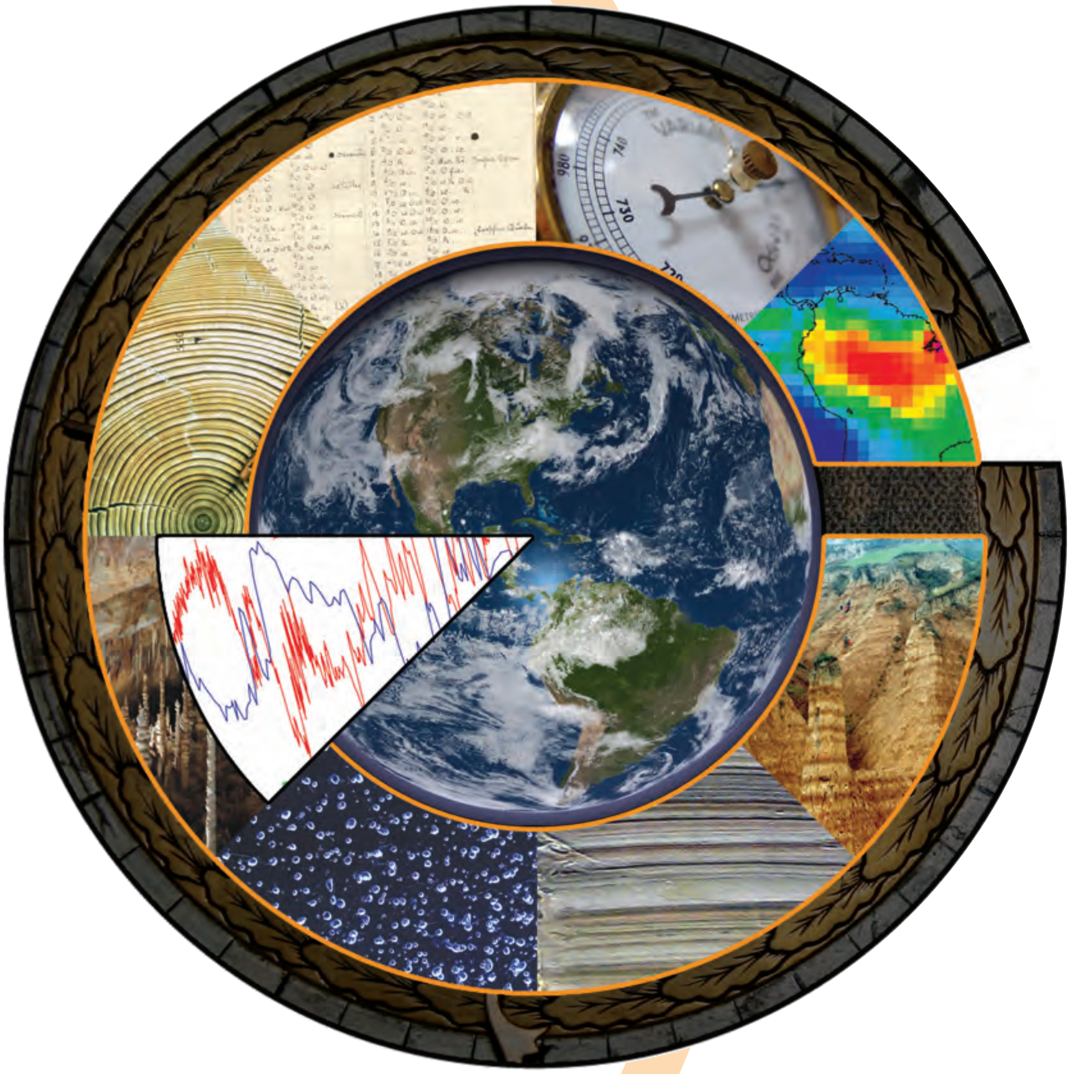
PAGES
PAST GLOBAL CHANGES

IGBP Report 57

Past Global Changes



Science Plan and Implementation Strategy

GLOBAL IGBP CHANGE

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Front Cover Image

The front cover illustration depicts images of various sources of global change information, placed within the PAGES logo. The positioning of these images represents the temporal coverage addressed by PAGES science, from millions of years (represented here by sediments) through to the modern day (instruments) and to future projections (models). Models in return are applied to and tested against past scenarios, hence closing the loop between the projection of future global change and reconstruction of the past.

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Preface

The PAGES Science Plan and Implementation Strategy defines the scientific objectives and key research issues of the Past Global Changes project of the International Geosphere-Biosphere Programme, and outlines a strategy for addressing them.

The ideas represented here were crystallised over the last 4 years from feedback provided by the palaeoscience community, from discussions that took place at the PAGES 2nd Open Science Meeting and subsequent annual Scientific Steering Committee meetings, and from issues raised in the 4th Assessment Report of the Intergovernmental Panel on Climate Change.

The Science Plan emphasises the importance of integrative scientific approaches and collaborations in order to successfully investigate connections in the Earth System in the past and to make sound projections for the future. It is intended for paleoscience researchers and potential sponsors, as well as for the wider Earth System Science community.

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Contents

Executive Summary

Past Global Changes (PAGES) was founded in 1991 as a Core Project of the International Geosphere-Biosphere Programme (IGBP), and has been jointly supported by the Swiss and U.S. National Science Foundations, and the National Oceanic and Atmospheric Administration (NOAA) since 1992. Since the end of 2008, PAGES has also received in-kind support from the University of Bern, Switzerland, where the PAGES International Project Office is located.

PAGES was set up, not as a research institution, but as an international effort to coordinate and promote past global change research. The aim is to identify the cutting-edge questions in palaeoscience and the high-priority research needs, and to ensure that they are addressed in a coherent manner. In addition, capacity building, education and outreach are an integral part of PAGES philosophy. PAGES is therefore a service-oriented project that works to promote integrative research activities and support the international palaeoscience community through fostering collaboration and communication, and ensuring access to and dissemination of results, data, and other relevant information. This is achieved by means of international workshops and conferences, educational products and outreach activities, publications, including the PAGES newsletter, and the PAGES website.

The ultimate objective underlying all of PAGES efforts is to address past changes in the Earth System in a quantitative and process-oriented way in order to improve projections of future climate, environment and sustainability.

In working towards this objective in the coming years, PAGES will target four sets of key overarching questions, within four *Foci*, each divided into a number of *Themes*. The goals of the Foci are addressed by *Working Groups* that target specific aspects of the scientific scope.

Focus 1: Climate Forcings

This Focus fosters activities that aim to produce improved, extended, and consistent timeseries of climate forcing parameters, both natural and anthropogenic, including solar insolation and irradiance intensity, volcanic activity, land cover, sea ice, and greenhouse gas and aerosol concentrations. Furthermore, Focus 1 aims to quantitatively understand the causes and impacts of variations in climate forcings, including climate sensitivity and the carbon cycle-climate feedback.

Focus 2: Regional Climate Dynamics

This Focus seeks to achieve a better understanding of past regional climatic and environmental dynamics through comparison of reconstructions and model simulations. Activities contribute towards a global coverage of high-resolution, well-dated palaeoclimatic data, reconstructions of past climate-state parameters (e.g., temperature, precipitation, atmospheric pressure fields), a better understanding of past modes of climate variability and their teleconnections, and of rapid and extreme climate events at the regional scale. The Focus hosts activities that promote data-model comparisons and collaborates closely with Cross-Cutting Theme 2 on proxy development and calibration. The timescales covered by this Focus encompass the last 130 ka, in particular the time streams of the last glacial-interglacial cycle, the Holocene and the last 2 ka.

Focus 3: Global Earth-System Dynamics

This Focus looks at large-scale interactions between components of the Earth System (atmosphere, biosphere, cryosphere, hydrosphere) and the links between regional- and global-scale changes. It hosts activities to synthesise records at a global scale, acting as an umbrella for the regional studies of Focus 2 and as a link to the forcings addressed in Focus 1. Working Groups address global-scale abrupt and gradual Earth System changes and their underlying processes, including their response to changes in forcings, internal feedbacks and teleconnections.

Focus 4: Past Human-Climate-Ecosystem Interactions

This Focus addresses the long-term interactions among past climate conditions, ecological processes and human activities during the Holocene. Emphasis lies in comparing regional-scale reconstructions of environmental and climatic processes using natural archives, documentary and instrumental data, with evidence of past human activity obtained from historical, palaeoecological and archaeological records. The Focus promotes regional integration of records and dynamic modelling to: 1) Understand better the nature of climate-human-ecosystem interactions, 2) Quantify the roles of different natural and anthropogenic drivers in forcing environmental change, 3) Examine the feedbacks between anthropogenic activity and the natural system, and 4) Provide integrated datasets for model development and data-model comparisons.

