International Geosphere-Biosphere Programme

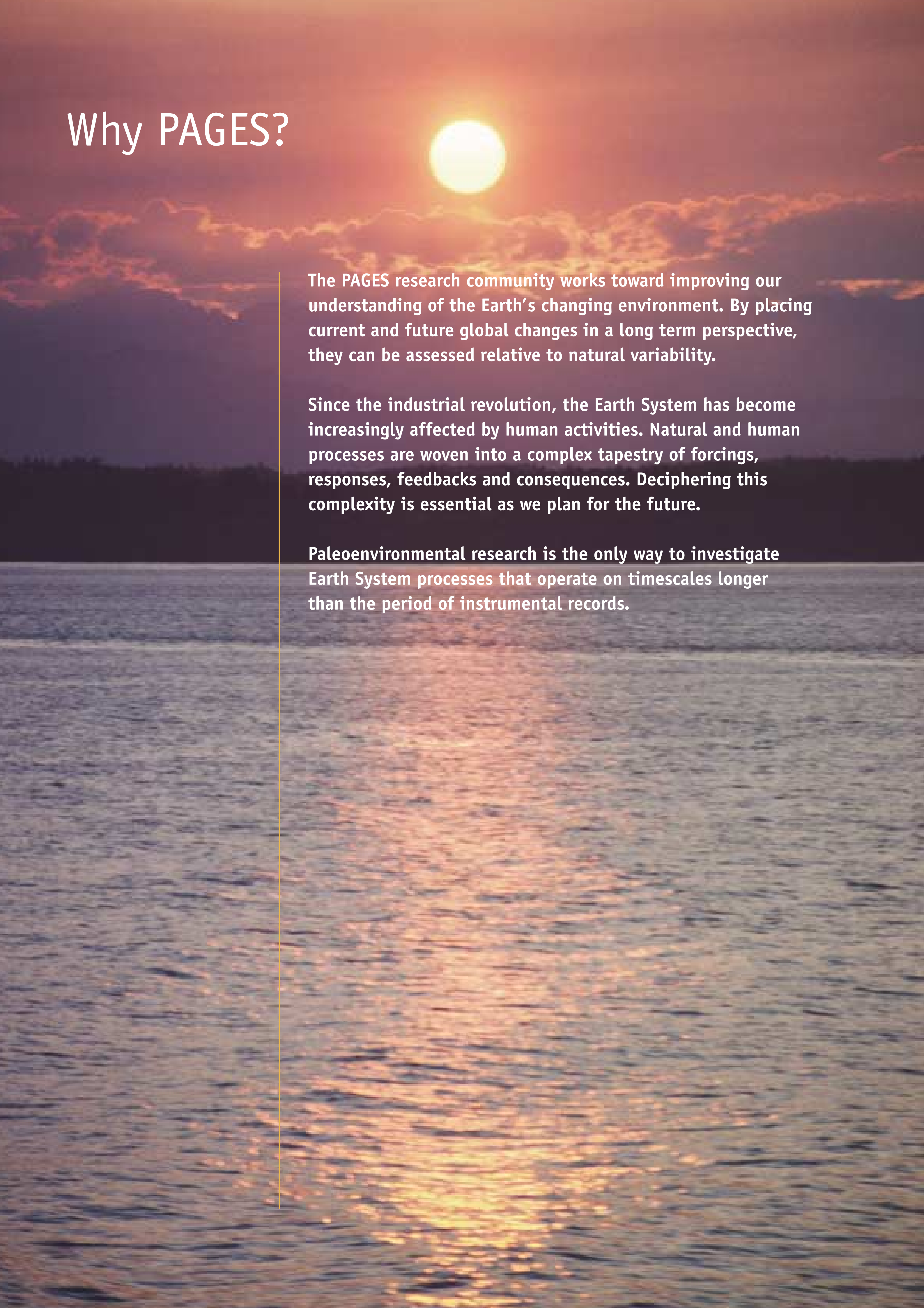
IGBP Science No. 3

GLOBAL CHANGE IGBP

Environmental Variability and Climate Change

Past Global Changes

PAGES
PAST GLOBAL CHANGES



Why PAGES?

The PAGES research community works toward improving our understanding of the Earth's changing environment. By placing current and future global changes in a long term perspective, they can be assessed relative to natural variability.

Since the industrial revolution, the Earth System has become increasingly affected by human activities. Natural and human processes are woven into a complex tapestry of forcings, responses, feedbacks and consequences. Deciphering this complexity is essential as we plan for the future.

Paleoenvironmental research is the only way to investigate Earth System processes that operate on timescales longer than the period of instrumental records.

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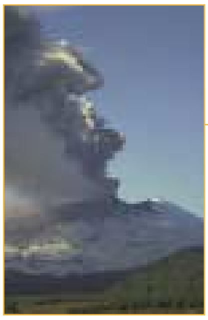


Foreword

WE LIVE IN UNUSUAL TIMES. Greenhouse gas concentrations are increasing rapidly and are now much higher than they have been for at least 420,000 years. Global average temperatures exceed anything seen in the last thousand years. The evidence is now overwhelming that such changes are a consequence of human activities, but these are superimposed on underlying natural variations. Climate on Earth naturally undergoes changes driven by external factors such as variations in solar output and internal factors like volcanic eruptions. How can we distinguish the human from the natural impacts? And what might the changes herald for the future of human societies as population pressure grows, as fossil fuel consumption increases and as land cover is altered?

Such questions are compelling, and the need for answers urgent. But the search for answers will only be successful when we have developed insight into the full range of natural variability of the climate system. That range is illustrated by the events of the past, and it is only by unravelling those events that we will be able to predict the future, and our place in it, with confidence.

This booklet stands as a progress report in the search for the past. It highlights a number of the extraordinary discoveries about the operation of the Earth System through time that have been made by natural scientists around the world over the last few decades. The great gains described in these pages have been wrought through exploration across the face of the planet and beyond: on land, sea, lakes, ice caps, via satellite observations and through simulations run on silicon chips. But that is only one dimension of the search, for critical to the future of human society is an improved understanding of the sensitivity of civilizations to climate change. Increasingly, paleoclimatologists are working with social scientists to disentangle the impacts of evolving social pressures and cultural practices from those induced by past climate change.

The scientific findings in these pages give cause for both exhilaration and concern. The exhilaration lies in appreciating the remarkable increase in our understanding of the complexity and elegance of the Earth System. The concern is rooted in recognizing that we are now pushing the planet beyond anything experienced naturally for many thousands of years. The records of the past show that climate shifts can appear abruptly and be global in extent, while archaeological and other data emphasize that such shifts have had devastating consequences for human societies. In the past, therefore, lies a lesson. And as this booklet illustrates, we should heed it.

Bachalpsee, in the Swiss Alps, is one of many lakes with an annually laminated sedimentary record of past environmental change.
photo: André Lotter

Tools of the Trade

> **"Except for the observations made over the last 130 or so years at weather stations and on ships, our knowledge of past climates is based on records kept in sediment and ice. The task of the paleoclimatologist is to decipher these proxies."**
>
> ***W. Broecker, 1993***

Paleo-environmental archives and proxies

Paleo-environmental archives such as ice caps, marine and lake sediments, trees and long-lived corals preserve records of past environmental changes. These and other archives, including documentary records, provide information about changes in the atmosphere, ocean, cryosphere, biosphere, and the dynamics of interactions among them. Deciphering the evidence that natural archives contain often involves extensive field-based research. Some of the key natural archives of past global change are rapidly disappearing, lending urgency to the task of retrieving them.

Paleo-environmental reconstruction requires that the properties measured in natural archives (proxies) be quantitatively translated into environmental parameters. For this approach to work the proxies must be rigorously calibrated against direct observations, such as July air temperature, sea-surface salinity or the makeup of vegetation cover. Thus, a period of over-

Cores taken from giant living corals such as this one provide multiproxy reconstructions of past sea surface conditions including El Niño/La Niña events. Sub-seasonal resolution over the past several centuries is possible. *photo: Julia Cole*

lap between the proxy record and contemporary data is vitally important for deriving well calibrated, quantitative paleo-reconstructions.

All natural archives contain many lines of evidence which serve as proxies for climatic and environmental change. For example, a single ice core contains indications of air temperature, atmospheric gas composition, volcanic activity and dust deposition rates. Similarly, within a single lake, sediments can record temperature, erosion rates and the makeup of terrestrial and aquatic ecosystems.

A hierarchy of models

Model building has always been an integral part of paleoclimate research. In fact, anything beyond description of raw observational data might be called modeling. Atmospheric flow, ocean currents, and the slow movement of ice sheets are all governed by basic physical and chemical laws. A climate model is simply a numerical procedure that solves the equations that describe these laws, together with numerous simplifications of processes for which the underlying physical laws are too poorly known or too complex to include.

In 1906, when the geologist Thomas Chamberlin began thinking about the causes of the ice ages, he formulated a theoretical model based on changing ocean circulation. Today, paleoclimatologists have a number of tools at their disposal to investigate such questions. These range from simple models comprising a few equations to computer-intensive coupled climate models. Although simple models cannot represent the full complexity of the system, they allow a wide range of hypotheses to be tested. On the other end of the scale, paleoclimatologists utilize coupled atmosphere-ocean-biosphere models. These require enormous amounts of computer time, severely limiting the number and length of simulations that can be carried out. Simplified, dynamical models (often called "models of intermediate complexity") bridge the gap between these two extremes of the climate model hierarchy. The same model hierarchy is also used to assess how climate will evolve in the future. The extent to which these models can realistically describe past changes in the climate system thus helps to assess the veracity of future predictions.

Chronologies

Understanding climate history requires a clear chronology of the past. Records must be dated so that the timing of events, rates of change and relationships among different archives can be established. Only in this way is it possible to build

Interior view of the historical archive in Seville, Spain in which records of the duration of the voyages of the Manila Galleons, used to reconstruct Pacific climate as far back as the late 1500's, are stored. *photo: Henry Diaz*

a coherent picture of the true temporal and spatial evolution of Earth System processes. Chronologies are developed using a wide variety of methods. Several of these, radiocarbon dating for example, depend on radioactive decay. Others rely on counting annual layers, whether of snow accumulation, tree rings or seasonally deposited sediments. Models of physical processes such as ice accumulation and flow can also be used. Markers of known age such as volcanic ash layers are especially useful for inter-site comparisons. These approaches all require a great deal of research into the environmental processes that make them useful as chronometers. The best chronologies are often established using several independent methods.

Earth System Dynamics

Raised and accurately dated coral terraces provide information about former sea level. The terraces shown here, on the Huon Peninsula in Papua New Guinea, provide estimates of sea level history for about the last 150,000 years.
photo: Sandy Tudhope

> **"...whereas all experiences are of the past, all decisions are about the future ... it is the great task of human knowledge to bridge this gap and find those patterns in the past which can be projected into the future as realistic images..."**
>
> **K. Boulding 1973**

How does the past record improve our understanding of how the climate system works?

The paleorecord shows us that over the past 500,000 years the climate has varied cyclically and has been dominated by cold conditions. Warm, interglacial climates like that of today persisted for only short periods once every 100,000 years. The cyclicity is driven by changes in the distribution of sunlight on the Earth's surface as the planet's orbit varies slightly through time. Analysis of the record of ice volume on Earth shows that ice accumulation responded to astronomical variations that have periodicities of about 100,000, 41,000 and 23,000 years. These are now recognized to be the pacemakers of the ice ages.

The glacial periods had global dimensions. The increased extent of ice on the land and surface ocean as well as variations in vegetation cover increased the reflectivity of the Earth's surface and reduced the amount of solar energy absorbed by the planet.

When colder surface waters were present in the mid- and low-latitude oceans, cold-tolerant plants were more widely distributed on continental interiors and snow-lines dropped even in tropical mountain ranges. Large parts of the Earth were drier resulting in a dustier atmosphere. More dust was deposited onto the ice sheets of central Antarctica and Greenland and onto the surface of the ocean at the same time as thick sections of wind-blown silts were being deposited in China and elsewhere. Simultaneously, the trade winds blew large volumes of desert sand across the Sahel toward the Atlantic Ocean. The dust settled through a glacial-age atmosphere that was strikingly depleted in the concentrations of the greenhouse gases carbon dioxide, methane and nitrous oxide.

