetation composition of a highland savannah in southern Africa under climate change. The far-reaching exchange of underlying ecosystems will also have socioeconomic and cultural consequences.

### GRADUAL CHANGE – CUMULATIVE IMPACTS

Globally averaged surface temperatures have increased by around 1°C since the start of the Industrial Revolution – and the impacts are now gradually becoming visible. Human-induced climate change is quite clearly a gamble with a massive Pandora’s box. At a temperature increase of 1°C, its lid is slightly ajar. An increase of 2°C releases many of its harmful climate impacts, and far beyond this margin, nothing can restrain its potent contents.

It is possible to postulate temperatures at which a specific ecosystem suffers significant harm or collapses. A further 1°C increase in global warming, for example, is likely to result in the dieback of the tropical coral reefs, as it will make the sea-water too warm, too deep and too acidic. Although continents and oceans respond slowly to rising temperatures compared with human beings, the rise would still be much too fast for most habitats to adapt.

Climate change warms the world unequally: in some regions, the rise will amount to three times the mean value, whereas in others, it will remain below the globally averaged surface temperature. The regional character of the climate is also strongly dependent on atmospheric and oceanic circulation – changes in these dynamic patterns may modify the

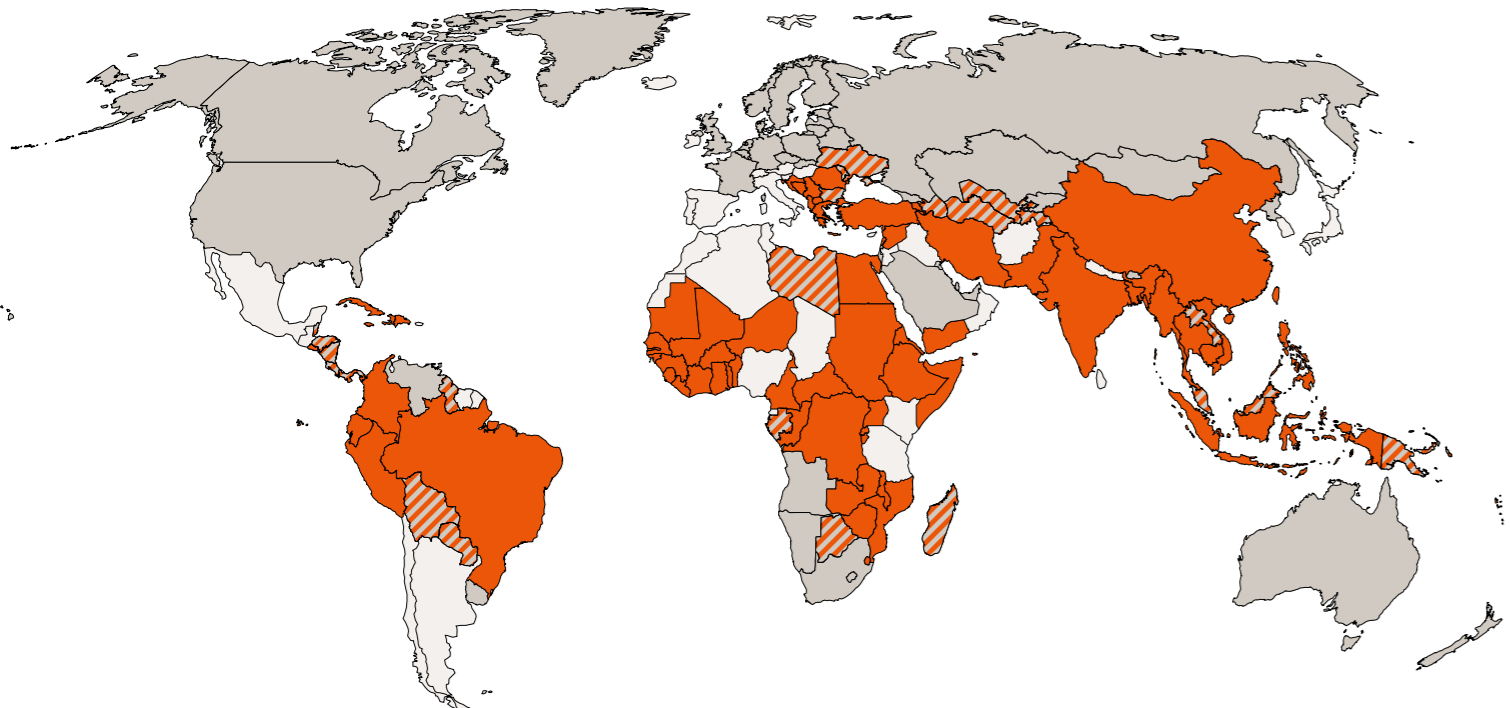
trajectory of low-pressure areas or the frequency of certain large-scale weather systems and thus affect the distribution of precipitation. Long-lasting fine weather conditions result in periods of drought, whereas air which is saturated with water vapour and charged with energy causes severe weather conditions, with torrential rainfall and storms. One and the same region can thus be adversely affected by floods alternating with water scarcity, making it increasingly difficult to plan agricultural production, for example.

The implications of climate change vary very significantly according to natural and social conditions. For example, more than one billion people already living in semi-arid zones will be impacted severely by food and water scarcity. In the industrialized nations which import most of their food, periods of drought will occur in the form of “heat waves”, leading to an increase in the number of forest fires, water scarcity and, in extreme cases, more deaths as a result of heat stress. These affluent countries will also have to accommodate increasing numbers of environmental migrants – including refugees from sea-level rise whose homes are submerging, and war refugees displaced by violent conflicts over increasingly scarce environmental resources.