In addition to the Foci, PAGES scientific structure includes four *Cross-Cutting Themes* that are of fundamental relevance to all the Foci and to palaeoscience in general:

Cross-Cutting Theme 1: Chronology

Chronology is crucial to palaeoresearch and often constrains the strength of conclusions from palaeoenvironmental reconstructions. This Theme supports efforts to improve tools for absolute and relative dating, and to enhance the reliability of reference timescales. It also encourages creative new approaches to solving chronology issues.

Cross-Cutting Theme 2: Proxy Development, Calibration and Validation

This Theme supports improvement of the precision and accuracy of palaeo-proxies as a basis for high-quality reconstructions of past global change to complement instrumental data. It includes efforts on proxy interpretation and development, analytical innovation, inter-laboratory comparisons, and calibration refinement, with the aim to reduce uncertainty in proxy-based reconstructions.

Cross-Cutting Theme 3: Modelling

Numerical models provide a comprehensive, quantitative and physically coherent framework for exploring couplings and feedbacks between the various components of the Earth System. As such, modelling is a key element of all the PAGES Foci. Some palaeo-specific modelling issues are generally not as relevant to the communities developing Earth System models for future projections. Accordingly, this Theme supports efforts to improve model components specific for palaeoresearch requirements.

Cross-Cutting Theme 4: Data Management

This Theme provides an umbrella for activities that support availability and access to palaeoscience data, as well as creative ways for their scientifically fruitful utilisation. It aims to mediate between the scientific community and international data centres such as WDC and PANGAEA, as well as the regional, national and thematic databases.

Activities under the PAGES umbrella are carried out by the palaeoscience community, PAGES Scientific Steering Committee and the PAGES International Project Office. The PAGES project plays a central role in integrating the themes of the other IGBP Core Projects and actively engages with the broader Earth System Science community.

The major outcomes that PAGES envisions as a result of the activities outlined in this Science Plan and Implementation Strategy include:

- Research results that address the major scientific issues in palaeoscience and come closer to answering the key overarching questions that PAGES has posed.
- Closing of critical knowledge gaps described in the Fourth IPCC Assessment Report.
- Support of innovative scientific approaches and new data acquisition in areas that will lead to a better understanding of the Earth System.
- Development of standardised reference datasets, such as on palaeoclimate forcings and chronology.
- Further synthesis and dissemination of palaeoscience research results.
- Establishment of a more interdisciplinary and internationally inclusive palaeoscience research framework.
- Better integration of palaeoscience into other global change research agendas.

Introduction

Importance of Palaeoscience for Global Change Research

Palaeoscience is the study of climate and environmental processes in the geologically recent past prior to the existence of instrumental records. It also involves research designed to complement or geographically extend these records. The palaeorecord (derived from marine and lake sediments, ice cores, tree rings, corals, cave deposits, historical documents, etc.) in concert with modelling of past scenarios provides a quantitative understanding of past Earth System variability and the underlying processes. In order to better understand current global changes and to project future scenarios, knowledge of what has happened in the past is imperative. The past does not provide a prescriptive guide to the future but can form the basis for an evaluation of present day trends, future probabilities and likely human consequences.

The hypotheses put forward by palaeoscience on the causes of past changes can be supported or challenged using a range of models, from a conceptual to a 3D approach. This forms a solid basis for benchmarking the same models that are used for climate projections. However, knowledge of long-term consequences of radiative perturbations of our planet cannot be fully explored by climate models, which for the moment do not include slow feedbacks linked to ice sheets or the carbon cycle. Here, evidence from past climate reconstructions provides a solid framework to estimate the importance of these long-term (centuries or longer) feedbacks, and in this respect can provide valuable expertise, for example, on stabilisation targets (Hansen et al., 2008).

A special chapter on palaeoclimate science and synthesis was included in the Working Group I (WG1) contribution to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), thereby acknowledging the vital role of palaeoscience in global change discussions. Moreover, environmental policy and decision makers worldwide are increasingly using palaeodata, particularly interannual to decadal long-term climate series, to guide environmental management policies.

Box 1.1 Why palaeoscience?

Past global change research shows us that what has happened can happen (e.g., abrupt climate change, ice sheet collapse, cessation of ocean overturning, perturbation of ocean chemistry).

In addition, palaeoscience provides:

- The only way to assess the operation of processes that act on timescales longer than the instrumental record.
- A large range of different scenarios as case studies for the sensitivity and operation of the Earth System (e.g., ENSO variability, abrupt changes, monsoon teleconnection, vegetation/ecology changes).
- A long-term (natural) context for recent changes (e.g., climate of the last millennia, greenhouse gas concentrations over glacial cycles).
- Data with which to assess the relative roles played by natural climate variability and anthropogenic forcing in global change.
- Testbed scenarios for aspects of the present and near future climate and environment (e.g., early Holocene, past interglacials, Pliocene, Palaeocene-Eocene Thermal Maximum).
- Palaeodata as benchmarks for model skill assessment (e.g., from the Last Glacial Maximum, the last interglacial, or rapid climate transitions).
- A quantitative understanding of Earth System processes through modelling palaeo-scenarios.

State of the Art in Palaeoscience

Some first-order palaeoscientific questions of the last decade have been answered and it is now clear that human activities are having a profound influence on the global climatic and environmental systems (IPCC AR4 WG1, 2007). It is also evident that these systems exhibited a range of natural variability in the past that went beyond what can be observed and measured today. The following list reflects fundamental findings of palaeoscience that were identified with a 90% or better confidence in the IPCC AR4 WG1 Paleoclimate chapter (Chap. 6: Jansen et al., 2007):

- The current increase of greenhouse gases in the atmosphere occurs at a rate that is unprecedented during at least the last 16 ka.
- Today's concentrations of carbon dioxide and methane exceed by far the natural range of the last 650 ka (now extended to the last 800 ka; Lüthi et al., 2008; Loulergue et al., 2008).
- Antarctic carbon dioxide and temperature co-varied over the last 800 ka, indicating a close relationship between climate and the carbon cycle.
- The Last Glacial Maximum was 4-7°C colder than the pre-industrial late Holocene, with the high-latitude cooling being more pronounced than the global average.
- Glacial-interglacial cycles were driven by orbital insolation changes and amplified not only by changes in greenhouse gas concentrations and ice sheet extent but also by feedbacks associated with ocean circulation, sea ice, dust, and biophysical processes.
- Marine carbon cycle processes were primarily responsible for the carbon dioxide variations between glacials and interglacials.
- The global warming that terminated the Last Glacial Maximum happened at an order of magnitude more slowly than the 20th century warming.
- The North Atlantic region experienced repeated abrupt warmings and coolings during the last glacial period. These occurred within decades and had climatic implications in remote regions around the globe.
- The structure and composition of regional vegetation is sensitive to climate change and can respond within decades.
- The intensity of the African-Asian summer monsoon and the regional frequency of tropical cyclones, floods and droughts changed on decadal to centennial timescales over the last 10 ka.
- The current increase in carbon dioxide and greenhouse gas forcing is at least five times faster than at any time during the pre-industrial era of the last two millennia.
- The warmth of the Northern Hemisphere during the second half of the 20th century was exceptional in its amplitude and hemispheric spread compared to the last ca. 500, and probably even 1300 years.
- Droughts lasting decades or longer were a recurrent climatic feature in northern and eastern Africa and the Americas over the last 2 ka.
- Climate models can simulate the Northern Hemisphere temperature trends of the last millennium based on natural forcings but require anthropogenic greenhouse gas forcing to simulate the temperature rise of the last half-century.

These and other robust results of palaeoresearch constitute substantial advances towards understanding how the Earth System operates. At the same time, the results inspire new fundamental questions on underlying processes, structural details and quantification. In addition to the findings listed above, IPCC AR4 WG1 makes numerous statements with lower confidence and identifies open questions, leaving the task for the palaeoscience community to verify or falsify these statements and to constrain uncertainties.

Role of PAGES

The more than 1400 publications that came out in 2008 with key words such as "paleoclimate", "palaeoclimate" or "past climate" (ISI Web of Knowledge) demonstrate the dynamics of this research community. With the magnitude of palaeodata generated worldwide on timescales from decades to millions of years, and the diversity of disciplines involved, there is a clear need for integration, coordination, and fast dissemination of results and interpretations, as well as an overarching scientific direction

Box 1.2 PAGES Mission Statement

PAGES facilitates activities that address past changes in the Earth System in a quantitative and process-oriented way in order to improve predictions of future climate and environment, and inform strategies for sustainability.

for palaeoresearch. Over 15 years ago, the founders of the Past Global Changes (PAGES) Project of the International Geosphere-Biosphere Programme (IGBP) recognised this need and established a community-driven, international coordinating and networking palaeoscience programme. The past 15 years have shown the benefit of PAGES and similar programmes in many ways, not least through the rise in the number of shared international research initiatives and the increasing role played by scientists from developing countries. The building of an international palaeoscience community has provided researchers with better access to data, regions, facilities and workshops, and has enhanced the ability for results to be cross-verified and uncertainties understood.