This close correspondence among changes in the planetary orbit, ice volume, sea-surface temperature, dust deposition, plant distributions, snow-lines and greenhouse-gas concentrations highlights the intimately interconnected nature of the Earth System. Detailed comparisons of the relative timing of such variations yield much insight into climate feedbacks and the dynamics of the interconnections. For example, simultaneous increases in temperature and greenhouse-gas concentrations slightly preceded the melting of the large continental ice sheets, leading to the conclusion that carbon dioxide and methane are important agents of climate change. Biological feedbacks are now also recognized to be important. Variations in the rate of dust fallout have been shown to modulate the growth of marine plants in the sea, and in so doing, change the rate of uptake of atmospheric carbon dioxide by the ocean.

Sea level changes over four glacial cycles

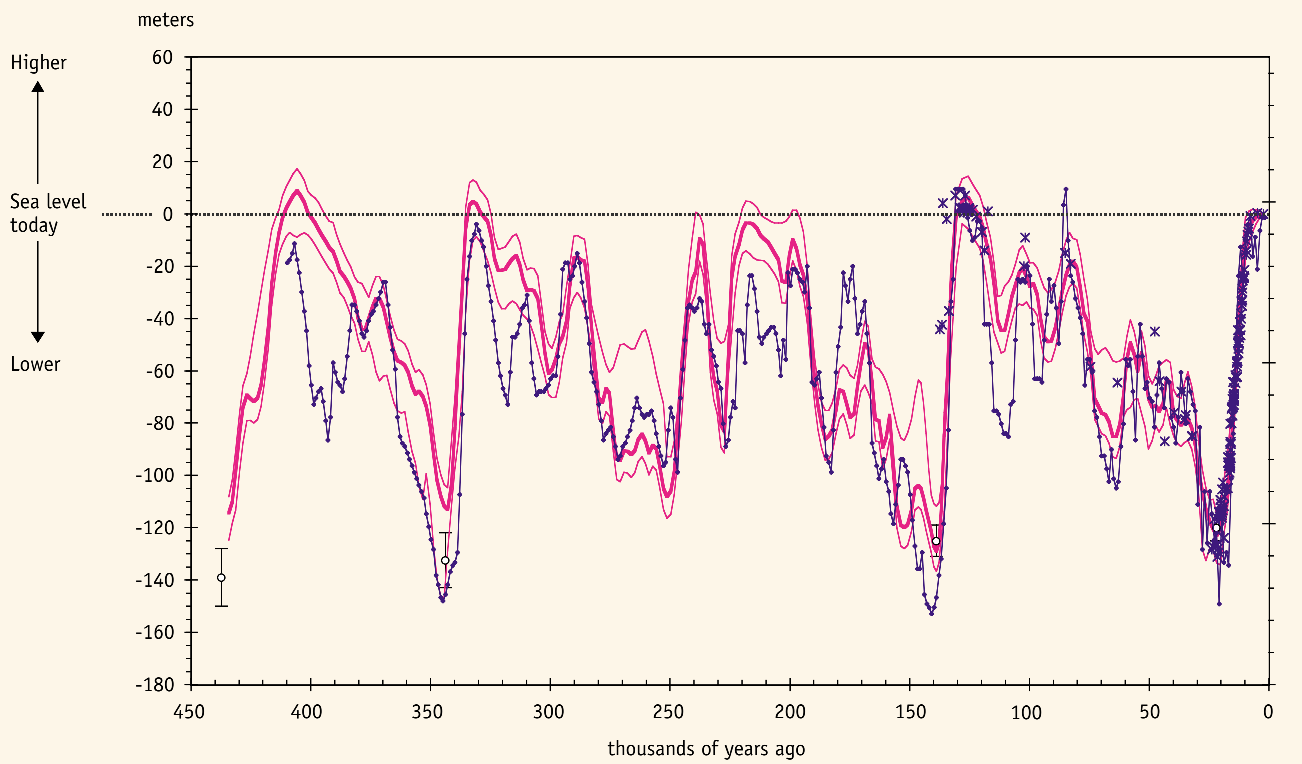
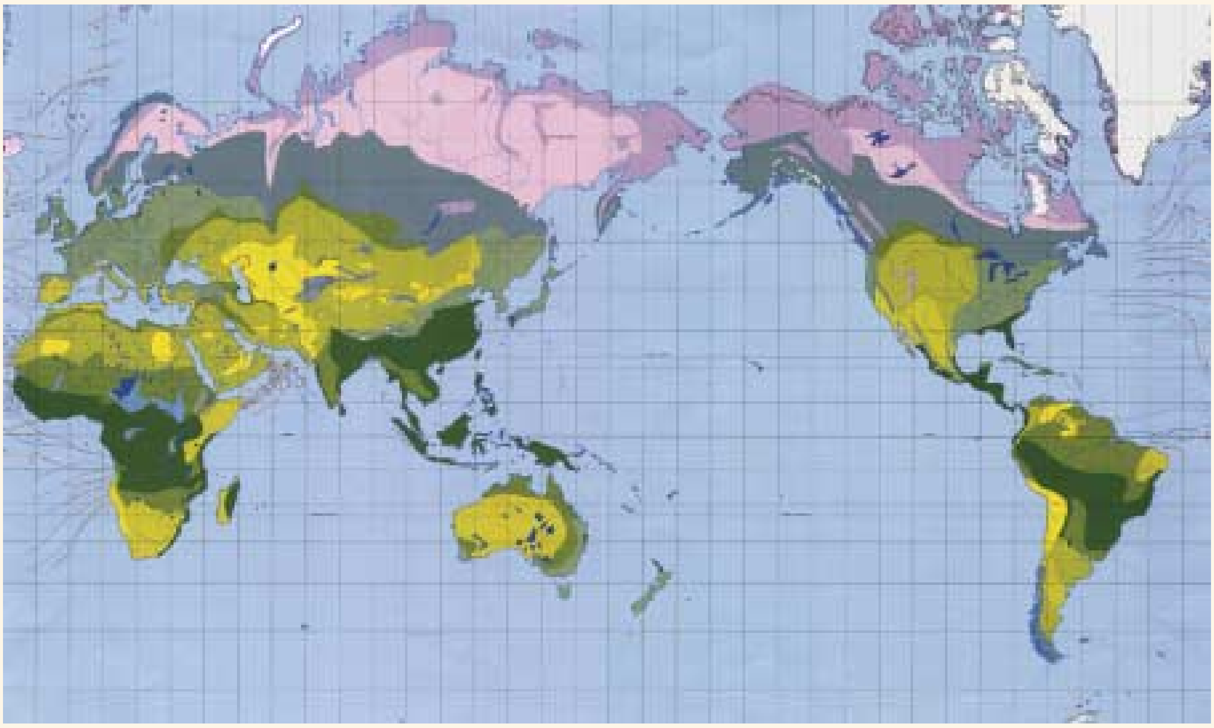


Figure 1 Various estimates of how sea-level has changed over the last four glacial cycles. These were obtained from evidence of former shorelines (such as those now uplifted by Earth movement above modern sea-level, as shown on the previous page) and from changes in ocean chemistry resulting from the growth of ice sheets on the continents, which altered ocean composition. According to the reconstructions shown here, during the maximum glacial conditions (e.g. around 20-30 thousand years ago) sea-level was 120-140 m below present (shown as zero on this graph). During past warm periods (interglacials), such as 125-130 thousand years ago, sea-level was higher (by 5-10 m) because global continental ice cover was less than that of today.

source: Labeyrie et al (in preparation) in Paleoclimate, Global Change and the Future, Springer.

Ice and biome distribution 6000 years before present



Ice and biome distribution at the last glacial maximum (21 000 years ago)

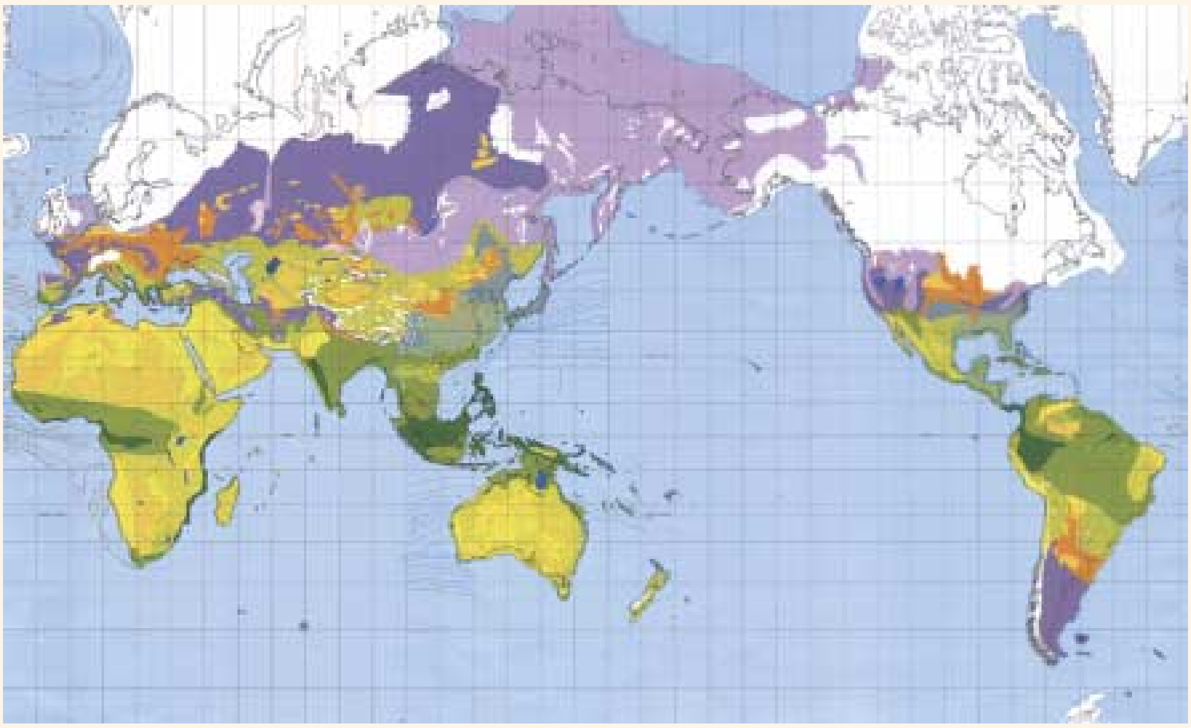


Figure 2 Two reconstructions of what the world looked like during the height of the last glaciation (below) and around 6000 years ago (above). Note that the extent of sea-ice is not shown (nor is Antartica). Work is continuing on refining these maps. There is a considerable debate over the former extent of ice cover (e.g. in North West Russia) and over the character of vegetation cover in many regions (e.g. Amazonia) during glacial times. On these maps greens represent vegetation requiring more moisture and browns and yellows are aridity tolerant biomes. Purples represent tundra, taiga and step vegetation and white is ice. Full documentation is available in the original publication.

source: Petit-Maire (1999) C.R. Acad Sci Paris, Earth + Planetary Sciences, 328, 273-279.