Some physiographic regions – such as permafrost zones – are directly struck by rising temperatures; others are affected indirectly. Many ecosystems offer benefits such as timber or food to human communities, while preserving others is desirable due to their beauty and diversity. However, some also serve an important function in the Earth System, notably the tropical rainforests with their influence on the global hydrological cycle. In its studies, the Potsdam Institute has shown, in particular, that the Amazon rainforest and the northern taiga are likely to respond to global warming by releasing massive amounts of carbon dioxide, further accelerating the process of climate change. In other words, global threats could result from ecosystem change as well.

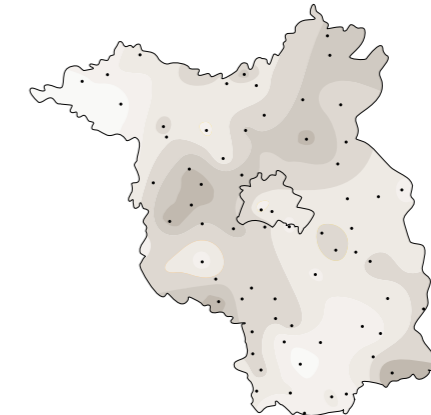
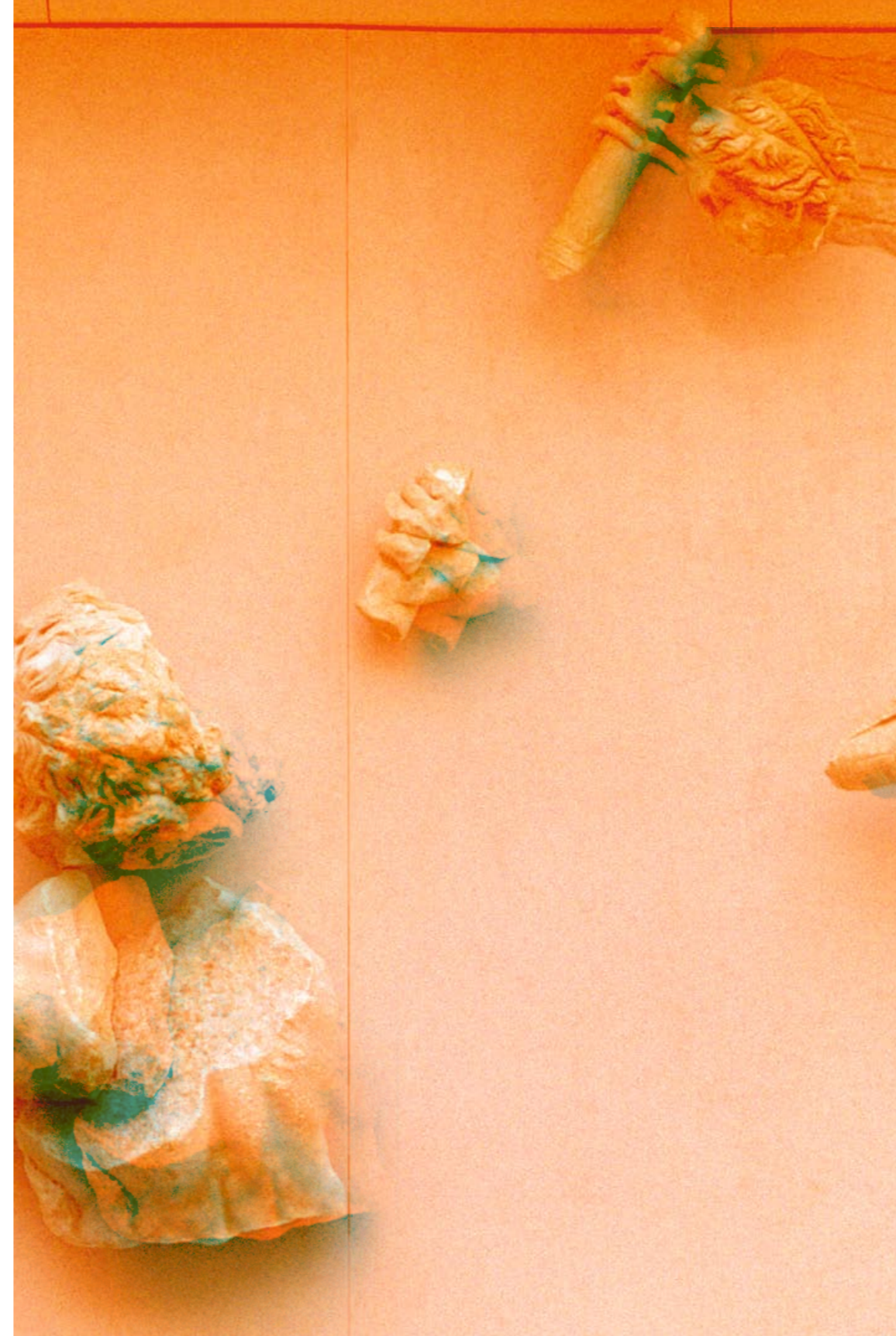
So will climate change cause severe disadvantages or perhaps even offer fresh opportunities? To answer this question, every region and sector must be considered individually. Vulnerability does not only depend on the type of habitat but also on whether adaptation is technically and economically feasible. The adaptive capacity of poor countries and low-lying island states is obviously minimal, and this is likely to further widen the North-South divide.

**Demeter** was worshipped as the goddess of fertility, harvest and health. When her daughter disappeared, the distress of Demeter caused a famine. On the frieze, Demeter survived only in fragments. There she fights with two torches against the giants.



Largest per capita CO<sub>2</sub> emitters  
 Highest social and/or agro-economic vulnerability  
 Largest per capita CO<sub>2</sub> emitters, and highest social and/or agro-economic vulnerability  
 Low or moderate both in per capita CO<sub>2</sub> emissions and social and/or agro-economic vulnerability

Countries most vulnerable to climate change (red) versus countries contributing most to global warming through the highest cumulated CO<sub>2</sub> emissions per capita (1950–2003, dark grey). Hatching indicates countries that belong to both groups.