In addition to facilitation of palaeoscience research, another of PAGES major roles is to provide a palaeoscience perspective on our understanding of the Earth as a dynamic system, and hence to contribute to research by the wider Earth System Science community into the future sustainability of a habitable planet.

PAGES Objectives and Approach

Since its establishment in 1991, the primary objective of PAGES has been to improve our understanding of past climate and environmental change. However, although PAGES is science-driven, it is not itself a hands-on programme that actively conducts research or supports individual research projects. Instead, PAGES builds on the research findings of the past global change community to yield a palaeoscience whole that is greater than the sum of its parts. This is accomplished by encouraging scientific approaches that investigate connections in the Earth System, such as between climate forcings and regional climate and environment responses; between land, ocean, and atmosphere; between high and low latitudes; between hemispheres; and between humans and their environment.

PAGES promotes integrative science that focuses on the reconstruction, analysis and modelling of past natural and anthropogenic changes of the climate and the environment. Associated research includes high-resolution timeseries, spatially dense mapping and modelling of past states of the Earth System, multi-proxy reconstructions, and transient and ensemble model runs.

PAGES employs a range of service-oriented approaches in seeking to meet its objectives:

- **Catalyzing international research activities** and fostering scientific exchange by establishing overarching science directions and organising workshops that establish new links between different scientific groups and themes.

- **Integrating scientific activities from developing countries** into all aspects of palaeoresearch by fostering collaborations, providing funding for participation in meetings and summer schools, and assisting in publication in peer-reviewed journals.

- **Facilitating communication** within the international palaeoscience community and highlighting important findings by means of workshops, newsletters and a website.

- **Providing access to palaeoscientific information** through web-based materials (e.g., portal to palaeoclimate and palaeoenvironmental databases, online directory of scientists, calendar of events, news highlights, postings of job opportunities, downloadable educational material and scientific publications).

- **Enhancing the visibility of palaeoresearch** and communicating the importance of palaeoscience through review papers, special journal issues, and scientific highlights in international newsletters.

- **Serving as point of contact** between the palaeoscience community and IGBP, as well as with the wider Earth System Science community.

Box 1.3 PAGES Philosophy: Integrating Science

In its current phase, PAGES explicitly aims to create synergies by overcoming boundaries that have historically existed between different:

- Approaches — reconstruction, data analysis and numerical modelling
- Spheres — land, ocean, ice and atmosphere
- Timescales — palaeoscience, modern processes and future projections
- Spatial scope — local, national and regional communities
- Resource levels — developed and developing country scientists

Implicit in this philosophy is openness towards cooperation with different organisations representing aspects of global change science that are complementary to the scope of PAGES.

Major Scientific Issues

PAGES has identified four sets of key overarching questions that represent the major palaeoscientific issues for the coming years. These were crystallised over the last four years from four major sources: 1) Feedback provided by the palaeoscience community to an open call for comment in 2004, 2) A plenary discussion that took place at the PAGES Open Science Meeting in 2005, 3) Formal discussions at subsequent annual PAGES Scientific Steering Committee meetings, and 4) Scientific gaps in current knowledge and follow-up issues identified in the IPCC AR4 WG1 (2007). These inputs resulted in the identification of common themes in national science agendas worldwide and in questions of key importance to palaeoscience.

The four sets of questions aim at developing a better understanding of climate-environment sensitivity, regional variability, global system behaviour and human interaction with climate and environment. They are as follows:

Climate Forcings

- How did the main climate forcing factors vary in the past?
- How sensitive was (and is) the climate system to these forcings?
- What caused the natural greenhouse gas and aerosol variations?
- To what extent can palaeodata constrain climate sensitivity and the carbon cycle-climate feedback?
- In what precise sequence and over what timescales did changes in forcings, climate and ecological systems occur?

Regional Climate Dynamics

- How did regional climate and the Earth's natural environment change in the past?
- What are the main patterns and modes of climate variability on sub-decadal to orbital timescales?
- How do climate variability and extreme events relate to the mean state of the climate system?

Global Earth-System Dynamics

- How do large-scale changes in the Earth System affect regional climatic and environmental conditions?
- How have regions or Earth System components interacted to produce climate and environmental variations on a global scale?
- What are the causes and thresholds of rapid transitions between quasi-stable climatic and environmental states, in particular on timescales that are relevant to society? How reversible are these changes?

Past Human-Climate-Ecosystem Interactions

- What are the historical patterns of human interactions with climate change and ecological processes?
- How can we learn from past patterns and interactions in order to better understand and manage natural ecosystems at present and in the future?

Timescales of Interest

Historically, PAGES focused on high-resolution records that fell into the three time periods of the last 2, 20 and 200 ka. However, over the past few years, palaeoscientists have generated high-quality data that allow quantitative process studies further back in time. In addition, future-climate projections have increased the need to understand Earth System behaviour in a world warmer than today. These two developments have created the opportunity and the requirement to extend PAGES timescales of interest.

The timescales of priority within PAGES now include any that enable palaeoscience to efficiently contribute to a better understanding of the most relevant global change issues (Fig. 1.1). An underlying requirement is that sufficient data must be available for the past scenario to allow quantitative study of the relevant issues. For example, for questions on pre-industrial short-term climate variability and the impact of recent human activity on the Earth System, the last 2 ka is critical. Yet, for questions on large-amplitude Earth System changes and quantification of the associated feedback processes, the timescale spans the last 800 ka of glacial-interglacial climate change, for which ice cores provide precise data on greenhouse gas forcing. For questions on the behaviour of the Earth System (or parts thereof) under projected future conditions with higher atmospheric CO_2 levels and average temperatures, and an ice-free Arctic, the early Pliocene warm period (ca. 3-4.5 Ma ago) or earlier periods in the Cenozoic can provide valuable insights. Finally, some effects associated with rapid warmings and greenhouse gas increases in an already warm world might best be studied at thermal maxima during the early Palaeogene around 50-65 Ma ago.