Millennial scale climate variability

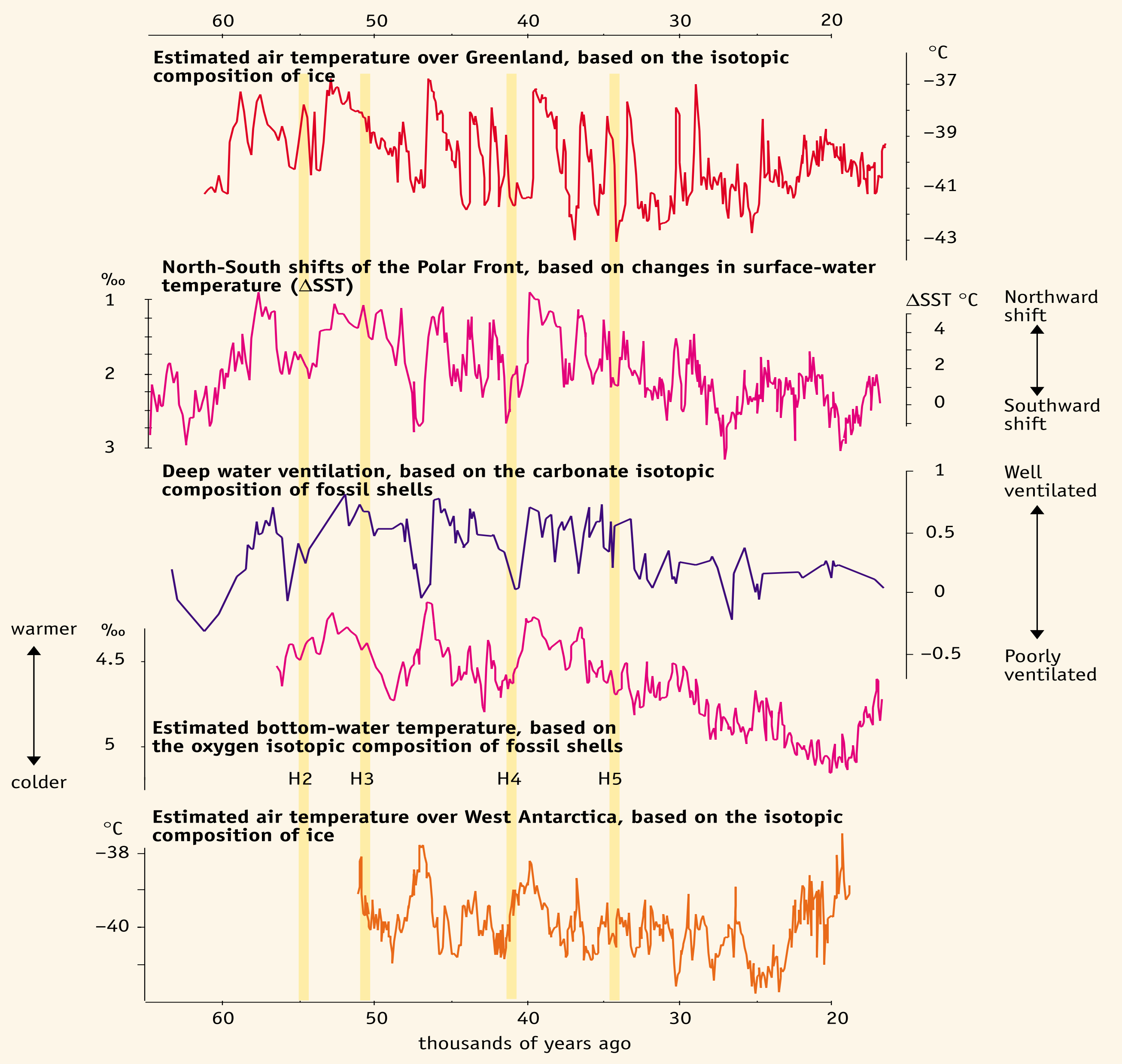


Figure 3 Millennial scale climate variability during the last glacial period as captured in proxy records of air temperature over Greenland and Antarctica, and latitudinal shifts in the polar front, deep ocean ventilation and bottom-water temperature, all in the North Atlantic. The labels H2 to H5 refer to Heinrich Events, short-lived episodes of catastrophic collapse of the Northern Hemisphere ice sheets. These are recorded in North Atlantic deep-sea sediments by layers of sand. The sand particles (Fig. 4 p.10) were carried into the deep ocean from the continents by armadas of icebergs (photo p. 11). The mechanisms behind the variability are not yet fully understood, but probably involve numerous feedbacks within the Earth System, with the ocean playing a major role. The scale of the global temperature changes associated with this variability in the interval shown is roughly half of that associated with full glacial-interglacial cycles.

source: Labeyrie et al (in preparation) in Paleoclimate, Global Change and the Future, Springer.

Climate has varied over intervals much shorter than glacial cycles and orbital variations cannot explain these fluctuations. Paleorecords from the oceans and the continents reveal that synchronous changes occurred on millennial timescales and these were often rapid. Such large-scale changes were particularly common during the ice ages. There is strong evidence that these were the result of changes in the North Atlantic ocean circulation caused by fresh water flooding the ocean surface as ice sheets on the continents collapsed. What caused these collapses is not well understood but they may have involved instabilities that developed within the large continental ice sheets when they reached a critical size.

The bipolar seesaw

During the last ice age and the transition into the present warm period (Holocene) the Earth System exhibited climate swings that provide important clues as to how atmosphere, ocean and ice cover work together. Among the most prominent are the Dansgaard/Oeschger (D/O) events, a series of rapid warmings – up to 16°C in Greenland – recorded in ice cores. If climate was unstable in the past, what does that tell us about the future?

In order to understand the mechanisms responsible for these instabilities, we need to know how the Earth as a whole reacted to these huge changes. Methane holds one of the keys. The atmospheric concentration of methane peaked at every warm episode. Even in locations far from the North Atlantic, there is a clear atmospheric "echo" of D/O events. When methane concentrations are used to synchronize high-resolution ice core records from Greenland and central Antarctica, inferred temperatures in Antarctica show a slow warming that preceded the abrupt warming in the north by 1000-2000 years. When the north finally warmed (within less than a century), a slow cooling began in the south. This remarkable pattern of warming and cooling that is opposite in phase between Greenland and Antarctica has become known as the bipolar seesaw.

This seesaw is a consequence of changes in the surface and deepwater circulation of the Atlantic and associated exchanges of heat. In the modern ocean, the overall transport of heat is from the Southern Atlantic to the Northern Atlantic. Thus, when the circulation in the north collapses, less heat is exported from the south, and the Southern Ocean warms. Re-establishment of the modern-type circulation produces a D/O event and the south starts cooling again. Nature is undoubtedly more complicated than this simple concept suggests; nevertheless, the bipolar seesaw is able to explain a number of characteristic features that are found in paleoclimatic records. The seesaw was predicted by numerical models before it was found in paleoclimatic records. Its discovery demonstrates the powerful insight that can be gained by comparing model results and paleoclimatic information.

Will the thermohaline circulation change in the future?

If the deep ocean circulation is sensitive to small perturbations, an enhanced fresh water flux to the high latitude North Atlantic ocean associated with global warming could drastically reduce the amount of heat that the ocean currently brings to Europe. Such potential future perturbations are many orders of magnitude smaller than fresh water inputs that have been used to drive modeled thermohaline shutdowns associated with D/O events. Although these models provide insight into a major dynamical mode of climate variability, they are not currently capable of accurately estimating how likely is a future shut down of the thermohaline circulation. If there is a shutdown in the future, its largest impact would be in Europe. However the associated cooling may be more than compensated by an even larger warming associated with greenhouse gases.

Closeup of Marine Sediments

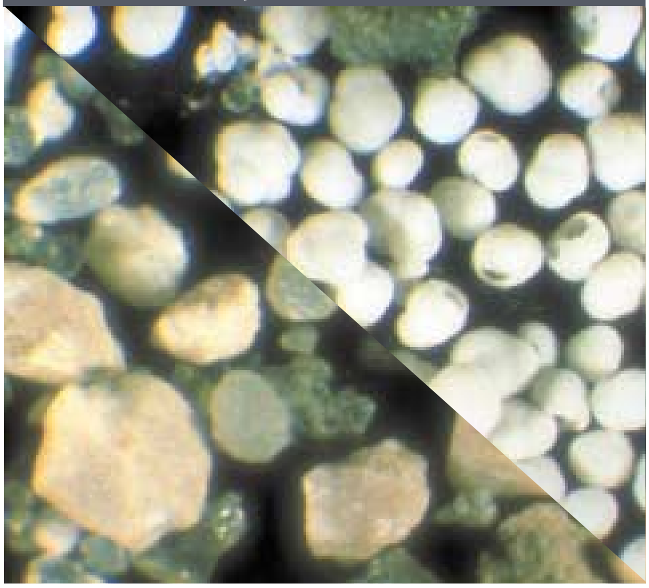


Figure 4 Two important sources of information about past oceanic conditions in the North Atlantic. Sand-sized rock and mineral particles (bottom left) found in mid-ocean sediments indicate transport by icebergs far south of present-day ice limits. Calcareous shells of foraminifera (top right) provide evidence about former oceanographic conditions (water temperature, water chemistry).
photo: Anne Jennings

Rapid events

The last major example of rapid climate change due to changes in deep ocean circulation occurred approximately 8200 years ago when a large lake on the edge of the North American ice sheet suddenly drained and sent huge amounts of fresh water into the North Atlantic. The resulting changes in the climate were recorded in sites as far apart as Greenland, Central Europe and Central North America.

An iceberg originating from northwestern Greenland floating in the northern North Atlantic. As such icebergs drift into warmer water and melt, debris particles rain down onto the sea floor leaving a record of the equatorward extent of iceberg drift. During the last glacial period ice-rafted debris in the North Atlantic was delivered as far south as the Portuguese margin.
photo: Anne Jennings

A widespread, abrupt climate change 8,200 years ago

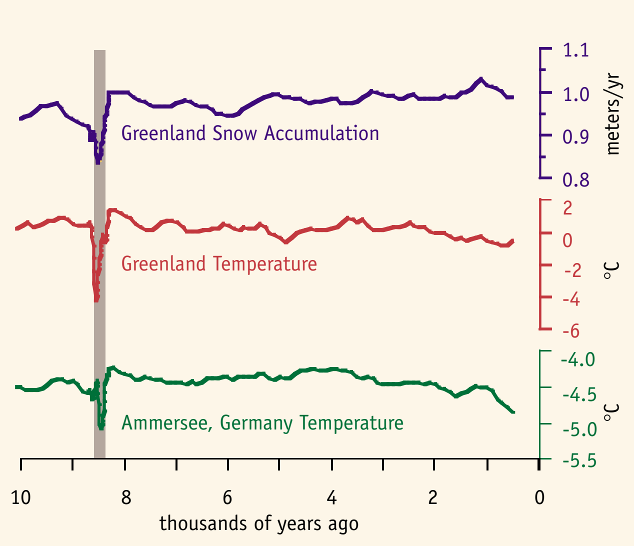


Figure 5 This figure shows snow accumulation and isotopically inferred temperature records in the Greenland GISP2 ice core and a temperature record derived from oxygen isotope measurements of fossil shells in the sediments of Lake Ammersee, southern Germany. These records all show a major climatic instability event which occurred around 8200 years ago, during the Holocene. The event was large both in magnitude, as reflected by a temperature signal in Greenland of order 5 °C, and in its geographical extent, as indicated by the close correlation of the signal in these two locations. The dramatic event is also seen in the methane record from Greenland (not shown here) indicating possible major shifts in hydrology and land cover in lower latitudes.
source: Von Grafenstein et al (1998) Climate Dynamics, 14, 73-81.

Why should societies be concerned about abrupt climate change?

The paleoclimatic record makes it clear that, compared to glacial times, "warm" interglacial climate conditions have prevailed over the last several thousand years. Although there were no large abrupt changes comparable to those of the last ice age during this recent interval, there have been numerous climatic anomalies such as droughts lasting for many decades, for which we currently have no adequate explanation. If such events were to recur in the future they would be catastrophic for modern societies. Understanding why these changes occurred is a critical challenge for future research.

Have rates of climate change predicted for the future occurred in the past?

Recent and predicted rates of hemispheric to global average temperature increase are more rapid than anything seen in the last millennium, while paleorecords of global sea level indicate natural rates of change faster than those predicted for the immediate future. However, this question is not directly relevant to the debate about human vulnerability to predicted climate change. For example, although rates of sea level rise were very rapid indeed at the end of the last glacial period, the direct implications for humans were minimal since there were no large and vulnerable coastal cities. Much slower rates of change would be devastating to human populations today.

A widespread, abrupt climate change 11,600 years ago

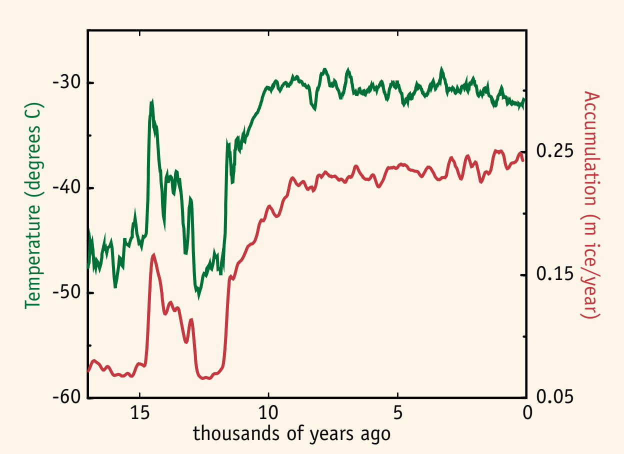


Figure 6 The termination of the Younger Dryas cold event some 11.6k years ago was an abrupt climatic shift. In this record, from Central Greenland, it is manifested as a warming estimated to be as much as 15°C, accompanied by a doubling in annual precipitation volume, that occured in less than a decade. Shown here are accumulation and oxygen isotope (interpreted as temperature) records from the GISP2 ice core for the period between 18 and 10 thousand years ago.
source: Alley, R. et al (1993) Nature, 362, 527-229.