Precipitation change for the Brandenburg region in the decade 2046 to 2055 relative to the period 1951 to 2003 related to the emission scenario A1B (business-as-usual). The black dots are weather stations.

-10 -20 -30 -40 -50 -60 difference (mm)

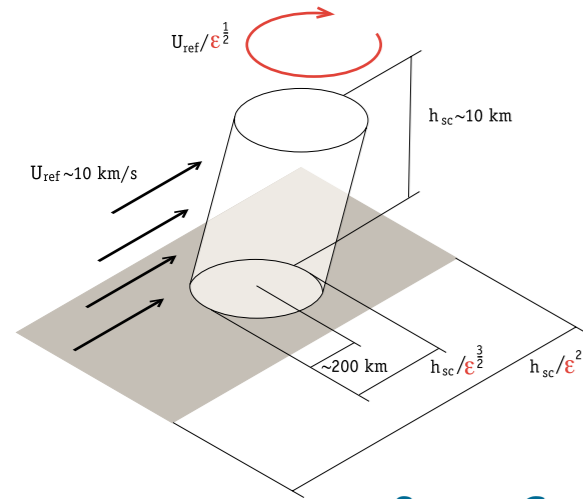
### CLIMATE CHANGE IN THE BRANDENBURG REGION

Climate change will affect individual landscapes first of all, both in a positive and a negative sense. As the harmful impacts will in most cases clearly predominate, they must be identified, their scale estimated, and appropriate adaptation strategies devised. Relevant procedures and methodologies have been developed at the Potsdam Institute for this purpose and are now being deployed for global analyses as well.

Brandenburg – the Institute’s home region, with its headquarters located in the capital Potsdam – was the first region to be subjected to such analysis. Based on various IPCC scenarios, a regional climate model provided data and offered conclusions about the climate trends which can be expected here in future. The key finding is that a temperature increase of just 1.4°C in the next 50 years is likely to result in a significant reduction in precipitation, especially in the summer months. Therefore, using a hydrological model, water availability was estimated. The findings are worrying: although Brandenburg has more lakes than any other area in Germany, a negative hydrological balance must be anticipated in the long term, and this will impact accordingly on the region’s ecology and agriculture. Marked decline in

crop yields can be expected. There is a very significant risk to the region’s forests – mainly conifers – from greater heat stress, forest fires and pests. People will also face growing health risks from longer-lasting heat waves in future, especially in the Berlin conurbations.

Despite – or indeed because of – these clear warning signals, there is a chance to take appropriate action. To this end, the Institute is developing adaptation strategies which can be implemented by decision-makers, and is underpinning these with specific recommendations for action. For example, plans for the further regulation of the Elbe have been shelved due to the low water levels expected in the summer months. The Brandenburg Government has also agreed a forest conversion programme to replace the coniferous monoculture with better-adapted species. Drainage of agricultural areas is being reduced in order to minimize surface runoff in favour of infiltration. A heat warning system for the Berlin area is under discussion. Further preventive measures are being planned, and the Potsdam Institute is actively contributing its expertise to facilitate their implementation.



Typical vortex diameters and wind velocities for hurricanes and their siblings. Mathematicians at PIK decompose these differing scales analytically by means of limit analyses for vanishing order-of-magnitude parameters  $\epsilon$ .

## STORM GODS

Some of the most awe-inspiring phenomena in our climate system are the powerful storms which, under certain conditions, form over the tropical seas. In the Caribbean, these storms are named “hurricanes”, after Hurakan, the Mayan god of winds. In the Pacific, they are known as “typhoons”. If they make landfall, these tropical storms are capable of wreaking devastation on a massive scale – through high winds, storm surges and torrential rainfall. As examples of their destructive power, we need only think of Hurricane Katrina, which ravaged the city of New Orleans in August 2005, and Super Typhoon Saomai, which inflicted massive damage in China in August 2006.

New hurricane records have been piling up in recent years. In 2004, a hurricane formed in the South Atlantic – an all-time first, although a British climate model had predicted that there could be hurricanes in this region in future as a result of global warming. The same year, Japan was hit by ten typhoons in a single season for the first time. The 2005 North Atlantic hurricane season was the most active since records began in 1851, with thirteen hurricanes in one year. That same year, Hurricane Vince moved toward the coast of Spain, while Hurricane Wilma showed a minimum air pres-

sure in its eye – 882 millibars – that was the lowest ever recorded in such a storm.

So an urgent question for climate research is whether human activities and the resultant global warming could be increasing the intensity of these hurricanes, making them even more dangerous than ever. There is some justification to this concern. Scientists have recognized for many years that the source of energy that powers these storms is the warm water in the oceans: that’s why they only form over waters with a minimum temperature of 26.5°C, and why their intensity rapidly drops back to that of a normal cyclone once they have made landfall. The fact that these storms swell over warm water and die down over colder seas is key information for scientists forecasting and tracking the progress of hurricanes on a daily basis.

Over the last 100 years, the surface temperatures of the world’s oceans have risen by 0.6°C. This has occurred in parallel to the rise in air temperatures and has the same cause: the accumulation of greenhouse gases in the atmosphere. The tropical seas are no exception. It is therefore logical to assume that this warming of the water has increased the intensity of tropical storms. Indeed, for the North Atlantic,

where the best measurement data exist, this link is well-documented. The increase in hurricane force has indeed kept pace with rising temperatures and has reached record levels here in recent decades. Similar increases have been observed in other ocean basins as well, but there is still some doubt about the quality of these data.