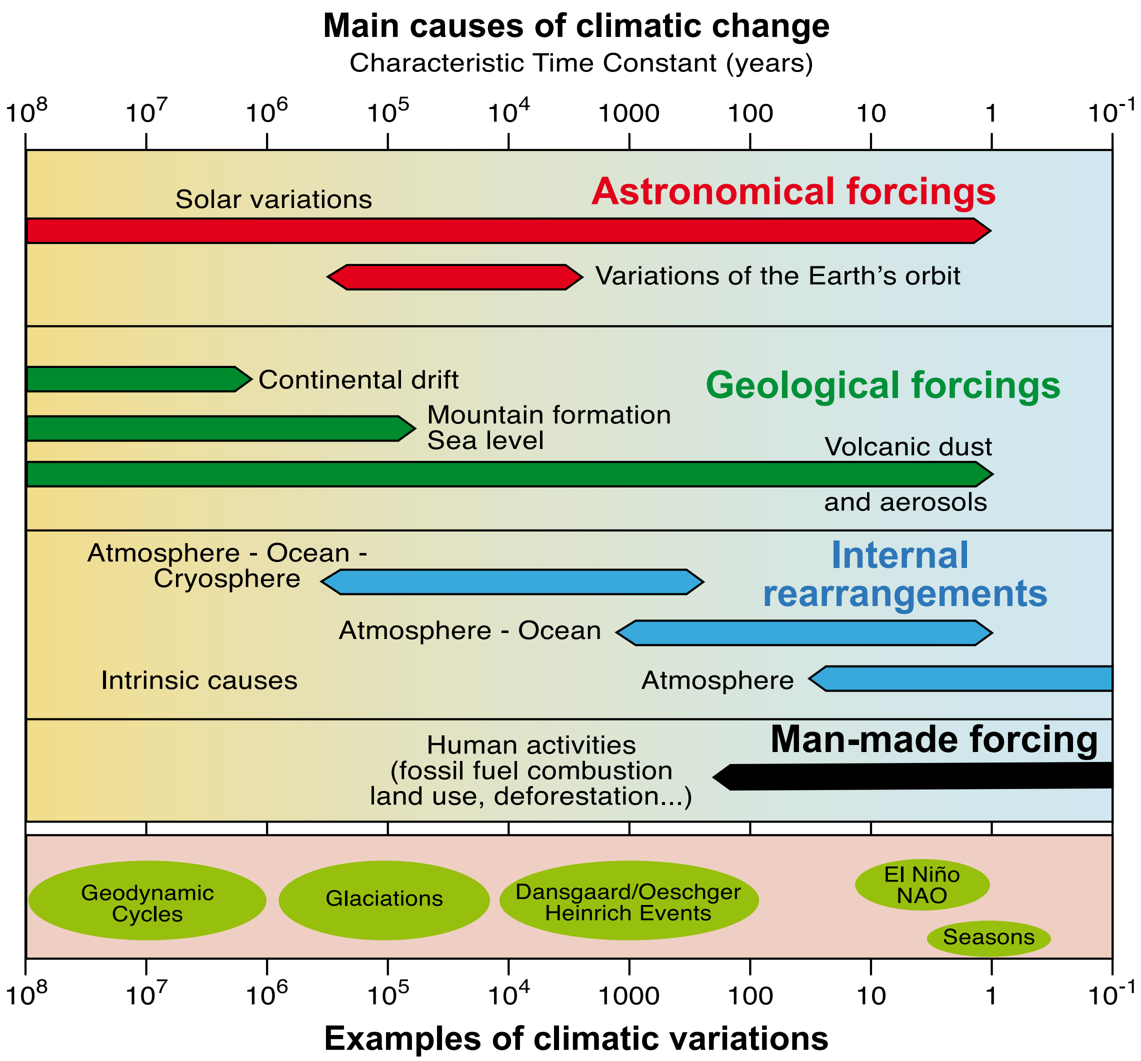

Figure 1.1: Scheme of climate forcings, processes involved and climate response as a function of their timescales (Bard, 2003).

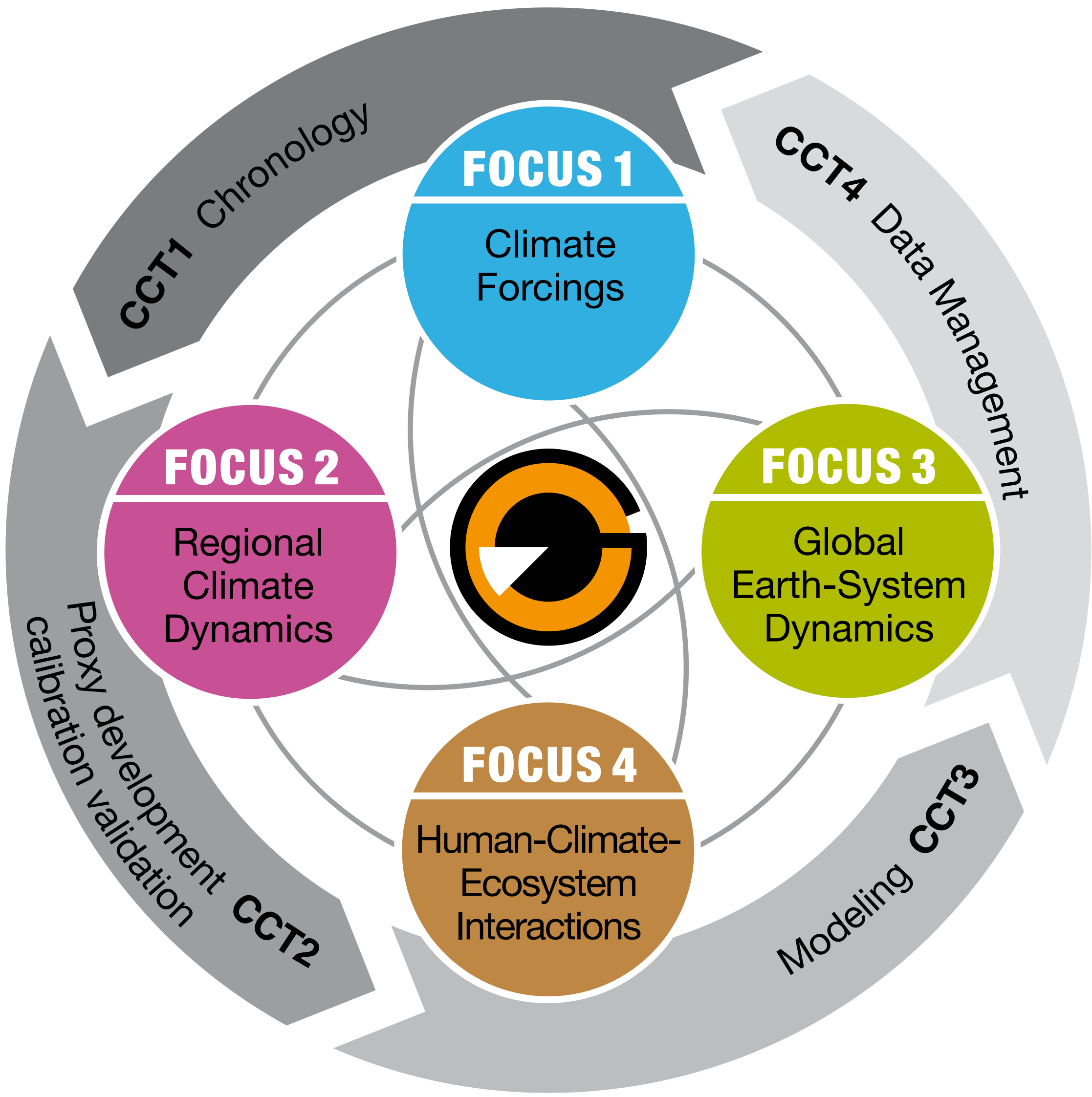

Figure 1.2: Overall structure and key elements of PAGES scientific emphasis. The four Foci are complemented by four Cross-Cutting Themes that are of relevance to all Foci.

PAGES Scientific Structure

During the last decade, PAGES was organised into programmatic Foci, which were dynamic and changed in topic and number with time. The new Science Plan, however, reflects a shift towards purely thematic organisation. In order to address the major scientific issues outlined above, the four sets of key questions have been encompassed within four thematic *Foci* (Fig. 1.2; coloured circles). In addition, four *Cross-Cutting Themes* (CCTs) (Fig. 1.2; grey arrows) have been identified that are of fundamental relevance to all Foci, and to palaeoscience in general. Programmatic elements of PAGES previous scientific structure that are of relevance to the questions addressed in the new Science Plan, have been incorporated into the four new Foci and CCTs.

Each of the Foci is divided into a number of *Themes*, the goals of which are addressed by *Working Groups* that target specific aspects of the scientific scope with activities and programmes (see Figs. 2.1, 2.6, 2.13, 2.19), similar to the way in which PAGES Foci were organised previously. As in the past, the new PAGES scientific structure will remain flexible, enabling PAGES to accommodate shifts in the scientific focus of global change research and to react to opportunities for new collaborations.

Figure 1.3: Relationship of the themes of the Core Projects of IGBP. PAGES and AIMES, as projects with an integrative role across all Earth System compartments, are located in the centre.

Figure 1.4: Structure and elements of the Earth System Science Partnership.

PAGES Context in IGBP and ESSP

The PAGES project is actively embedded in the IGBP framework as one of nine international Core Projects. In the second phase of IGBP, launched in the summer of 2003, PAGES was allotted (alongside the Analysis, Integration and Modeling of the Earth System (AIMES) project) a central role in integrating the themes of the other Core Projects. The other IGBP themes concentrate on present-day processes in one particular Earth System compartment or at the interface between two compartments. The central placement of PAGES and AIMES within the IGBP structure (Fig. 1.3) demonstrates the linkages and crucial nature of palaeoscience and modelling research within IGBP.

PAGES has also established active links with projects of the World Climate Research Programme (WCRP), especially through the PAGES/CLIVAR Intersection, as well as overlaps with the International Human Dimensions Programme (IHDP) and DIVERSITAS, sister programmes of IGBP within the Earth System Science Partnership (ESSP) (Fig. 1.4).

Structure of the Science Plan and Implementation Strategy

The main part of the Science Plan covers the four Foci and four Cross-Cutting Themes in detail. The overarching questions and rationale are presented, along with a review of the current state of understanding and science gaps. Key goals are outlined and the means with which they will be addressed are discussed. Linkages to other projects are also included.

In the last part of the Science Plan, the implementation strategy is outlined, including an overview of the organisational structure, management and funding of PAGES, as well as PAGES policies on data issues and on capacity building, education and outreach. Major outcomes of the project and a project timeline are also outlined.

Science Plan

Focus 1: Climate Forcings

This Focus fosters activities that aim to produce improved, extended, and consistent timeseries of climate forcing parameters, both natural and anthropogenic, including solar insolation and irradiance intensity, volcanic activity, land cover, sea ice, and greenhouse gas and aerosol concentrations. Furthermore, Focus 1 aims to quantitatively understand the causes and impacts of variations in climate forcings, including climate sensitivity and the carbon cycle-climate feedback.