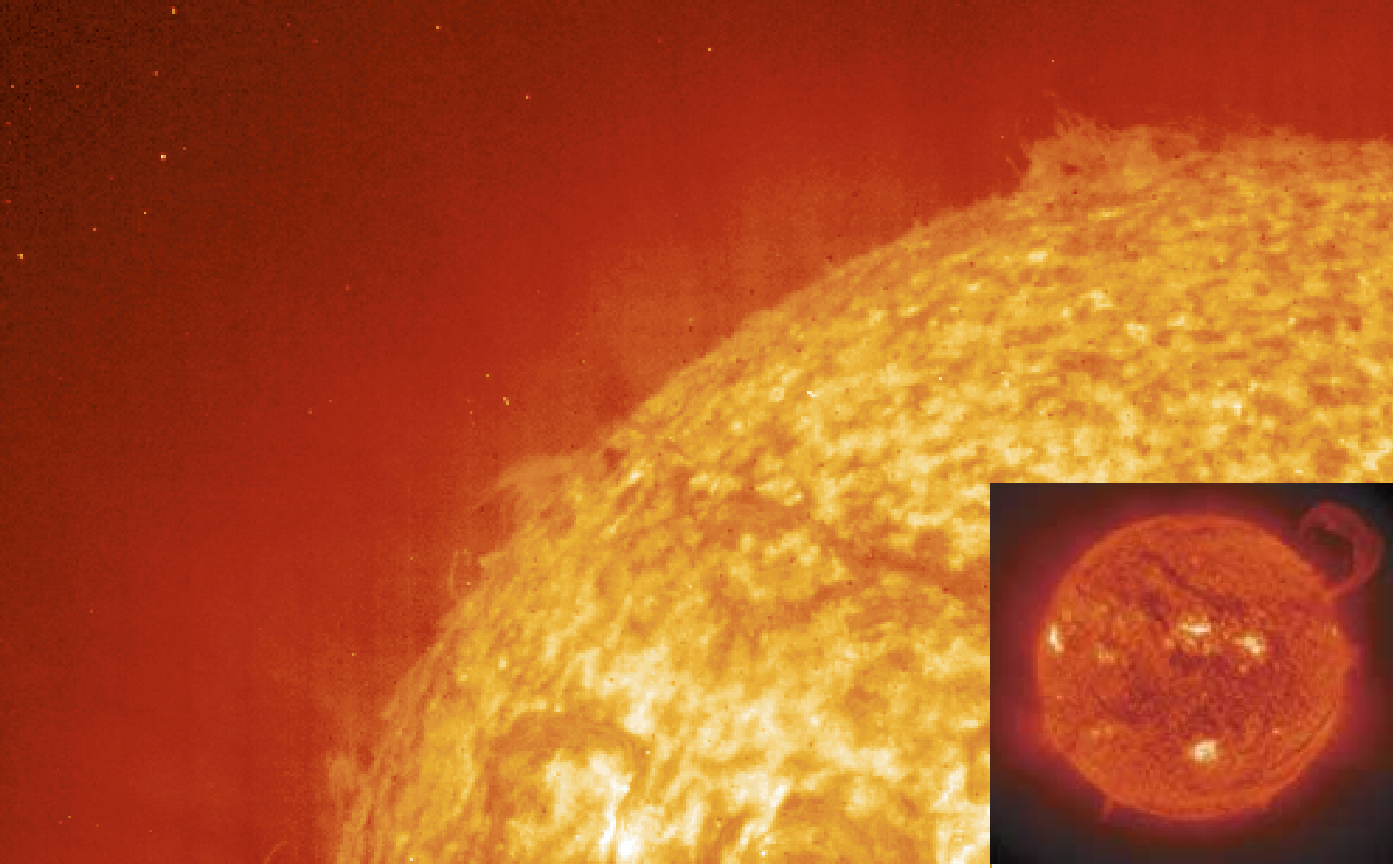


Image of the sun. The hottest areas appear almost white, while the darker red areas indicate cooler temperatures. Relatively minor changes in solar output due to dynamical processes within the sun can have a marked effect on climate.
photo: Solar & Heliospheric Observatory (SOHO). SOHO is a project of international cooperation between ESA and NASA.

Climate Forcing

Variations in the intensity of solar radiation have a significant impact on the Earth's climate. Volcanic eruptions can also influence global climate by emitting gases and dust into the atmosphere. Studying the past helps us to understand climatic responses to changes in forcing and helps to distinguish human and natural influences.

Orbital Forcing

Changes in the orientation and position of the Earth in relation to the sun have caused the distribution of sunlight reaching the Earth's surface to vary over time. These changes (known as orbital variations) are primarily responsible for the cycle of ice ages and interglacials that have repeatedly caused changes in the global environment.

Solar Forcing

Changes in solar activity affect the production of certain isotopes (such as ^{10}Be and ^{14}C) in the upper atmosphere. A record of these changes can be extracted from ice cores and tree rings. Numerous paleo-records show intriguing correlations with these proxies of solar activity suggesting that changes in radiation emitted by the sun can explain some aspects of climate variability. Further research is needed to understand these correlations.

Volcanic Forcing

Explosive volcanic eruptions throw millions of tons of sulfur gases and fine debris into the upper atmosphere where they are swept around the globe by high-level winds. Tree ring records from the boreal treeline of North America and Eurasia reveal the history of these events. Each major eruption led to sharply lower summer temperatures. This reduced tree growth as seen in narrow, dense tree rings for these years.

Hydrological variability linked to solar forcing

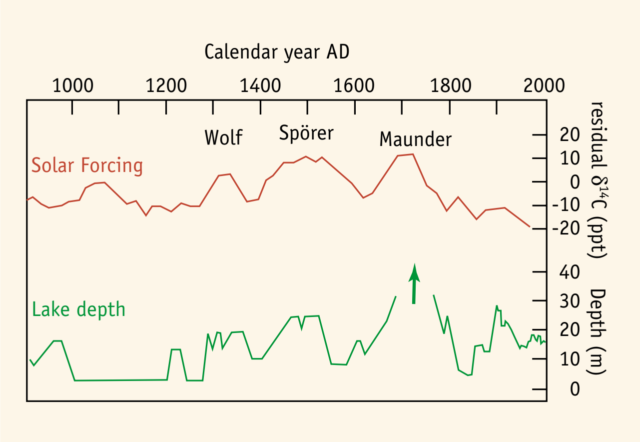


Figure 7 A comparison between the sedimentary record of inferred water depth in the Crescent Island Crater Lake, Ethiopia as an indicator of prolonged drought incidence, and the decadal record of atmospheric ^{14}C production, a proxy for solar activity.

source: Verschuren et al (2000) Nature 403: 410-414.

Modeling natural and anthropogenic climate forcings

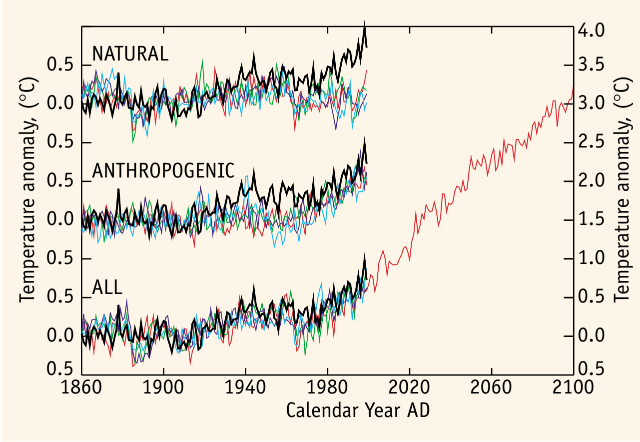


Figure 8 Annual-mean global near-surface (1.5 m) temperature anomalies (relative to 1881-1920) for a series of model experiments (colors) using the U.K. Hadley centre coupled ocean-atmosphere general circulation model. Black line shows instrumental records of the same period. The combination of natural (top) and anthropogenic forcings (middle) employed by the model reproduce the observed decadal to century scale climate variability over this period. The bottom graph shows how well the model reproduces the observed record when both natural (solar, volcanic) forcings are considered together with the anthropogenic effects (greenhouse gases, sulfates). The red line shows future prediction based on greenhouse gas increases from IPCC scenario B2 with no changes from 1999 solar and volcanic forcings.

source: Stott et al (2000) Science 290: 2133-213.

Hemispheric coolings linked to volcanic eruptions

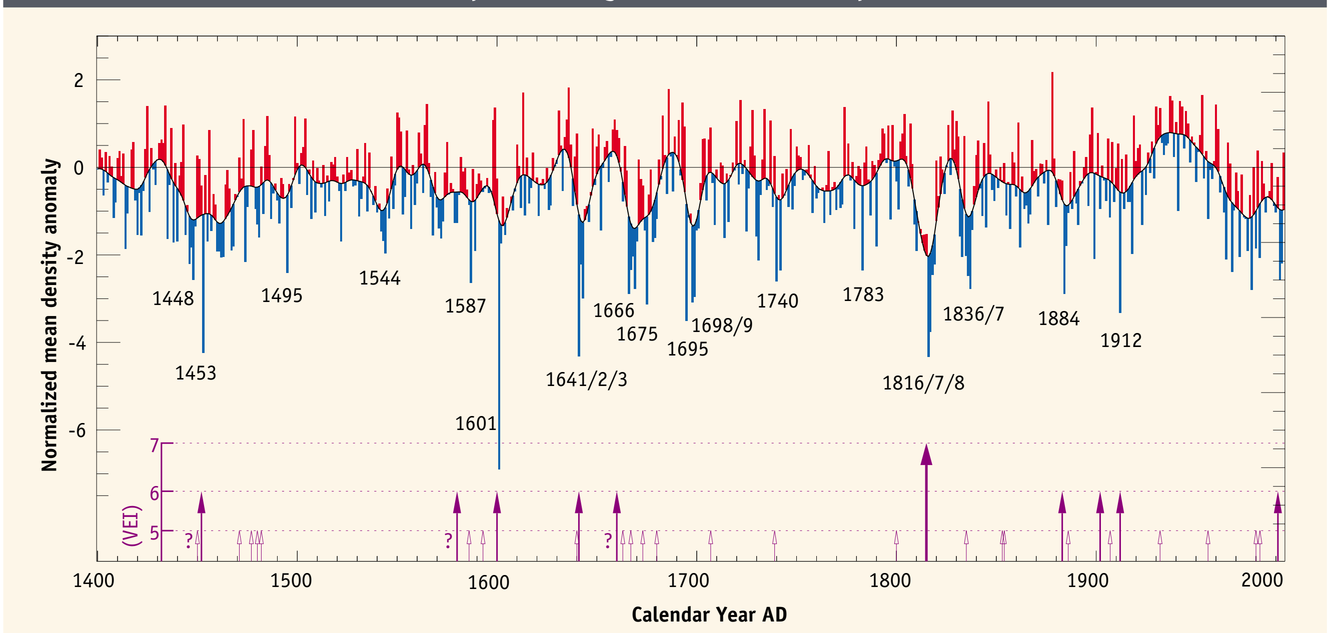


Figure 9 Over the last 600 years, all the known (and several, as yet unidentified) major volcanic eruptions are marked by changes in mean tree ring density (linked to lower spring/summer temperatures) for a set of records covering much of the boreal forest zone in the Northern hemisphere. The Volcanic Explosivity Index VEI is a rough measure of magnitude. Note that most events have an annual impact, but the impact of strong events, as in 1641 and 1816, lasted for several years.

source: Briffa et. al. (1998) Nature, 393, 450-455.

Natural Environmental Variability and Climate Change

Eroded cliffs in the Chinese loess plateau. The natural exposures show paler and darker bands that reflect, respectively, alternations between loess deposition (glacials) and soil development (interglacials). *photo: Barbara Maher*

How does the warming of the last century superimpose on natural climate variation? Average global temperatures had been falling gradually over the past 1000 years due to volcanic activity and variations in solar radiation. However, temperatures began to rise abruptly in the early 1900s and are now at their highest levels for the entire millennium. Similarly, greenhouse gas concentrations are now higher than at any other time in the past 420,000 years.

How have the levels of greenhouse gases in the atmosphere varied in the past?