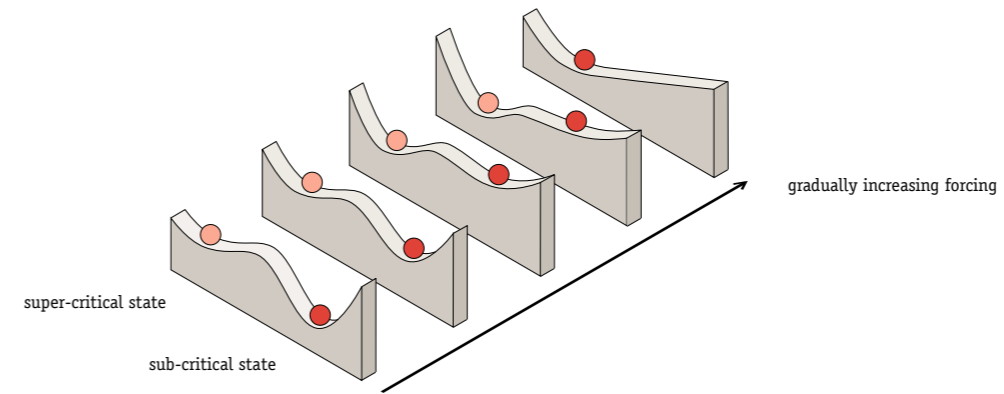
When it comes to predicting future trends relating to the force of tropical storms, the large-scale climate models still lack the resolution needed to give accurate forecasts. For that reason, PIK is developing asymptotic methods in order to improve our understanding of the physical correlations. The fact that the vortex core of tropical storms is almost axially symmetric provides vital clues in this context. With these new methodologies, PIK’s aim is to achieve better simulation of these storms, first in weather forecasting, then also in climate models.



**The Winds** as represented in Greek mythology by four winged horses, belong to Zeus, the god of weather. On the side of the giants fought Maimaches, the “storm-man”, whose name is evocative of Maimakterion, the month of autumn gales in Attika. Hurricanes were certainly not known to the Greeks; their name derived from the Mayan wind-god Hurakan.



**Poseidon** was the god of the sea and the water in general. In the battle depicted in Pergamon he emerged – as one can reconstruct from the heavily fragmented frieze – from the waves in a chariot drawn by powerful seahorses.



A system's distance from a tipping point can be determined through the character of its natural fluctuations. This analysis is based on the fundamental insight that sluggish excursions from equilibrium increase disproportionately as the system moves towards a critical threshold under gradually increasing forcing. The potential on the right becomes shallower and finally vanishes.

## SYSTEMIC CHANGE – TIPPING POINTS

When Poseidon, the god of the sea, was angry, he would lash the sea into fury with his trident. The seafarers of antiquity were often caught unawares by the unleashed forces of nature to which they were helplessly exposed. Thanks to modern weather forecasting, the surprise element of these phenomena has largely disappeared, but Poseidon's trident can still jolt the mechanisms of the Earth System in a way which is beyond our comprehension. Indeed, we are provoking the “climate gods”, awakening giants, without even realizing it. Perhaps we can solve the conundrum by asking a question. What do the following have in common: water heated to boiling point, a lake which is tipping into eutrophication, and the French Revolution? The answer is that in all three cases, a system property changes abruptly in response to a steady forcing: the cooker applies constant heat; the local community perpetually pipes its untreated sewage into the lake; and the French bourgeoisie becomes more economically powerful while developing its claim to political codetermination under the incessant influence of Enlightenment philosophy.

In the same way, climatic properties of entire subcontinents could “tip” as a result of global warming. Here, the level of abrupt-

ness depends on the system concerned: for example, the boiling point of water is reached within seconds, political revolutions may take days or weeks, while the timescale in the Earth System ranges from a few years to centuries. Atmospheric and land-use changes may result in the Indian monsoon becoming unpredictable – but the region's agriculture and thus the food security of a billion people depend upon it occurring regularly. The depletion of the protective ozone layer over Europe and the Antarctic, which is exacerbated by global warming, also takes place within this timescale.