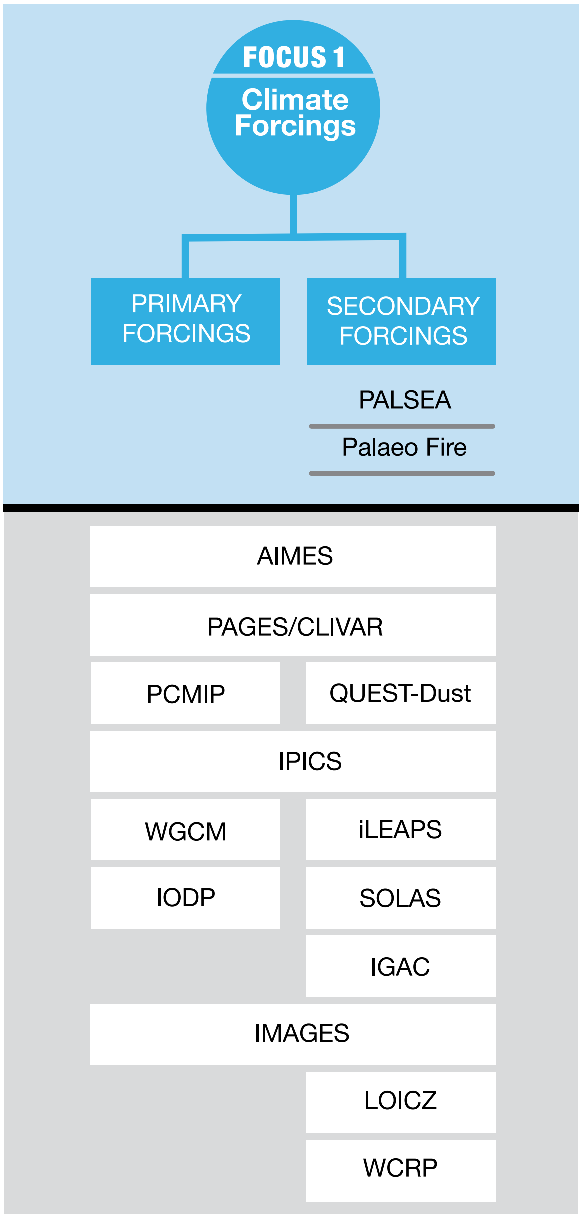

Figure 2.1: Structure of Focus 1. Top: Focus Themes (blue boxes) with the corresponding Working Groups below. Bottom: Overlap with external programmes and projects (white boxes). For explanation of acronyms, see Acronyms and Abbreviations List.

Overarching Questions

- How did the main climate forcing factors vary in the past?
- How sensitive was (and is) the climate system to these forcings?
- What caused the natural greenhouse gas and aerosol variations?
- To what extent can palaeodata constrain climate sensitivity and the carbon cycle-climate feedback?
- In what precise sequence and over what timescales did changes in forcings, climate and ecological systems occur?

Rationale

Direct measurements of climate forcings from ground-based and satellite-observing systems are available for the last few decades to half-century. These measurements allow us to understand and calibrate indirect measures of past climate forcings recorded in proxy evidence from historical records, ice cores, tree rings, and lake and ocean sediments, etc. A fundamental challenge of this Focus is to produce improved, extended and consistent timeseries of climate forcings, both natural and anthropogenic. Accurate reconstructions of climate forcings allow climate system models to be used to quantify the spatial and temporal sensitivity of the climate system, and to understand its natural variability (Fig. 2.2). This allows us to put the present, past and projected future climate changes in context. The combination of data on greenhouse gas concentration, radiative forcing and temperature provides constraints on climate sensitivity and the carbon cycle-climate feedback (Schneider von Deimling et al., 2006; Joos and Prentice, 2004). These are two important metrics to quantify the response of the climate system to the anthropogenic perturbations. Emphasis of this Focus lies on the last 2 ka, the Holocene and the Pleistocene, at annual, annual to centennial, and glacial-interglacial to sub-millennial timescales, respectively.

Climate forcings are imposed radiative perturbations of the Earth's energy balance and can be of natural or anthropogenic origin (National Research Council, 2001). The sensitivity of the climate system to an imposed forcing is dependent not only on the magnitude and character of the climate forcing but also on the feedbacks within the climate system, which amplify or diminish the responses. We distinguish between primary and secondary forcings. "Primary" climate forcings are those that are externally imposed on the climate system, and do not result from natural feedback processes in the Earth System. Orbital solar insolation, irradiance intensity and volcanic aerosols are therefore classified as primary forcings. Secondary natural climate forcings include those induced by mineral dust, greenhouse gases, land cover, sea ice, continental ice, glacial meltwater, and sea level. They also impact the radiative balance of the atmosphere but are classified as "secondary" because their level is controlled by feedbacks in the Earth System, and hence depends directly on the climate state itself. Some forcings can be both primary and secondary, such as greenhouse gases, land cover and aerosols. For example, over glacial-interglacial cycles, greenhouse gases varied naturally as a feedback of the climate system to orbital solar forcing (Fig. 2.2). On that timescale, greenhouse gases amplified the climate response as a secondary forcing. However, over the last few hundred years, anthropogenic emissions of greenhouse gases have imposed a significant primary climate forcing on the system.

Focus 1 Structure

Focus 1 is divided into two Themes (Fig. 2.1):

- Primary Climate Forcings
- Secondary Climate Forcings

The questions raised under each Theme are addressed by a number of Working Groups.

Theme: Primary Climate Forcings

State of Science and Knowledge Gaps

Orbital Solar Insolation

The amount of energy received by the Earth from the Sun varies on different timescales. Changes in the Earth's orbital parameters modulate the seasonal and latitudinal distribution of insolation on timescales of 10^4-10^5 years. These changes drove the ice age cycles of the Neogene, shaped the individual expressions of past interglacials, and modulated the climate and environment during the Holocene warm period. While the orbital parameters can be calculated precisely for several million years back in time and into the future (Berger and Loutre, 1991; Laskar et al., 2004), today's challenges lie in precisely tying together the timing of insolation changes with Earth System responses, and in deciphering how the components of the orbital insolation changes affected the Earth System. Key questions remain about the interplay between orbital