Bubbles of air trapped in glaciers when snow turns to ice provide an extraordinary history of changes in the composition of the atmosphere. That history now spans some 420,000 years and four glacial-interglacial cycles. At times of maximum ice sheet volume, the so-called glacial maxima, the carbon dioxide (CO_2) content in the atmosphere reached a minimum of about 190 ± 10 parts per million by volume (ppmv), only to rebound in each interglacial stage to levels 50% higher (280 ppmv ± 20 ppmv). Methane (CH_4) concentrations varied in a similar, but not identical, fashion. Low concentrations of some 350 ± 40 parts per billion by volume prevailed during glacial stages while levels twice that high occurred during interglacials. But these trace gas concentrations didn't just march to the beat of the 100,000 year glacial-interglacial metronome. Higher frequency but lower-amplitude variations are superimposed across the full 420,000 year record. The controls on such natural variability are not yet understood, but both marine and continental processes are implicated. Due to human activities, carbon dioxide and methane levels today are much higher than any time in the past 420,000 years and are continuing to rise at an unprecedented rate.

Greenhouse gas concentration reconstruction extrapolated to 2100

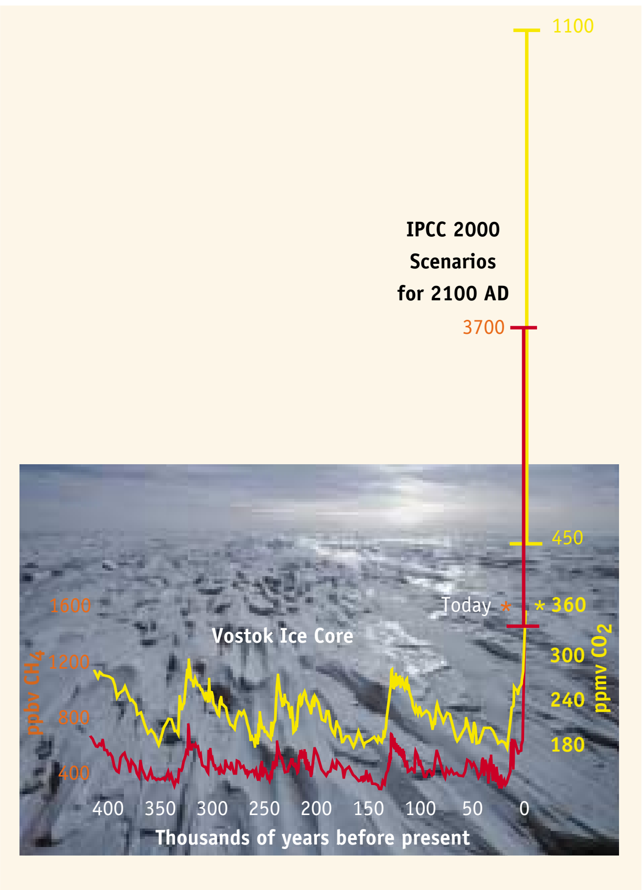


Figure 10 Greenhouse trace gas (CO_2 and CH_4) changes over the last four climatic cycles from the Vostok ice core. The present-day Antarctic values as well as estimates for the year 2100 from the IPCC 2000 report are also indicated.
sources: Petit et al (1999) Nature 399, 429-436 and IPCC 2000 report

Is climate sensitive to greenhouse gas forcing?

Gases such as carbon dioxide and methane absorb infrared radiation emitted from the Earth thereby raising its temperature. During the last four ice ages these greenhouse gas levels have closely mirrored changes in temperature. Numerical models can not reproduce the observed past temperature changes without including the effects of these greenhouse gases.

To what extent was the warming of the last century the result of natural processes?

A wide variety of paleoclimate data - from tree rings, ice cores, banded corals, laminated lake sediments and documentary records – is available year by year for the last millennium.These data demonstrate that northern hemisphere mean annual temperatures gradually fell for most of this period but abruptly increased in the early 1900's. Temperatures then continued to rise, reaching the highest levels of the millennium in the late 20th century. Comparisons with records of changes in solar radiation and explosive volcanic eruptions, as well as modeling studies, show that these factors were responsible for most of the temperature changes prior to the 20th century. However the rate of temperature change over the last hundred years cannot be explained without taking into account the increase in atmospheric greenhouse gases due to human activity.

Was there a Medieval Warm Period?

There is no evidence for a Medieval Warm Period that affected the whole world. There were some particularly warm decades around the North Atlantic and some other regions during the 9th to 14th centuries but they did not all occur at the same time. There were also extended cold periods during those centuries. Current evidence suggests that on a global scale the warmest decades of the Medieval period were not as warm as the late 20th century.

Improving Climate Predictions

Models generate future global climate scenarios, but how reliable are they? One test is to see how well they can simulate past events.

The Marion Dufresne, capable of taking 60 meter long ocean sediment cores, is the principal research vessel carrying out the work of the PAGES marine program, IMAGES.
photo: L' Institut Français pour la Recherche et la Technologie Polaires

Can models used to predict future climate reproduce conditions we know occurred in the past?

One important test of climate prediction models is to check if they are able to reproduce climates of the past.

Although coupled general circulation models (GCMs) at present require too much computer time to simulate climate over a full glacial cycle, selected points in time have been modeled. These experiments have had mixed success in matching paleoclimate data available for the same periods. Model-data discrepancies made apparent in these experiments have often led to improvements in model development, for example including dynamic biospheric feedbacks in order to properly capture the enhanced mid-Holocene African monsoon.

Both GCMs and more simple models have only been able to reproduce plausible millennial scale climate events such as the Younger Dryas when forced with fresh water input in the North Atlantic. Using the same models, some of the physical processes that are involved in such rapid changes have been shown to be potential consequences of future warming.

GCMs have been able to reproduce instrumental records of global average temperature changes of the last 100 years with reasonable accuracy (see figure

8, page 14). Attempts to extend such experiments to the last 1000 years and compare with multi-proxy global climate reconstructions are currently underway. Intermediate complexity models have reconstructed the mean annual, northern hemisphere average temperature of the last millennium with reasonable accuracy. In these experiments, the warming of the last century is achieved only when enhanced greenhouse gas levels due to human activities are included.

1000 year record of global average temperature

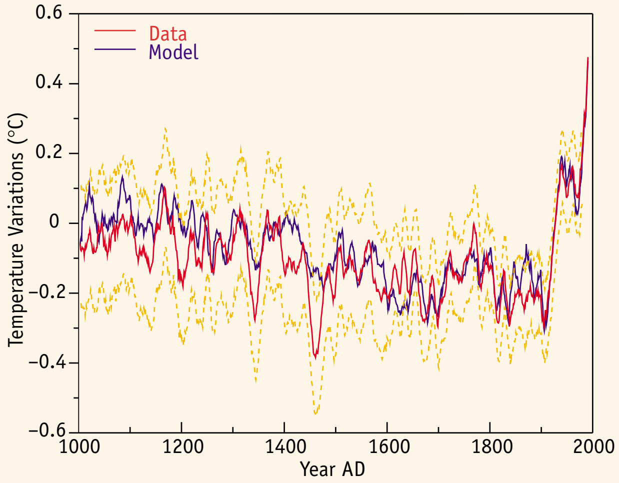


Figure 11 Comparison of decadally-smoothed Northern Hemisphere mean annual temperature records for the past millennium and an energy balance model calculation employing both natural forcing and recent greenhouse gas level increases. The dashed yellow lines define the upper and lower boundaries of the 95% confidence interval.

sources: Crowley (2000)Science 289:270-277.

Modeling the Younger Dryas climate event

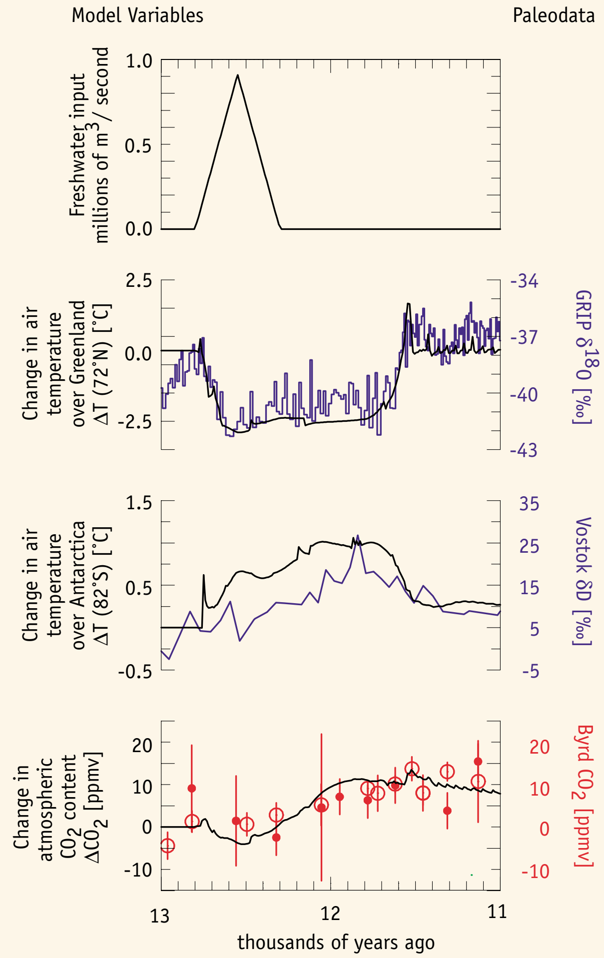


Figure 12 A simulation of the Younger Dryas cold event using a simplified climate-carbon cycles model. Model results (black lines) are compared with several different paleo proxydata records from northern and southern hemispheres (colors).

source: Stocker and Marchal (2000). P.N.A.S., 97, 1362-1365

How has El Niño activity changed over time?

Annual growth bands laid down by corals provide rich archives of paleoclimatic information. Changing proportions of the stable isotopes of oxygen in the calcium carbonate layers, along with variations in the relative abundances of such elements as strontium and calcium are used to assess past temperature and salinity of the near-surface waters in which the corals grew. These show that the frequency of El Niños in the tropics has changed through time. This has global implications because El Niños affect worldwide weather patterns.

El Niños are marked by widespread warming of the surface waters in the eastern equatorial Pacific, intensified rainfall and the collapse of fisheries off the coast of Ecuador and Peru, the northward penetration of warm surface waters along the western coast of North America, and drought in Indonesia and northern Australia. Annual coral records show that El Niño events prior to the 20th century recurred less frequently than in the last 100 years. Since instrumental records are too short to capture this shift, paleo information is critical to illustrate the full range of variability.

A compelling question remains: how will El Niño vary in the future, given global warming? Understanding the longer-term natural variability of such events is crucial to meeting this challenge.

Reconstruction of the North Atlantic oscillation

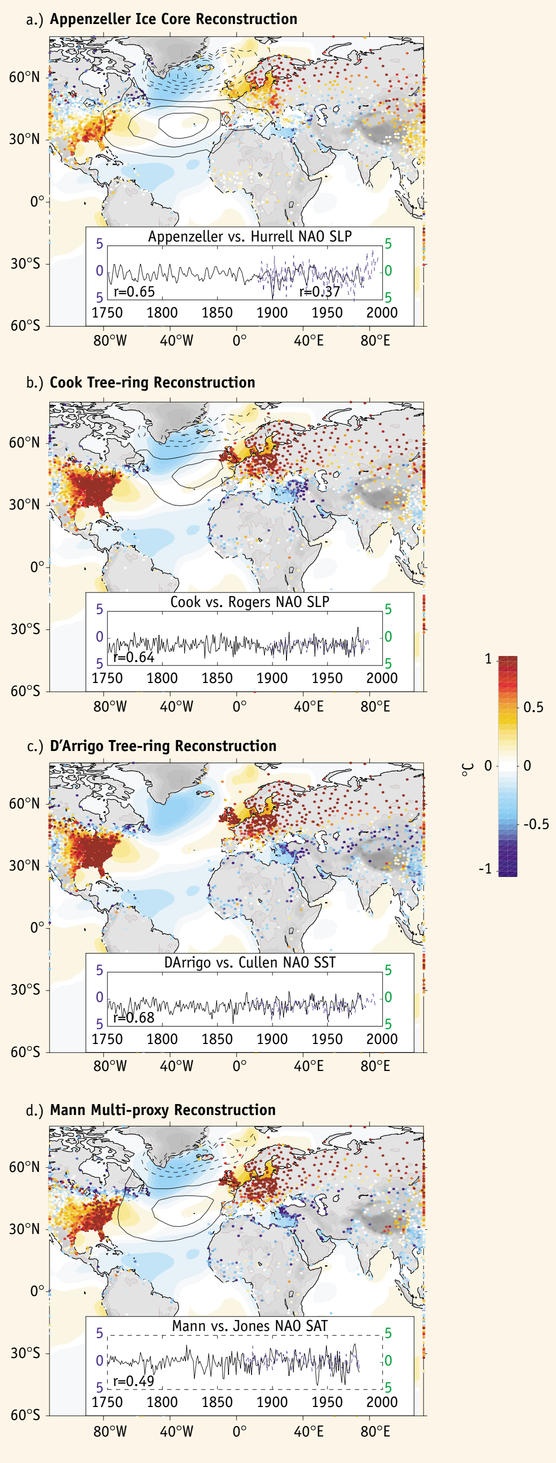


Figure 13 Spatial maps of winter sea level pressure, sea surface temperature , and surface air temperature showing the response to a large change in four different proxy based indices of the North Atlantic Oscillation. Multiproxy records successfully capture the spatial expression of the North Atlantic Oscillation, and extend records of this oscillation back in time before the period of instrumental records.

source: H. Cullen et al (2001) paleoceanography, 2, 27-39.