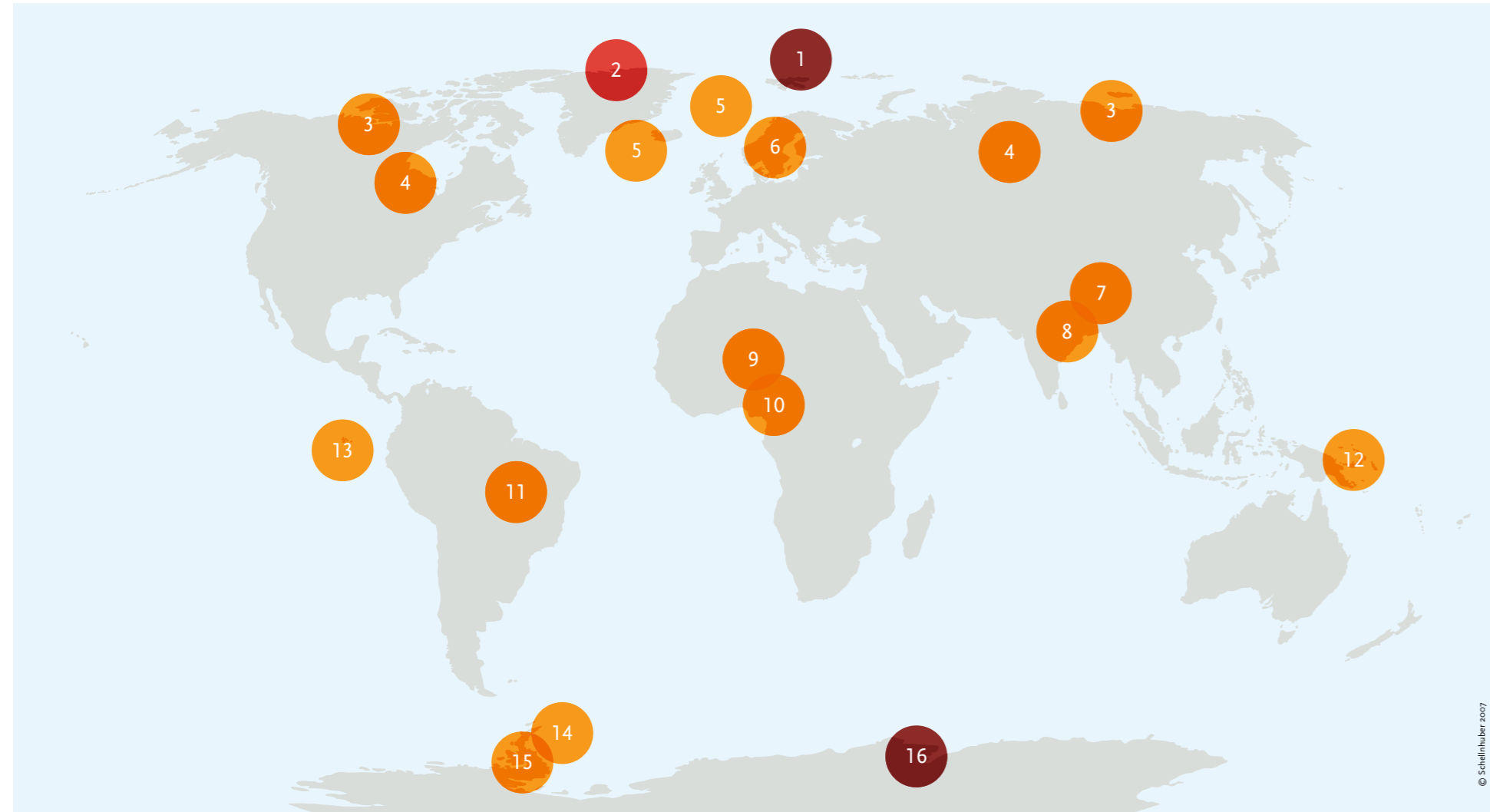
The impacts which could occur over a timescale of years and decades include, for example, the emergence of a permanent “El Niño”. At present, this climatic caprice, with its extreme weather conditions, inflicts suffering upon the South American population every four years or so. Over a similar timescale, the possible dieback of the Amazon rainforest would result in massive loss of its unique biodiversity and further accelerate the process of global warming.

The most dangerous phenomena which are likely to occur over decades or centuries include changes in ocean currents and ice melt. For example, human-induced climate change could

impede deep water formation in the North Atlantic Ocean and result in a shutdown or slowdown of the thermohaline circulation there. Another dangerous consequence would be shifts of precipitation in the tropical belt. The Tibetan plateau could become snow-free, leading to floods in the short term and water scarcity in Central Asia in the long term. Global warming would also be likely to speed up the disintegration of the Greenland and West Antarctic ice sheets. Complete melting of the Greenland ice would result in a 7 m sea-level rise.

Most of these effects (see world map, p.22) have not been adequately considered in analyses of how much global warming we can still afford. Their common feature – namely that they are likely to occur *abruptly* and/or *irreversibly* as a result of global warming – presents climate policy with even greater challenges than the climate impacts which occur gradually. On the other hand, some of the switches mentioned above have properties which make risk assessment easier (see figure) and enable early warning systems to be developed.

## POTENTIAL ANTHROPOGENIC TIPPING ELEMENTS IN THE EARTH SYSTEM



- tipped already
- in limbo
- still stable

### 1 Arctic Sea Ice Loss

As sea ice melts in a warming climate, it exposes a dark ocean surface, which absorbs more solar radiation and thus amplifies the warming. Over the last 30 years the area covered by sea ice has decreased significantly. This is also bad news for many species, like seals or polar bears, which depend on that ice for hunting and breeding. *Time Frame: ~100 yr.*

### 2 Melting of Greenland Ice Sheet

Greenland's ice sheet is melting due to the extraordinary warming of the Arctic region. Recent observations suggest an accelerated destabilization also due to melt-water lubrication effects. The complete collapse of the Greenland ice sheet would cause a global sea-level rise of 7 m. *Time Frame: Unknown due to highly non-linear processes. Current estimates: 300–1000 yr.*

### 3 Methane Escape from Thawing Permafrost Regions and Continental Shelves

Huge amounts of methane, which is a highly potent greenhouse gas, could be released by global warming. On the one hand, terrestrial methane will emanate from thawing permafrost areas in Siberia and Northern America. On the other hand, 'methane ice' assembled by natural processes over millions of years off many coasts might be activated by changing ocean temperatures and currents. *Time Frame: ~1000 yr.*

### 4 Boreal Forest Dieback

Northern boreal forests account for almost one third of the global forest inventory. They are declining in a warming climate because of enhanced disturbance stress through fires, pests, and storms. At the same time, their regenerative capabilities are diminished by temperature and water stress as well as direct human interference (logging, fragmentation, etc.). The dieback would trigger massive release of carbon dioxide, which in turn enhances climate change, as well as significant losses in biodiversity. *Time Frame: ~50–100 yr.*

### 5 Suppression of Atlantic Deep Water Formation

The warm Atlantic surface ocean current is responsible for the benign climate in Northwestern Europe. This great 'conveyor belt' is ultimately driven by cold and dense water sinking to the bottom of the North Atlantic off the coasts of Greenland and Labrador. A warming climate leads to an increased freshwater flow into the ocean, thus decreasing the water's density and slowing down the deep water formation. *Time Frame: ~100–500 yr.*