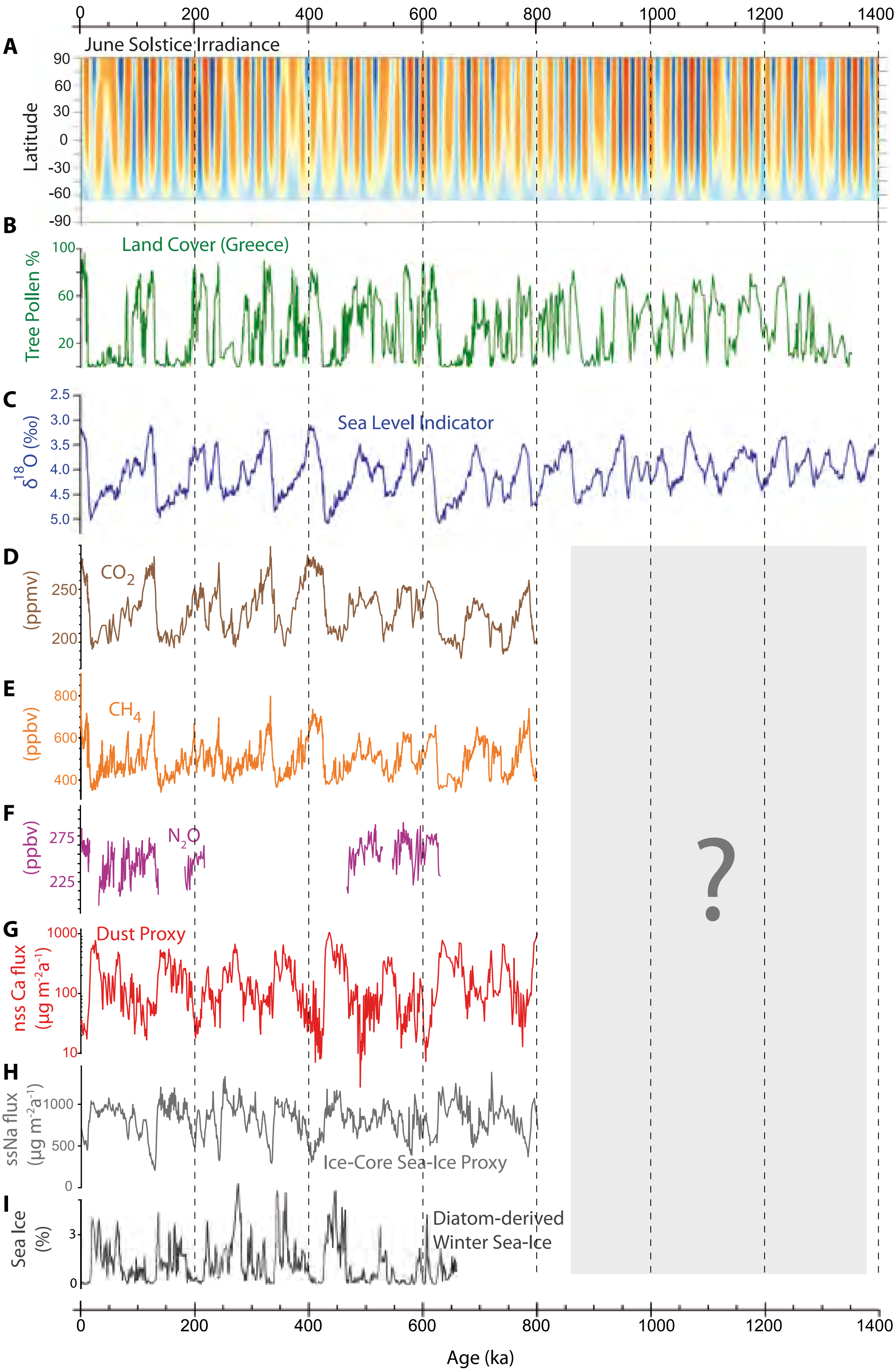

Figure 2.2: Timeseries representing the most relevant primary and secondary forcings of long-term climate variability over the last 800 ka. A) Laskar et al., 2004; Red and blue indicate high and low June solstice irradiance, respectively; B) Tzedakis et al., 2006; C) Lisiecki and Raymo, 2005; D) Lüthi et al., 2008; E) Loulergue et al., 2008; F) Spahni et al., 2005; G) and H) based on Wolff et al., 2006; I) Schneider-Mor et al., 2008. Ice core records are on the third EPICA Dome C timescale (EDC3), other records are on their own age scales.

parameter configurations (obliquity, precession, eccentricity) and different climate states (ice sheets, CO_2) in driving climate dynamics.

Solar Irradiance

On shorter timescales of several years to decades, the Sun's emission of radiation varies with the frequency of occurrence of dark sunspots, bright faculae and other solar phenomena (Fig. 2.3). Direct space-based radiometer measurements available since 1978 indicate that the total solar irradiance has varied by only about 0.1% over the last two 11-year solar (sunspot) cycles (Fröhlich and Lean, 2004). These direct measurements show a good correlation between sunspot number and irradiance during cycles 21 and 22 but not during the most recent cycle, 23, when the irradiance was as high as during the previous two cycles but the sunspot number was 20-30% lower (Fröhlich and Lean, 2004; Lean, 2005).

Different solar indices, such as sunspot number, length of the solar cycle, and cosmogenic isotopes of carbon and beryllium (^{14}C and ^{10}Be), have been proposed as proxies for total solar irradiance, and are available from historical records, ice cores and tree rings. However, the relationship between irradiance and cosmogenic isotopes is complex, not necessarily linear, and potentially affected by climate (Wang et al., 2005b; Muscheler and Beer, 2006). Early reconstructions used a long-term trend in solar irradiance based on cosmogenic isotope records and comparisons to Sun-like stars, yielding a solar irradiance estimate for the Maunder Minimum (1645 to 1715) of about 0.2-0.4% below contemporary solar minima (Hoyt and Schatten,

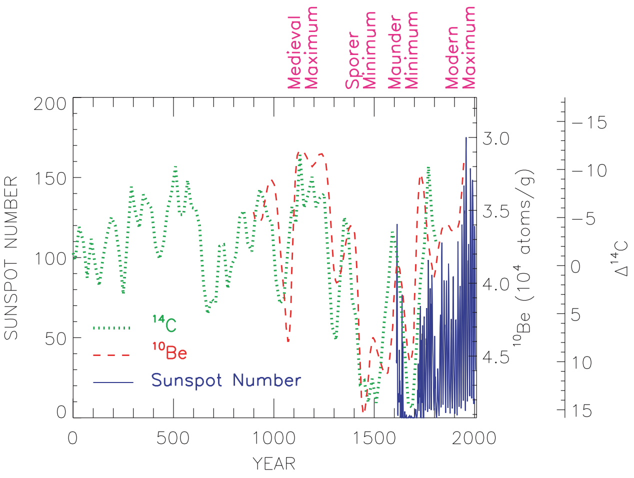

Figure 2.3: Records of sunspot number and cosmogenic isotope fluctuations in tree rings (^{14}C) and ice cores (^{10}Be) associated with solar activity over the past 2 ka (National Research Council, 2006; updated from Fröhlich and Lean, 2004).

1993; Lean et al., 1995). However, recent reconstructions consider solar output during the Maunder Minimum to be closer to that of the present-day solar minima (Foukal et al., 2004). Records of past solar irradiance on glacial-interglacial timescales are yet to be obtained.

Volcanic Aerosols

Volcanic aerosols affect the climate directly by scattering and absorbing radiation, and indirectly through interactions with clouds. The direct radiative effect of aerosols from a volcanic eruption depends on its magnitude, location, the time of year, the vertical orientation of the eruption, and the types and sizes of the ejecta (Robock, 2000). Explosive volcanic eruptions add large amounts of ash and sulfur gases to the atmosphere, which diminish the amount of solar radiation reaching the surface, thereby cooling the Earth. Larger ash particles settle rapidly to the surface and generally only cool the surface temperature over a small region for several days to a few weeks. The sulfur gases combine with water vapour to form sulfate aerosols and, in large explosive eruptions, may reach the stratosphere and remain for up to several years. Sulfate aerosols from tropical eruptions are transported globally by high-altitude winds, whereas sulfate aerosols from high-latitude eruptions are more spatially restricted.

Satellite instruments provide aerosol measurements for eruptions during the modern era. Further back, historical records have been used to document large eruptions in populated regions. Palaeovolcanism can be discerned from ice cores by looking at the varying frequency and intensity of acidity and sulfate concentration (Fig. 2.4). Ice cores from Greenland and Antarctica record the acidity and sulfate from the settling of volcanic sulfate aerosols in annual ice layers (Crowley, 2000; Hegerl et al., 2006). Disentangling whether the volcanic debris was from a high-latitude volcano nearby or from a large tropical volcano requires records from multiple ice cores located at both poles, and is sensitive to which ice cores are used. Considerable uncertainties on the radiative effect of volcanic eruptions also arise in estimating factors such as extent of stratosphere penetration by eruption products, and the radiative properties of different volcanic aerosols and their residence time in the stratosphere. New isotopic tracers in ice cores now offer a promising perspective to distinguish between tropospheric and stratospheric eruptions (Baroni et al., 2007) but their general application will be a long-term research commitment.

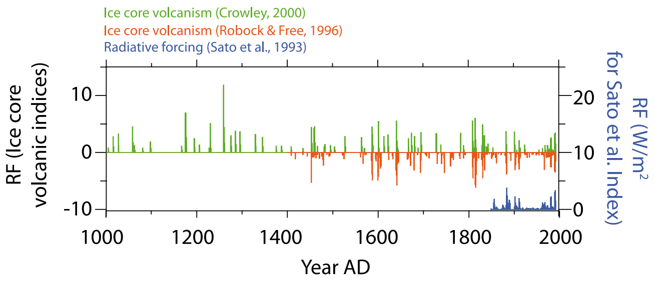

Figure 2.4: Radiative forcing (RF) inferred from three reconstructions of volcanism for the last 1 ka. Blue and green lines have been multiplied by -1 for display purposes (figure modified from Crowley, 2000).

Ice core analyses indicate that the amplitude and occurrence of volcanic forcing varied significantly during the Holocene (Zielinski, 2000). Recent work carried out on the EPICA Dome C ice core suggests a broad anti-correlation between the number of volcanic events and Antarctic temperature (Castellano et al., 2005). This possible link is poorly understood and may involve feedbacks between the cryosphere (growth and decay of the main ice sheets) and the mechanical stress on inner Earth magmatic reservoirs. Global evaluation of volcanic data suggest that deglacial release of ice-load induced decompressional melting in the mantle and hence an increase in volcanic activity (Huybers and Langmuir, submitted).