Changing El Niño recurrence frequency

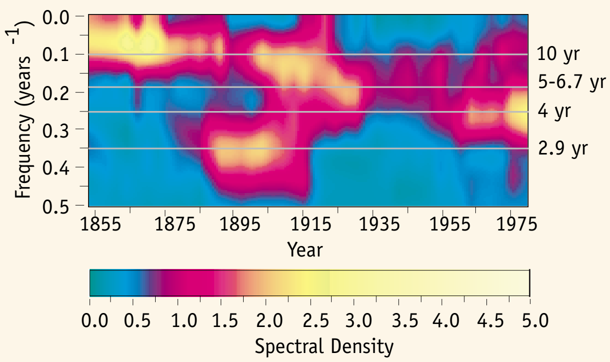


Figure 14 Evolutionary spectral analysis of sea surface temperature estimates as recorded in a coral from Mariana atoll in the equatorial Pacific Ocean. Colors show how sea surface temperatures (related to El Niño/La Niña conditions) have varied over time. In recent years, this oscillation has been centered on a 4 year period, but in the 19th century the oscillation occured only once every 10 years. The shift from low to high frequencies took place early in the 20th century. Predicting the frequency of El Niño in the future requires that we have a long perspective on how (and why) this system has varied in the past.

source: Urban et al (2000) Nature, 407, 989-993.

Changing El Niño teleconnections.

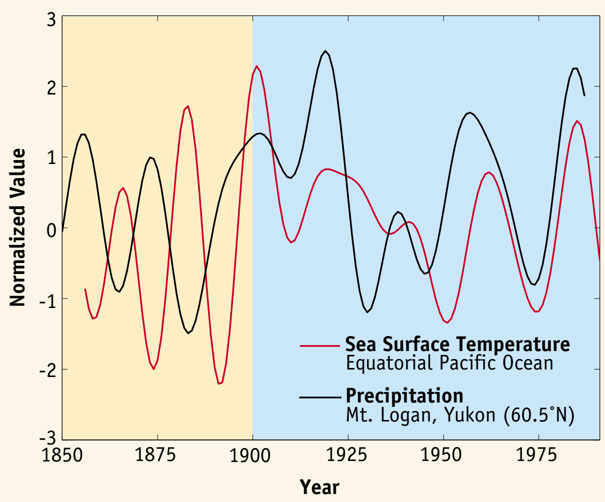


Figure 15 A smoothed record of reconstructed sea surface temperature in the tropical Pacific, and precipitation recorded in an ice core from Mt. Logan in the Canadian Yukon. The two records are highly correlated, providing an example of the climatic sensitivity to conditions in the Tropics far away in the extratropics. Previous to 1900 (tan background) the records are anti-correlated, while after 1900 (blue background) they match. This shift in the climate connection highlights the difficulties of both future regional climate predictions and past regional climate reconstructions that rest on the assumption that climatic teleconnection patterns have remained the same over long periods of time.

source: Moore et al (in press) G.R.L.

Hydrological Variability

Studies of the past reveal regional flooding and drought episodes significantly more severe and longer lasting than anything experienced in the past 100 years. Irrespective of global warming concerns, there is no reason to believe such events will not also occur in the future.

Monsoon flooding in Southeast Asia. The Asian monsoon system has changed dramatically in the past. Reconstructing and understanding past changes in monsoon dynamics is important in order to develop predictive capabilities.
photo: CLIVAR Project Office

How have the frequency and persistence of droughts varied in the past?

Profound, persistent droughts are one of the most devastating hazards faced by human societies. Lake-level reconstructions coupled with oral and documentary evidence show that civilizations in equatorial East Africa flourished during three main wet episodes of the last millennium but sharply declined during intervening dry periods (see figure on page 27). In central North America, compilations based on tree-ring records indicate that decade-length droughts occurred about once every 500 years over the last two millennia. Shorter more extreme droughts defined by paleo reconstructions appeared once or twice a century over the past 300-400 years, most recently in the 1930s and 1950s when exceptionally dry conditions prevailed on the southern Great Plains of the U.S.A. (fig. 16 p.21).

Such dry periods are linked to global-scale climate variations. Low-frequency changes in sea-surface temperatures, evaporation rates and patterns of water vapour transport underlie persistent historical drought conditions on the continents. The full range of past natural drought variability suggests that droughts more severe than any observed last century are likely to occur in the future.

How have rainfall patterns changed in the past?

Images of animals on rocky outcrops in the Sahara (page 22) reveal that dramatic environmental changes have occurred in this region over the last 20,000 years. Between 5,500 and 15,000 years ago it was considerably wetter, enabling a savanna ecosystem to exist. Giraffes, elephants, antelopes, ostriches and a wide array of other species lived in the area. Agricultural activities were also possible; domestic cattle were raised and fishing took place in lakes and rivers. Today, in this utterly arid environment it is hard to imagine such activities, yet prehistoric rock art and sedimentary deposits from extensive lakes vividly testify to the dramatic changes in climate that have taken place over this relatively short period of time.

Holocene lake level changes in Northern Africa

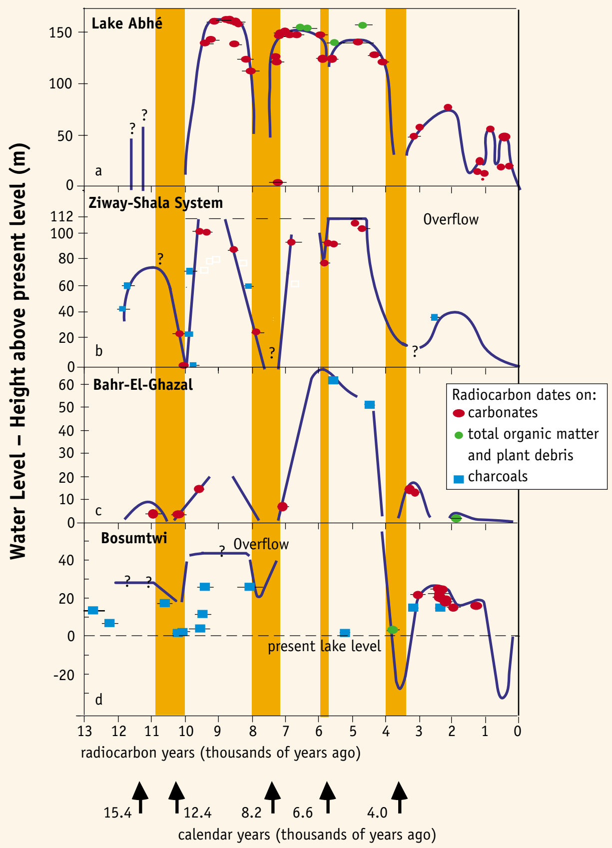


Figure 17 Changes in lake level over the past 15,000 years in an east to west transect of lakes in the northern monsoon domain of Africa. During this period lake level variations have been as much as 100 meters, indicating enormous changes in the regional hydrological balance.

source: Gasse (2000) Q.S.R. 19, 189-211

Multiyear drought reconstructed from tree rings

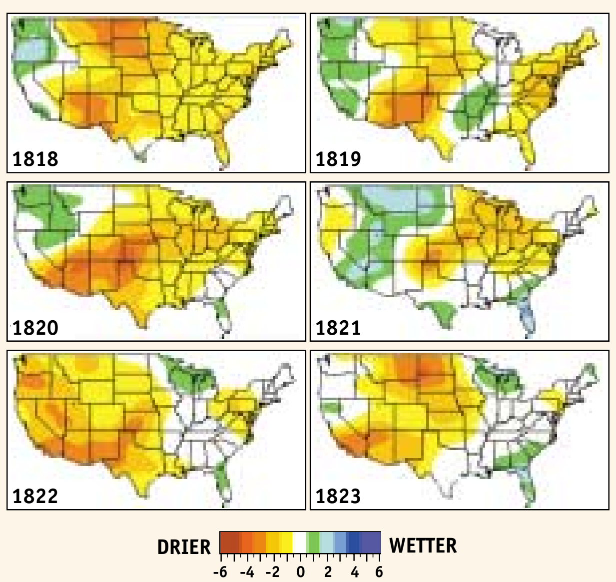
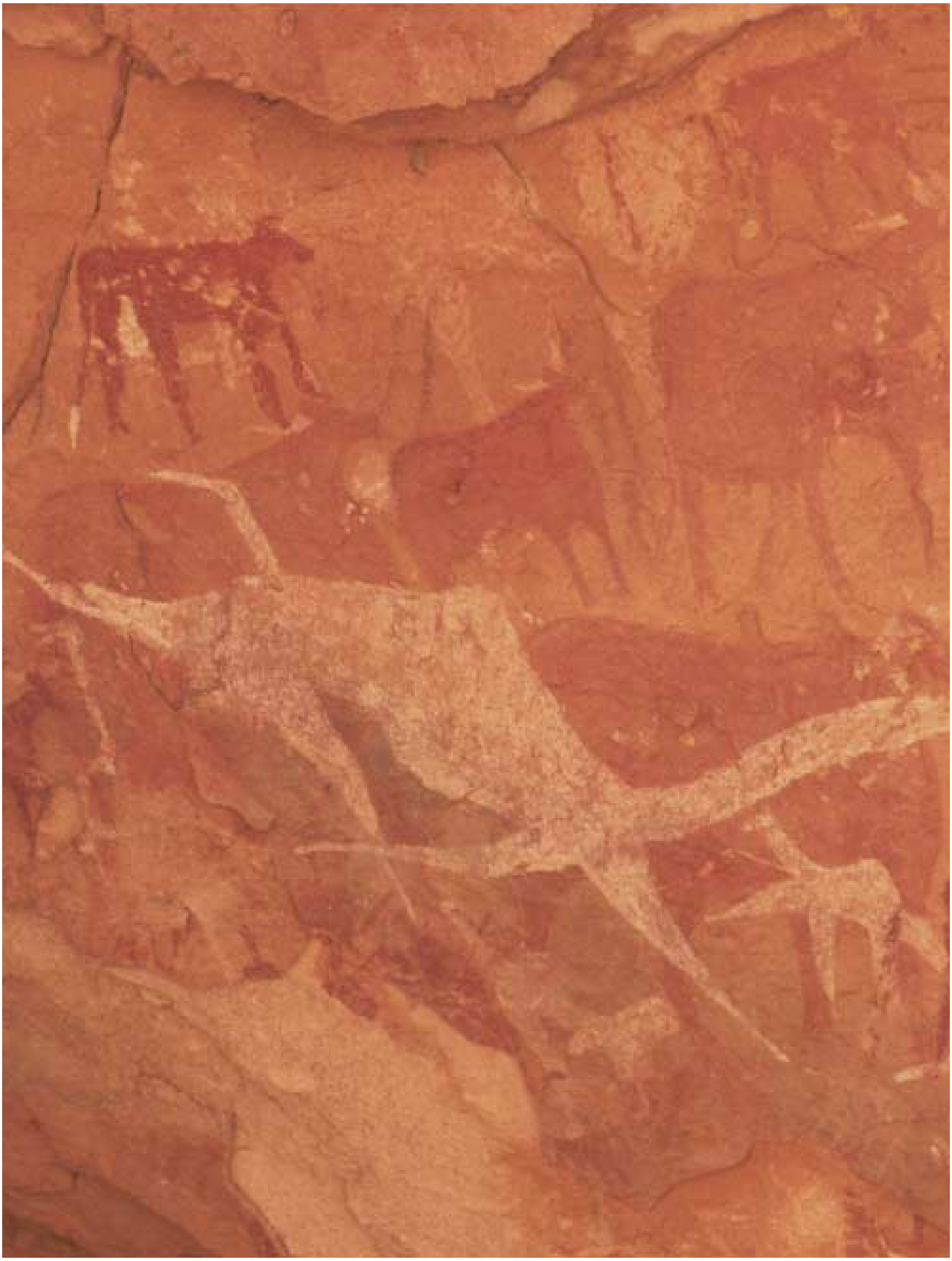


Figure 16 A severe drought occurred through much of the central USA for several years centered around 1820. The extent and severity of the drought was significantly greater than the dustbowl of the 1930s and is represented here using reconstructions based on tree ring data.

source: Cook et al (1998) NOAA NESDIS drought variability. http://www.ngdc.noaa.gov/paleo/drought.html

Have there been persistent failures of the Indian monsoon?