### 6 Climatic Change-Induced Ozone Hole over Northern Europe

Particularly Northern Europe could face a climate change-induced ozone hole. Global warming at the bottom of atmospheric strata implies cooling in the stratospheric "roof". This cooling induces ice cloud formation which in turn provides a catalyst for ozone destruction. *Time Frame: ~10–1000 yr.*

### 7 Darkening of the Tibetan Plateau

As the snow cover of the Tibetan territory melts due to global warming, the exposed dark rock surface will amplify regional warming through increased absorption of solar radiation. As a side effect, the freshwater supply for many Asian countries, which depend on glacier melt water, will be reduced. Moreover, it is possible that the darkening of the Tibetan plateau could affect the Indian monsoon system. *Time Frame: ~50–100 yr.*

### 8 Disruption of Indian Monsoon

Up to 90% of India's precipitation is provided by the regular summer monsoon. Carbon dioxide as well as aerosols play a key role in this highly variable system. Air pollution, land-cover change and greenhouse gas emissions could bring about a roller-coaster succession of intensified and weakened monsoons in South Asia causing extreme droughts and floods. *Time Frame: 30–100 yr.*

### 9 Re-Greening of the Sahara and Sealing of Dust Sources

Vegetation could re-appear due to higher precipitation in the Sahel region, but this greening of the Sahara may be overridden by intensive land-use, especially grazing. If the re-greening happened, it could seal major sources of dust that is blown across the Atlantic and fertilizes South American ecosystems. *Time Frame: ~50 yr.*

### 10 West African Monsoon Shift

The West African monsoon is affected both by heavy deforestation in coastal areas and increasing sea-surface temperatures. The future of this monsoon system is still uncertain. Global warming may bring about a doubling of dry years in the Sahel by the end of the century or a complete monsoon collapse, both of which would have profound large-scale impacts. *Time Frame: ~50–100 yr.*

### 11 Dieback of Amazon Rainforest

A large fraction of precipitation in the Amazon basin is recycled evaporation water. The reduction of regional rainfall in a warming climate, intimately connected to El Niño/Southern Oscillation, as well as forest fragmentation due to human activity could bring the forest cover to a critical threshold. Amazon dieback would have profound influence on the global climate and at the same time result in a huge loss of biodiversity. *Time Frame: ~50–100 yr.*

### 12 Change in Southern Pacific Climate Oscillation

Although uncertainties are large, some climate models predict an increased frequency and/or intensity of El Niño conditions in the Southern Pacific. The impacts of such a change in the oceanic oscillation patterns would be felt around the globe, especially in the form of droughts in South-East Asia and many other regions. *Time Frame: Rapid changes possible in 10–100 yr.*

### 13 Disruption of Marine Carbon Pump

This "pump" acts as a sink for both natural and anthropogenic excess CO<sub>2</sub>. There is a risk of a decline of this sink caused by increased ocean acidification and stratification owing to rising atmospheric CO<sub>2</sub> levels. The acidification impedes floating and

fixed organisms, such as plankton algae and corals, in building their skeletons, which bind carbon. *Time Frame: unknown.*

### 14 Suppression of Antarctic Deep Water Formation and Nutrients Upwelling

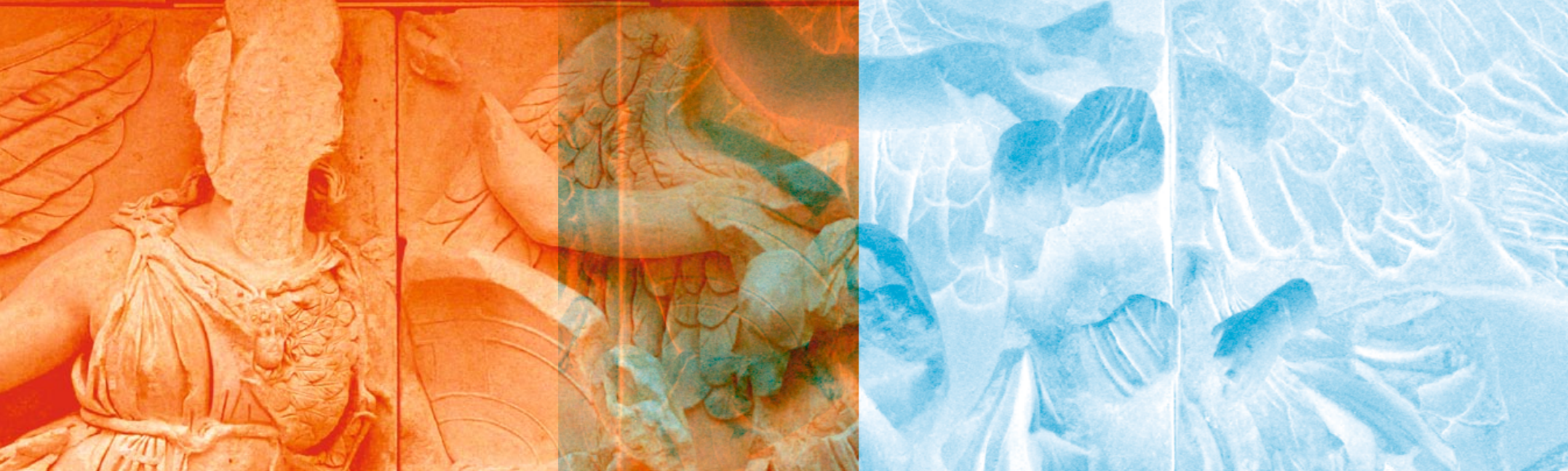
Similar to the North Atlantic, convection of water masses in the Southern ocean can be suppressed by freshwater inflow from melting ice. If there is a critical threshold, it has not been assessed so far. The resulting decline of nutrients would reduce phytoplankton and krill, which marks the basis of the marine food chain. *Time Frame: ~100 yr?*