Theme Goals

- Orbital Solar Insolation – To tie together the timing of insolation changes and of climatic and environmental responses. To unravel how the geometric, spatial and seasonal components of orbital insolation changes affected the Earth System.
- Solar Irradiance – To improve documentation and understanding of solar irradiance variations. This necessitates progress in understanding of irradiance proxies, such as sunspot numbers and cosmogenic signatures in ice cores and tree rings, and that solar and non-solar influences are disentangled. The ultimate goals are to extend the low-frequency solar-forcing record back through the entire Holocene, to retrieve more detailed and spatially distributed records of cosmogenic isotopes, and to interpret them in association with modelling of the mechanisms affecting the isotope concentration in ice and marine sediments.
- Volcanic Aerosols – To establish dates, latitude, magnitude and radiative impact of explosive volcanic eruptions through correlation of additional ice core records and the development of new tracers, such as the identification of stratospheric eruptions through studies of isotopes in sulfate. The ultimate goal is to extend the detailed record of volcanic forcing through the entire Holocene.

Implementation

This Theme does not yet have a formal Working Group. To unify the international research effort, Focus 1 will organise a number of activities, with initial emphasis on:

- Developing high-resolution records of solar and volcanic activity and ensuring availability of the datasets to modellers.
- Understanding cosmogenic isotopes and associated modelling of the different mechanisms that affect their concentration in ice and marine sediments as a measure of solar activity.
- Developing key primary forcing curves that can be used by all modelling groups.

These implementation goals also fall within the scope of the PAGES/CLIVAR Intersection Panel, which will be instrumental in carrying out the activities.

Theme: Secondary Climate Forcings

State of Science and Knowledge Gaps

Mineral Dust

Mineral dust aerosols affect the Earth's radiative balance through the absorption and scattering of both shortwave and longwave radiation. Mineral dust aerosol variations on glacial-interglacial timescales have been estimated from terrestrial, marine and ice core deposits (Fig. 2.5). These record the concentration and size distribution of dust particles, and the source regions can be inferred from their chemical composition. There is ample evidence that glacial climate was associated with a larger dust concentration in the atmosphere. However, the IPCC AR4 (Chap. 6; Jansen et al., 2007) classifies the knowledge about the forcing effect of dust during the Last Glacial Maximum as "very low". As is true for the present, there was considerable regional variation of atmospheric dust loading (Kohfeld and Harrison, 2001; Mahowald et al., 2006; Winckler et al., 2008) and it is unresolved whether the large increases during glacial periods, as recorded in polar ice cores, were restricted to the higher latitudes. Periglacial landscapes may have provided an important additional dust source during glacial periods. There is still a need to better characterise the dust size, shape and mineralogy on a regional scale during glacial conditions, as these dust properties directly affect their radiative forcing characteristics.

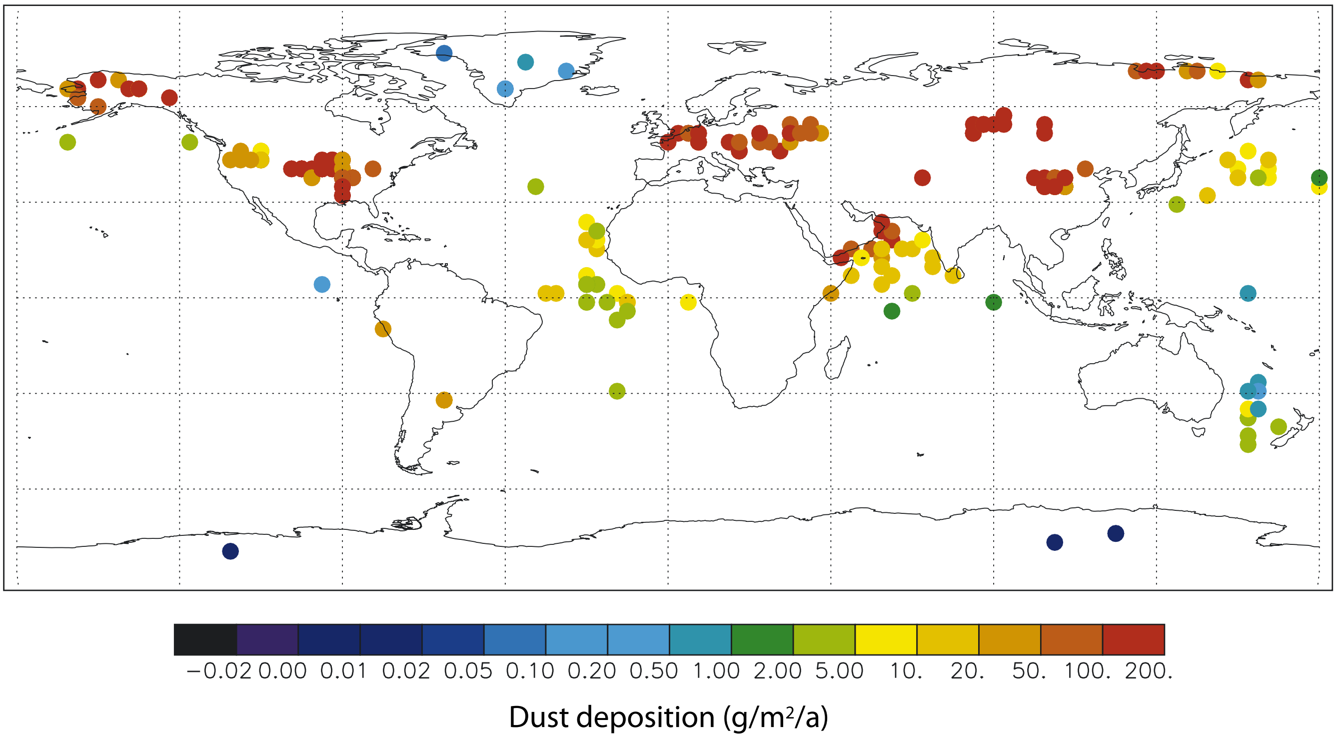

Figure 2.5: Observational estimates of dust deposition (g/m²/a) for the Last Glacial Maximum from ice core, marine and terrestrial records (Kohfeld and Harrison, 2001; Mahowald et al., 2006)

Greenhouse Gases

The primary natural greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapour (H_2O). Water vapour accounts for about 60% of the natural greenhouse effect for clear skies (Kiehl and Trenberth, 1997). The well-mixed greenhouse gases, CO_2, CH_4 and N_2O, have atmospheric lifetimes of decades (CH_4) to centuries (N_2O) to millennia (CO_2). Water vapour, on the other hand, has considerable regional variability and the overall e-folding (timescale for a quantity to decrease to 1/e of its previous value) residence time of atmospheric moisture is just over 8 days (Trenberth, 1998). Continuous atmospheric measurements of CO_2 have been available since the mid-20th century from the Mauna Loa Observatory, and all of the significant greenhouse gases have been monitored since 1980 by global air sampling networks (Keeling and Whorf, 2005).

The greenhouse gas concentrations for previous centuries and millennia are well known from ice core analyses. Over the industrial period, the atmospheric concentrations of CO_2, CH_4, and N_2O increased far above the natural concentration range of the past 800 ka, the period spanned by the ice core record. The 20th century increase in their combined forcing occurred one to two orders of magnitude faster than any sustained change during the past 20 ka (Joos and Spahni, 2008). For the 2 ka prior to the industrial era, ice core measurements indicate that CO_2 and N_2O remained within a few ppm and ppb, respectively, of their mean concentrations and within the uncertainties of the data (Raynaud et al., 2003; Gerber et al., 2003; McFarling Meure et al., 2006). Over the entire Holocene, CO_2 and N_2O varied by about 30 ppm and 10 ppb, respectively. The exact figure for N_2O is difficult to assess because available records show considerable scattering. CH_4 fluctuations over the Holocene were larger, changing with the climate and likely resulting from fluctuations in natural and early anthropogenic sources (Blunier et al., 1993; Ruddiman and Thomson, 2001; Raynaud et al., 2003; Keppler et al., 2006).

On glacial-interglacial timescales, CO_2 and CH_4 evolution has been reconstructed for the last 800 ka from Antarctic ice cores (Fig. 2.2: Vostok and EPICA Dome C). A tight link between greenhouse gas concentrations and each glacial-interglacial climate change is observed, with amplitudes of up to 100 ppmv for CO_2 and 400 ppbv for CH_4 (Petit et al., 1999; Siegenthaler et al., 2005; Spahni et al., 2005; Lüthi et al., 2008; Loulergue et al., 2008). Associated with millennial-scale glacial climate variability, CO_2 varies by up to 20 ppmv, in line with Antarctic temperature changes, whereas CH_4 varies between 50-250 ppbv, in close association with Dansgaard-Oeschger events recorded in the Northern Hemisphere. N_2O measurements have been carried out on the EPICA Dome C ice core, indicating glacial-interglacial changes of about 100 ppbv but the record suffers from glaciological artefacts, which precludes a detailed comparison with the other two greenhouse gases outside interglacial periods.