Ice core records from the Himalayas show pronounced variations in atmospheric dust that signify failures of the monsoon rains over northwest India during the last millennium. For example, extreme drought began abruptly in 1790 and persisted until 1796. Historical records confirm that more than 600,000 people died as a consequence. This unusual episode was unprecedented in at least the last 1000 years, though other less extreme drought periods are recorded in the ice cores. Understanding why such events occurred, and how they relate to climatic anomalies elsewhere in the world is a challenge for future paleoclimatic research.



Rock art from the Ennedi in NW Chad. These rock paintings of domesticated cattle in a currently arid region illustrate humid conditions during the early and middle Holocene. Particularly interesting here is that late Holocene drier conditions are indicated by superposed camel drawings, which are less than 2000 years old.
photo: Stefan Kroepelin

Ecosystem Processes

Both past climatic changes and ecosystem responses to these are recorded in the paleorecord. Understanding such interactions, together with the increasingly important systemic changes due to human activities, provides the key to predicting likely future changes to ecosystems.

The Cape Floral Kingdom in southwestern South Africa is the smallest floral kingdom in the world, covering approximately 90,000 square kilometers, with approximately 8,600 species of plants. Of these, 5,800 species are endemic to the region. Understanding the basis for the persistence of this unique and diverse ecosystem is part of the key to ensuring its future survival. Four fifths of the vegetation in the Cape Floral Kingdom is composed of Fynbos, shown here with *Ericaceae*, *Proteaceae* and *Restionaceae*.
photo: Percy Seargeant Memorial Collection, Janet Allsopp

How fast have ecosystems responded to past climate changes?

Plants and animals respond as individuals to climate change, not as coherent communities or ecosystems. In this way, ecosystems have often re-constituted themselves through time in response to environmental stress. Evidence from the latest period of rapid climate warming, at the end of the last glaciation, shows that in some areas, for example the Swiss Alpine region and Western Norway, the initial responses involved replacement of species and whole communities over a few decades at most. However, this does not imply attainment of an equilibrium state or the establishment of globally climatically adapted ecosystems. Results from Northern Sweden show that during the same period, establishment of forest ecosystems lagged behind temperature changes by up to two thousand years, depending on altitude. Although past climate changes are marked by disruptions of ecosystem composition, the responses vary greatly from species to species and between different types of ecosystem. In more recent times, the impact of human activities on many ecosystems has been both to fragment and to impoverish. These changes are likely to exacerbate the disruption of ecosystem function and complicate understanding of ecosystem response to future climate change.

Can biota adjust to ongoing and projected rates of climate change?

The rate and magnitude of projected climate change will cause major disruptions of present-day ecosystems and species distribution. Individual species, for example, will need to shift their ranges at rates that are 10-40 times faster than has been observed since at least the last ice age if they are to maintain equilibrium with projected climate changes. It seems unlikely that such adjustments will be possible given the presently fragmented nature of most landscapes. In light of these potential lags in the biotic response to climate change, ecological instability and the occurrence of natural disturbances, like wildfires, will probably increase.

To what extent have past ecosystem changes affected climate?

Most of the evidence for climate feedbacks from the terrestrial biosphere comes from model simulations and data-model comparisons. Model simulations often best match paleodata when feedbacks from vegetation and soils are included. The rapid pace of warming at high latitudes in Eurasia at the end of the last glaciation, for example, involved changes in the amount of solar energy reflected into space associated with the transformation of land cover from permanent snow to soils and forests. The maintenance of vegetation in the Sahara several thousand years ago also probably involved climatic feedbacks. The vegetation seems to have been a crucial element in driving the climate to a state which then supported more vegetation. In more recent times, some feedbacks may have resulted from deforestation as demand for pasture and farmland has increased.

Multiproxy climate reconstruction and ecosystem response

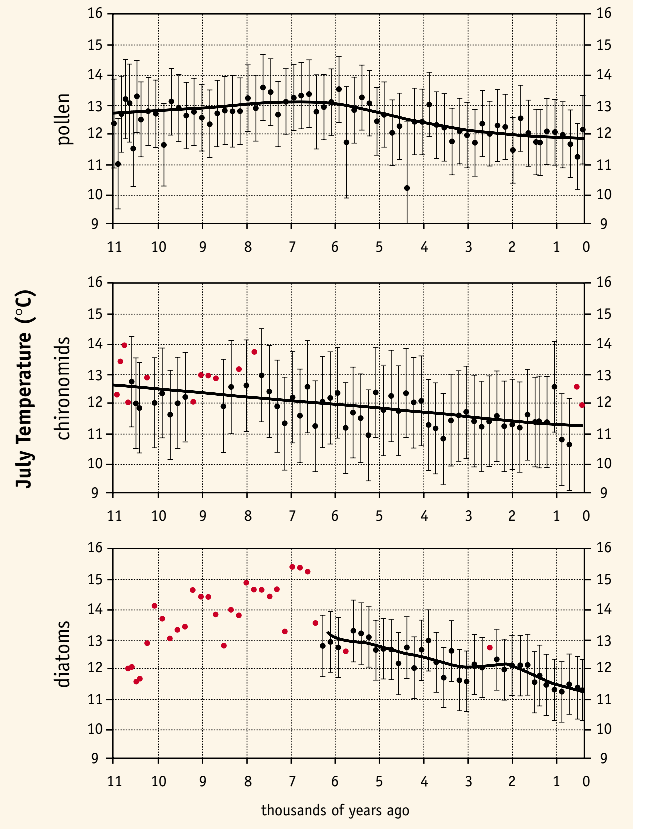


Figure 18 Multi-proxy reconstruction of temperature using pollen, chironomid and diatom transfer functions developed in Northern Scandinavia. Both pollen and chironomid surface temperature estimates are within 0.1°C of the measured temperature. The red circles indicate communities without any modern analogue. Although the temperature decrease was subtle through the Holocene, diatom communities sharply changed after 6000 years ago. Chironomid assemblages also varied through time with non-analogues periods after deglaciation. The striking non-analogues for chironomids in the two most recent levels might indicate changes of communities following fish introduction by humans.

source: Bigler et al (submitted) The Holocene

Human Impacts

An excavated sample of residential occupation (600 m^2) within the lower town of Tell Leilan, northeast Syria (100 ha). During the terminal Akkadian empire occupation, abrupt climate change (ca. 2200 B.C.) recorded in sediment cores from the nearby Gulf of Oman (figure 19 p. 27) forced the Akkadian abandonment of rain-fed agriculture plains of northern Mesopotamia.
photo: H. Weiss

Paleorecords show that extreme variations in climate are a natural part of the Earth System. Human societies have collapsed due to such variations in the past. Today high population densities, over-reliance on limited resources, and global warming, mean many societies are more vulnerable than they were in the past.

How have past climate changes affected human societies?

Archeological records from around the world provide many examples of flourishing societies that abruptly collapsed. In some cases, the paleo-record indicates that these events were related to sudden and persistent environmental changes. For example, the rapid demise of Akkadian civilization (in what is today Syria) around 4,200 years ago is associated with the onset of an unprecedented dry episode. This is clearly seen as a dust increase in marine sediment cores from the Gulf of Oman. Other records indicate this change in climate was registered over a vast area, from North Africa to Tibet.

Prolonged drought is also implicated in the collapse of other cultures, such as the Maya in Central America around A.D. 800. With the rapid growth of world population over the last century, and the severe exploitation of ground and surface water resources, modern society is increasingly vulnerable to persistent climate anomalies.

Will society be more vulnerable to environmental changes in the future?

The paleo record provides insight into past rates of environmental change and system responses. Much of society's infrastructure (such as dams, drainage systems and coastal defences) are designed for extremes that are based on the limited perspective provided by short instrumental records. Paleoenvironmental records extend such perspectives into the past, providing important insights into concepts such as the probability of "hundred year floods" or the likely extent of coastal flooding from severe hurricanes. However, at the end of the 20th century, the vulnerability of societies to environmental changes is rapidly increasing. More and more people are affected by natural disasters every year. Areas with high population densities and limited resources (including fresh water), and regions with sensitive ecosystems are under threat from both environmental degradation and climatic changes. This is especially so in those regions that are already susceptible to environmental extremes such as urban areas in hazard-prone settings, low-lying coastal zones and river flood plains, and steep mountain regions. The combination of additional population pressure and increasing property values, at a time of rapid global climate change may be catastrophic for many natural and human systems.

Will there be technological solutions to the consequences of future climate change?

Human ingenuity cannot be underestimated or predicted. Societies have repeatedly demonstrated the ability to develop technologies to help adapt to external changes and to ameliorate their environment. However, for many societies, future environmental changes are likely to be larger than they have encountered for thousands of years. Technological adaptations are likely to be targeted towards relieving local symptoms of an evolving Earth System, not to the underlying changes themselves. Furthermore, such technological adaptations will be expensive. Thus, technological fixes to environmental problems associated with future climate change are likely to be of limited benefit, and only relevant to a very small percentage of the world's population. Technology is unlikely to provide a panacea for human vulnerability to future climatic and environmental change.

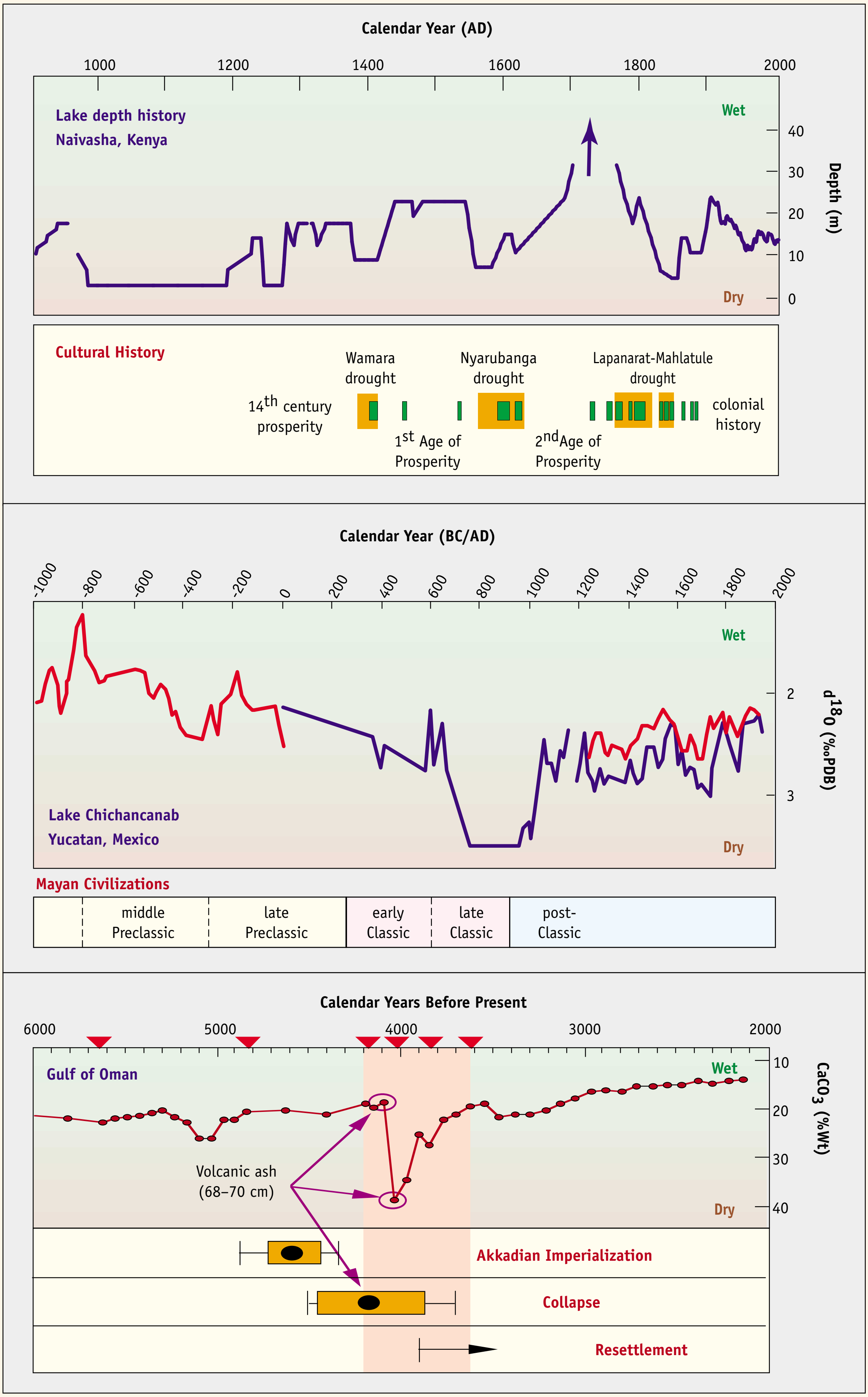
How can ecosystem responses to past climate variations help us to anticipate responses to future changes?