### 15 Collapse of the West Antarctic Ice Sheet

Although assumed to be not as vulnerable as the Greenland Ice Sheet, a collapse of the West Antarctic Ice Sheet could be initiated within this century. Warming oceans result in melting of offshore ice shelves, which currently impede the out-flow of the continental ice masses behind. Furthermore, the warm water could be undercutting the ice sheet and yield further separation from the bedrock, thus accelerating the decay. The complete ice sheet collapse would raise the global sea level by 4–5 m. *Time Frame: ~300–1000 yr.*

### 16 Antarctic Ozone Hole

Already strongly perturbed by humanity's emissions of chlorofluorocarbons in the past, the protective ozone layer is believed to be regenerating after these chemicals have been banned. Yet strong interactions between stratospheric ozone depletion and global warming may widen the ozone hole over the Antarctic once again. *Time Frame: ~10–100 yr.*



**Athena**, the goddess of wisdom and craftsmanship, is usually portrayed as strong, fair, and merciful. She was renowned for her superb logic and her well-considered, highly ethical decisions. But she was also known to be good in war tactics. On the frieze, she is seen near to her father, Zeus, killing one of Gaia's sons.

## WHY SOLVING THE CLIMATE PROBLEM DOES NOT COST THE EARTH

The debate with the “climate sceptics” is over – they were unable to produce any viable arguments to counter the observation that the rise in atmospheric CO<sub>2</sub> concentration is mainly human-induced and that global warming is therefore primarily an anthropogenic effect. In future, the debate will be dominated by other issues: how we can adapt to shifting climatic patterns and what must be done in order to avoid dangerous climate change.

The damage caused by climate change can probably be limited to a manageable level if the rise in globally averaged surface temperatures does not increase to above 2°C relative to the pre-industrial value. A political consensus on a 2°C target will also facilitate “burden-sharing” between adaptation to climate change, on the one hand, and its mitigation, on the other. Even a successful mitigation strategy will require adaptation to the residual warming which will undoubtedly take place. At present, however, there is little sign of a suitable adaptation strategy being put in place. It would therefore be quite irresponsible to ease global climate protection targets and thus intensify the pressure on the developing countries, in particular, to achieve a high level of adaptation.

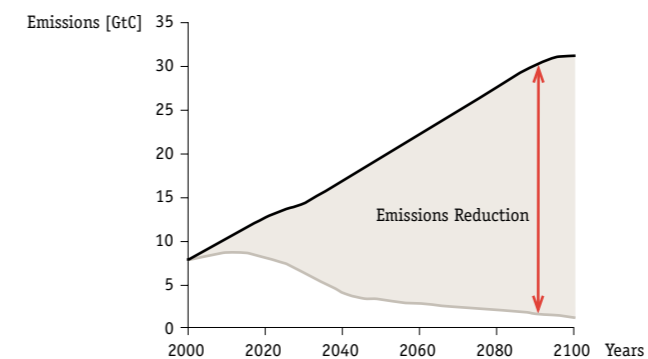
However, many economists are worried that effective climate protection is unaffordable. In many models, the costs of ambitious emissions reduction have been estimated at levels which suggest that it would be inadvisable, from an economic perspective, to limit the rise in globally averaged surface temperatures to 2°C relative to the pre-industrial value. The resources which would be tied up in climate protection – so the argument goes – would be better invested in poverty reduction. However, from a scientific perspective, a maximum of 2°C is absolutely imperative to avoid dangerous climate change (see p. 21). Is a goal conflict between economic growth and climate protection inevitable? Or could there be a strategy on which Athena, the goddess of science, and Hermes, the god of economists and thieves, might agree?

More and more researchers are now taking the view that the costs of climate protection have been overestimated in most economic models as they do not take account of the innovations which could be initiated by a well-designed mitigation policy. So in 2003, the physicist Hans Joachim Schellnhuber and the economist Michael Grubb proposed the establishment of a modelling comparison

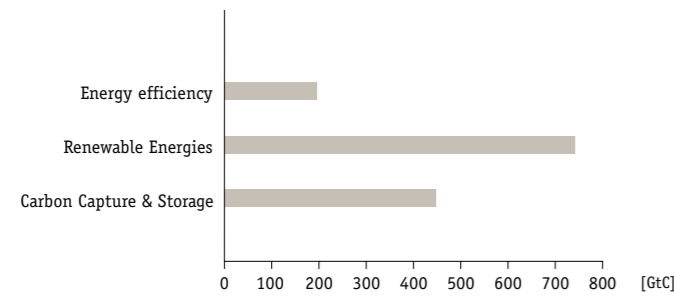
project, to be coordinated by Potsdam Institute scientists. The project – now known as the Innovation Modelling Comparison Project (IMCP) – is well known in the scientific community and among decision-makers in politics and business. Its findings have been presented to Germany's Chancellor, the IPCC, the oil company BP and the International Energy Agency, with all parties discussing the results with great interest.

The majority of models analysed in the IMCP came to the remarkable conclusion that the costs of achieving the 2°C climate protection target amount to less than 1.0 per cent of gross world product. The comparison showed that based on previous estimates, the costs of mitigation require a significant downward correction. However, this is only realistic if climate policy actually implements appropriate solutions. The findings of the models indicate that the following approaches are extremely significant in achieving the 2°C target.

- Improving energy efficiency;
- Large-scale deployment of renewable energy sources;
- Capture of the carbon produced by coal- and gas-fired power stations and its storage in geological formations.



Projected carbon dioxide emissions from two scenarios: business as usual (black line), and climate protection policy in line with the EU 2°C temperature target (grey line). The difference between these projections depicts the world's mitigation challenge.



CO<sub>2</sub> reduction in gigatons of carbon [GtC], attributed to the options in the mitigation portfolio. Total reduction reflects the difference of business as usual and atmospheric stabilization at 450ppm CO<sub>2</sub> from 2000 to 2100.

What role should nuclear energy play in the context of climate protection policy? This is rightly a contentious issue: nuclear energy could make a significant contribution – but not until the second half of the century, and only if technological development results in a plutonium economy which extends the uranium supply and defuses the key problem of storage of nuclear waste. An international congress held at the Potsdam Institute in March 2006 focussed on these issues. At present neither the technological nor the political problems associated with a closed plutonium system have been resolved.

The extensive use of biomass in conjunction with carbon capture and storage is under discussion as a promising element of the mitigation portfolio, with the aim of drastically cutting emissions and limiting atmospheric CO<sub>2</sub> concentration to a maximum of 450 ppm during the course of the 21st century. There are still a number of unresolved issues here which require thorough scientific analysis, such as the influence of extensive biomass use on the global hydrological cycle or the competition with food production.

The Potsdam Institute's research over recent years shows that we do not have to

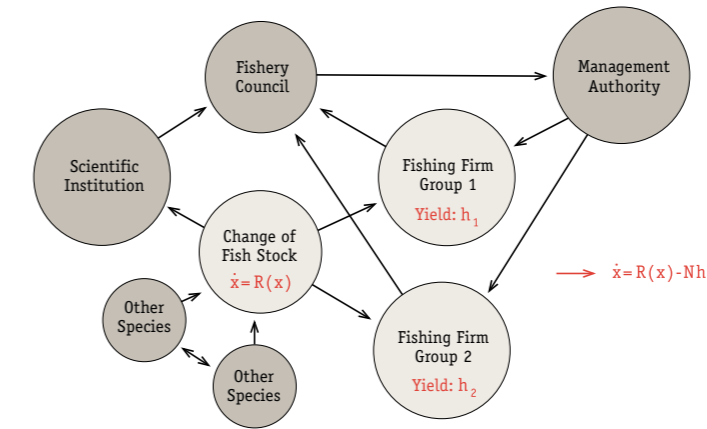
choose between two options: either economic growth without mitigation, or mitigation without growth. There can be harmony between Athena and Hermes – but wisdom and recognition of the limits to human action are also required in solving the climate problem. Just as Odysseus had to lash himself to the mast of his ship so as not to succumb to the sirens' song, so humankind must bind itself voluntarily to a long-term and credible climate policy with the aim of coming as close as possible to an emissions-free global economy by the end of the 21st century. Furthermore, the developing countries must be compensated for unavoidable damage and their efforts to adapt to "residual climate change" must be supported. Humankind must commit to a credible long-term climate policy in the coming decades. For otherwise, it will be reminiscent of the heroes of Greek tragedies, whose desperate efforts to stop their entire world crashing down around them simply hastened their pitiful end.



**Hermes**, son of Zeus, had many meanings during Antiquity. He was the god of dreams, the protector of travellers and cattle, a guide to Hades, and a messenger between gods. Cunning and quick, he was also the Greek god of commerce, markets and thieves.



**Eirene** was the goddess of peace and of the seasons, especially spring, when peace in Greece was most at risk. The marble statue shows Eirene holding the infant Ploutos (wealth) in her arms.



## SUSTAINABILITY RESEARCH

If we are to achieve a sustainable civilization which allows humankind to live in dignity and peace, cooperation between social and natural scientists is essential.

This is readily explained. Whereas in Greek antiquity, it was the moral order and the consensus between city-states which were important, while the desire for control over nature was axiomatic, we now face a global and far more complex threat to peace: humankind has intervened so dramatically in natural cycles that we are increasingly being confronted with the consequences of an environmental system in disarray.

It is understandable if people regard nature as the “natural enemy” in the truest sense of the word – it is dangerous to underestimate it. And humankind has underestimated nature, especially its response to newly developed synthetic compounds and the impacts of generating energy from fossil fuels. The Earth System, as sophisticated and finely tuned as the human hormone system, clearly reacts badly if its chemistry is disrupted. What humankind currently regards as unusual changes or even an assault by natural forces is no more than the response of an environment which – in line with the laws of natural science – is attempt-

ing to restore its balance, and reacts more strongly the more its biogeochemical balance is disturbed. How can we avoid a fatal clash between civilization and the Earth System, leaving room for adaptation to a natural environment in transition?

So the question is not only how to deal with the impacts of climate change, but also – and above all – how to slam shut the lid of Pandora’s box as quickly as possible. And that requires joint action by a world community which is currently organized, first and foremost, through its markets. What is required is a new definition of the relationship between humankind and nature which is no longer driven by utilitarian interests. This requires both a catalogue of measures and a timetable: how can we decarbonize industrial society within a matter of decades without heightening the conflicts between rich and poor and deepening geostrategic imbalances? Here, we must look to science, for it can provide “integrated” strategies for this purpose.

From the outset, the Potsdam Institute has aimed to bridge the gap between the social and the natural sciences. But only now, after 15 years, is the paradigm shift – whose first tentative steps were set in train by the Club

Avoiding overexploitation of marine resources is of vital interest for global food security. Integrated modelling is one prerequisite to anticipate critical developments and allows to develop sustainable management regimes in a complex interplay of different interests. Shown here is just the basic dynamic of the system.

of Rome – finally complete. Research can and must offer its services to a process which pacifies the now precarious relationship between humankind and nature.

The Potsdam Institute is therefore taking a further step forward in 2007: it is adding transdisciplinary research to its field of activities alongside its single-discipline research domains and interdisciplinary collaboration. It is doing so in the recognition that an understanding of global problems must include an awareness of sustainable solutions.

The time has come for Eirene and Athena to depart from their Olympian homeland and embark on a journey across the globe, bringing their vital wisdom, knowledge and peaceability to the megacities, farmlands, primeval forests and steppes in order to create sustainable environments for the future.

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