Policies designed to sustain ecosystem goods and services should be based on knowledge of ecosystem responses to past climate variability. Paleo-archives document ecosystem responses to changes in the magnitude and frequency of extreme events as well as changes in mean climate. At the very least, plans for sustainability should be designed in light of the full range of regional climatic and hydrological variability revealed in the paleo-record over the last few centuries. Of particular concern are past changes in hydrological regimes, the consequences of which take on increasing significance as human pressure on water resources grows.

Figure 19 Three examples of paleo-records where the combination of environmental and cultural history, coupled with rigorous chronological constraints points to a strong link between the incidence of drought and the collapse of human cultures. In the upper graph, changing lake level in equatorial East Africa has been inferred from the well-dated sediment record. The dips in lake level indicate periods of partial desiccation. Over the last six centuries, each dip coincides with droughts that had severe consequences for human societies in the region. In the middle graph, drought in Yucatan, Mexico is inferred from changes in the stable isotope ratios found in fossil shells from two different species of ostracod (red and blue lines), preserved in lake sediments. The persistent drought around AD 850 coincides with the collapse of Mayan Civilization. In the lower graph, the steep fall in carbonate percentage in the marine core represents a major episode of dust deposition that can be directly linked to drought conditions in the nearby region of the Akkadian Empire. The marine and archaeological records can be precisely synchronized by a volcanic ash layer found in both. The episode of drought can thus be shown to coincide with the Akkadian collapse.

sources (top to bottom): Verschuren et al. (2000). Nature 403: 410-414; Hodell et al. (2001) Science 292: 1367-1370; Cullen et al (2000) Geology 28(4): 379-282.

Past societal collapses



About PAGES

The research community that lies at the heart of the PAGES project works towards a better understanding of the Earth's changing environment in the geologically recent past, focusing always on those aspects that best inform our evaluation of current and future global changes and their consequences for human populations.

Frequently, archives that are the most sensitive recorders of climate change are located at the margins of their ecological ranges, or at environmentally stressed sites within their ranges. This is the case for these foxtail pines, located near alpine treeline in the Sierra Nevada Mountains, California, where their growth is strongly influenced by the harsh climate.
photo: Anthony Caprio

Integrating international paleoclimate research

PAGES programs are structured to bring researchers from a variety of disciplines and countries together to work on common themes. These are designed to erase constraints imposed by geography and artificial disciplinary boundaries like those that commonly separate physical oceanography from continental paleoecology or archaeology from historical meteorology. The PEP (Pole-Equator-Pole) programs, for example, are stimulating the direct exchange of information among marine and terrestrial scientists, anthropologists and archaeologists, all of whom are working to decipher environmental history along North-South geographic transects. PAGES has built bridges with other major scientific programs including the World Climate Research Program on Climate Variability and Predictability (CLIVAR), which focuses on modern climate change, and the Global Marine Ecosystems Study (GLOBEC), a core project of the International Geosphere Biosphere Programme, through which the relationships between ecosystem variability and fisheries are being explored. Through such intersection activities, PAGES injects the historical context into modern process studies.

Fostering development of paleoclimate data archives

Internationally accessible data archives provide a primary foundation for paleoclimatic research. PAGES recognized the value of such data libraries at its outset and was an important early supporter of the World Data Centre-A in Colorado. The WDC-A is now a key source of paleoclimatic information that is made freely available to scientists across the globe. PAGES continues to encourage the development of easily accessible relational paleoclimate databases, most recently the PANGAEA initative in Kiel, Germany. Future progress in understanding climate history will depend increasingly on the provision of well-documented data by such centres to their regional communities. The science-packed PAGES Newsletter is sent free of charge to 70000 subscribing scientists in more than 70 countries. Such wide distribution coupled with active solicitation of information that has often been published only in regional journals or in a language other than English has made the PAGES NEWS an important vehicle for the dissemination of research results in countries with limited access to western journals.

Encouraging North-South research partnerships

PAGES strives to include scientists and students from less-developed countries in international paleoclimate research initiatives. A number of approaches are used. PAGES supports the attendance of active young scientists at key conferences and summer schools when their national funding agencies are unable to do so. Scientific proceedings volumes are made available free of charge to libraries in less-developed countries. Scientists from Asia, Africa and South America sit on the PAGES Science Steering Committee and act as liaisons with their regional communities. In this role, they distribute information and nominate members of their respective communities, particularly young scientists, for membership on international scientific committees.

Spheres of PAGES interest

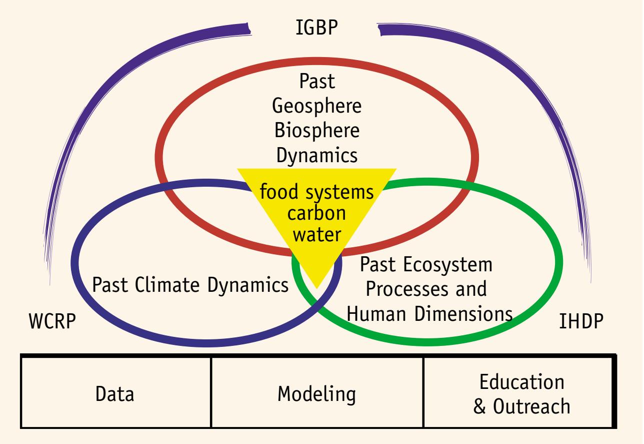


Figure 20 The PAGES research agenda is more than paleoclimate. It explicitly identifies the need to improve understanding of geosphere-biosphere changes at the global scale and to link human-environment interactions with studies of ecosystem processes. This schematic provides a simple visualization of the overarching themes that express:

- the major research areas with which the PAGES community is concerned
- the way these overlap and link into the three emerging cross-cutting theme on food carbon and water shared by the major global change programs
- the main areas of interaction with not only IGBP, which spans all the themes to a major extent, but also WCRP and IHDP
- the under-pinning and cross-cutting aspects of PAGES research that are essential to the success of the whole enterprise.

web addresses

http://www.pages-igbp.org

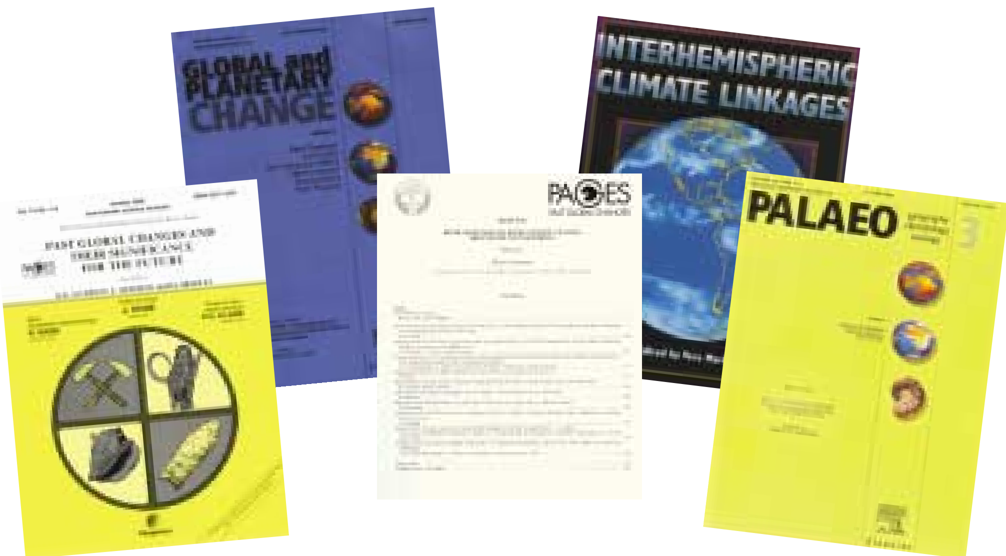
http://www.ngdc.noaa.gov/paleo/paleo.html

Access to paleo data and information

One major PAGES task is to provide easy access to paleodata and information about paleoarchives. This information is available through the web site (http://www.pages-igbp.org). The site is modified regularly and includes new products, databases, science highlights, upcoming events and general information on paleoarchives.

A set of overhead view graphs is available to download from the website. These overheads are regularly used by scientists for educational and public outreach lectures. The overheads are sent free of charge to scientists in developing countries who are unable to download and print them from the website.

Another PAGES forum for communication is our newsletter. PAGES NEWS is produced three times a year and sent free of charge to 3000 subscribing scientists in more than 70 countries. Such wide distribution, coupled with a high degree of proactive submission by the research community, has made the newsletter an important vehicle for the dissemination of research results and program news, especially in countries with limited access to western journals.



PAGES strongly encourages publications in the peer reviewed literature as a result of its scientific activities. An exhaustive list of publications which have come about in part due to PAGES activities is difficult to construct because of the inclusive nature of the PAGES organization. However, some examples of recent books and special journal issues which are directly attributable to activities organized and supported by the PAGES program are listed in Further Reading.

Alverson, K., R.S. Bradley and T. Pedersen eds. (in preparation). *Paleoclimate, Global Change and the Future*, IGBP book series, Springer Verlag.

Battarbee, R.W., Gasse, F. and Stickley, C.E. eds (in prep.) *Past Climate Variability through Europe and Africa,* Developments in Paleoenvironmental Research book series, Kluwer.

Mix, A.C. et al eds (in press) *Environmental Processes of the Ice age: Land, Oceans, Glaciers* (EPILOG), Quaternary Science Reviews.

Markgraf V. ed. (2001), *Interhemispheric Climate Linkages,* Academic Press, 454 pp.

Alverson, K., F. Oldfield and R.S. Bradley eds. (2000). *Past Global Changes and their Significance for the Future*. Quaternary Science Reviews 19:1-5, 479pp. [Also available hardbound].

Ammann, B. and F. Oldfield eds (2000) *Biotic Responses to Rapid Climatic Changes Around the Younger Dryas.* Paleo geography climatology ecology, 159:3-4, 366 pp.

Kroepelin, S. and N. Petit-Maire eds (2000) *Paleomonsoon Variations and Terrestrial Environmental Change During the Late Quaternary.* Global and Planetary Change, 26:1-3, 316pp.

Andres, W. and T. Litt eds (1999) *Termination I in Central Europe.* Quaternary International 61:1-4, 72pp.

Dodson, J.R. and Z.T. Guo (1998) *Past Global Change.* Global and Planetary Change, 18:3-4, 202pp.

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Cover Photo: The extent of ice cover on Mt. Kilimanjaro decreased by 81% between 1912 and 2000. In 1889 when Hans Meyer first climbed Kibo (elev. 5,895m), the crater rim was nearly encircled by ice. Today only a small fraction of this ice remains; this block, with banding associated with annual cycles clearly visible, lies between the Eastern and Northern Icefields. [credit: Douglas R. Hardy]

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