Existing records suggest that the start of the greenhouse gas increases during the glacial terminations take place a few hundred years after the start of the Antarctic temperature increase (Fischer et al., 1999, Monnin et al., 2001; Caillon et al., 2003). During glacial inceptions, however, polar temperatures drop, while CO_2 remains high until quite late in the process. The causes of glacial-interglacial greenhouse gas changes are expected to mainly involve ocean dynamics and the biological pump for CO_2, and wetland extent, biomass burning and the oxidative capacity of the atmosphere for CH_4. An improved quantitative understanding of these factors would allow a more reliable assessment of their contributions to past greenhouse gas changes than is currently possible.

Land Cover (Land Use, Vegetation, Fire)
Although humans have been changing the natural vegetation for thousands of years (Ruddiman, 2003), the largest regional changes in land cover have occurred in the Northern Hemisphere since the mid-19th century and in the Southern Hemisphere since the early 20th century (Bertraud et al., 2002). Natural vegetation has also changed over glacial-interglacial timescales with changing climate (Fig. 2.2). For example, terrestrial records of the mid-Holocene (ca. 8-5 ka ago) indicate major land cover changes, such as expanded forest cover at the expense of tundra at mid- to high latitudes of the Northern Hemisphere (Prentice et al., 2000), and higher lake levels, extensive wetlands and shrubby vegetation over North Africa (Jolly et al., 1998). Changes in land cover affect the dust loading of the atmosphere and impact water and carbon cycles. In addition, they directly affect the Earth's albedo and thus the radiative balance of the atmosphere. Changes in fire regimes can be particularly effective in modulating the vegetation cover and consequently the budget of greenhouse gases. Palaeofire of natural or cultural origin is therefore an important component of land cover dynamics that requires better reconstruction and representation in models.

Sea Ice
Sea ice is an important climate forcing factor and feedback in the climate system. The low albedo created by diminished polar summer sea ice has a positive feedback on climate warming because more solar radiation is absorbed at high latitudes. Furthermore, sea ice coverage modulates moisture, heat and gas exchange between the atmosphere and the ocean, and can modify aspects of the atmospheric and oceanic circulation (Polyak et al., 2009). The polar regions have experienced both dramatic and rapid fluctuations in climate over the past few glacial cycles, as recorded by a variety of proxies in ocean sediments and ice cores (Fig. 2.2) (Voelker et al., 2002). Today, the areal extent of summer sea ice in the Arctic is rapidly declining (Meier et al., 2005; Overpeck et al., 2005). Antarctic sea ice, on the other hand, shows an increase of 0.8% per decade from 1978 to 2006 (NSIDC, 2009). It is timely to develop interdisciplinary links and synergies between palaeoclimate research and present-day sea ice observations. Climate models can be tested using the history of sea ice in the geological past.

Continental Ice and Sea Level
Continental ice sheets varied considerably on glacial-interglacial timescales (Fig. 2.2) and through their albedo modulated the Earth's radiative forcing. Their volume change affects sea level, which in turn modifies the land albedo. Sea level itself feeds back on ice sheet shape and dynamics through processes that are still poorly represented in ice-sheet models. Continental ice sheets also represent a reservoir of freshwater that can be discharged to the nearby oceans, as icebergs, meltwater and floods, with consequences for the ocean and atmospheric circulation, as well as the carbon cycle. Improved reconstructions on the magnitude, duration, timing and location of past freshwater forcing are needed. Building a master sea level curve and improving reconstructions of the geometry of past ice sheets remain important challenges.

Theme Goals

- Mineral Dust – To better understand dust loading at a variety of sites—high and low latitudes, continental and oceanic—in order to better constrain the temporal and spatial character of mineral aerosol forcing over glacial-interglacial cycles, and to unravel past atmospheric dynamics.

- Greenhouse Gases – To improve the record of atmospheric N_2O variations and the temporal resolution of the CO_2 records. To better constrain the phasing between insolation, greenhouse gas concentrations and climate-environment responses during climate transitions. To improve understanding of the causes of natural fluctuations in greenhouse gases, and to combine greenhouse gas and temperature reconstructions to constrain the carbon cycle-climate feedback, i.e., the sensitivity of atmospheric CO_2 to a change in climate.

- Land Cover – To obtain better records and understanding of regional changes in land use and land cover through vegetation reconstructions and indirect evidence, such as palaeofire activity, denudation and soil erosion rates.
- Sea Ice – To improve seasonal reconstructions of past changes in sea ice cover for a better quantification of the albedo and ocean-atmosphere gas exchange of the high-latitude oceans, and to understand regional climate dynamics.
- Continental Ice and Sea Level – To improve the reconstruction of the extension, geometry and volume of past ice sheets and their freshwater discharges to surrounding oceans, and to produce a master sea level curve for the last glacial-interglacial cycles.

Implementation

The Focus 1 Secondary Forcings Theme has a number of Working Groups (WGs) established (Fig. 2.1). The Palaeofire WG was formed through collaboration with other IGBP Core Projects (AIMES and iLEAPS). This group will hold several regional workshops to gather palaeofire information from areas that were left underrepresented in the group's predecessor, the IGBP Fast Track Initiative on Fire. The Paleo-Constraints on Sea Level Rise (PALSEA) WG resulted from a mid-2008 IMAGES-PAGES workshop, "Empirical Constraints on Future Sea-Level Change", and is planning a series of another four workshops before 2012. A comprehensive overview of sea level projection from a palaeo-perspective will be the major final product, intended to be produced in time for the fifth assessment report of the IPCC. The Past Atmospheric Dynamics (ADOM) WG will study aeolian records from ice, terrestrial and marine archives in combination with atmospheric modelling to reconstruct dustiness and atmospheric circulation patterns over the last glacial cycle.

Additional activities will be organised with the aim to:

- Promote a PalaeoCarbon Modelling Intercomparison Project (PCMIP) activity on palaeo-carbon system modelling, as an intersection activity with AIMES and the CLIVAR WG on Coupled Modelling (WGCM), where modellers discuss current results and plan standard simulations.
- Develop regional-scale land cover reconstructions in close collaboration with PAGES Focus 4 and the Integrated History and Future of People on Earth (IHOPE) project, a joint AIMES, PAGES and IHDP initiative.
- Synthesise palaeodata, model sea ice cover, and develop new proxies for palaeo sea-ice reconstructions. This effort will involve the PAGES/CliC Intersection, IMAGES, and the International Trans-Antarctic Scientific Expedition (ITASE).

Linkages

PAGES anticipates close collaboration and linkages with the efforts of several internal and external groups. Questions around orbital solar insolation will involve palaeoceanographic groups organised within the International Marine Past Global Changes Study (IMAGES) and Integrated Ocean Drilling Program (IODP), and various ice core groups under the International Partnerships in Ice Core Sciences (IPICS) umbrella. Solar and volcanic forcing, as well as a number of secondary forcings relevant to millennial timescales, fall within the scope of the PAGES/CLIVAR Intersection, which will therefore be instrumental in supporting related activities. Towards a greater understanding of the role of fire as a climate forcing, expected links beyond the IGBP Palaeofire WG are with AIMES, iLEAPS, and possibly other IGBP projects. The PALSEA WG will interact with the Past Interglacials (PIGS) WG and IMAGES, and maintain links with modern sea level researchers in the realm of the World Climate Research Programme (WCRP), LOICZ and SOLAS. CO_2 fluxes measured by SOLAS in the ocean and in association with sea ice dynamics can assist in the interpretation of palaeodata, in order to quantify atmosphere-ocean gas exchange processes. The ADOM WG, studying the role of dust in the climate system, will interact with IPICS, IMAGES, QUEST-Dust and PIGS for the palaeo-component, and seek interaction with the International Global Atmospheric Chemistry (IGAC) Project for modern process expertise.

Focus 2: Regional Climate Dynamics

This Focus seeks to achieve a better understanding of past regional climatic and environmental dynamics through comparison of reconstructions and model simulations. Activities contribute towards a global coverage of high-resolution, well-dated palaeoclimatic data, reconstructions of past climate-state parameters (e.g., temperature, precipitation, atmospheric pressure fields), a better understanding of past modes of climate variability and their teleconnections, and of rapid and extreme climate events at the regional scale. The Focus hosts activities that promote data-model comparisons and collaborates closely with Cross-Cutting Theme 2 on proxy development and calibration. The timescales covered by this Focus encompass the last 130 ka, in particular the time streams of the last glacial-interglacial cycle, the Holocene and the last 2 ka.

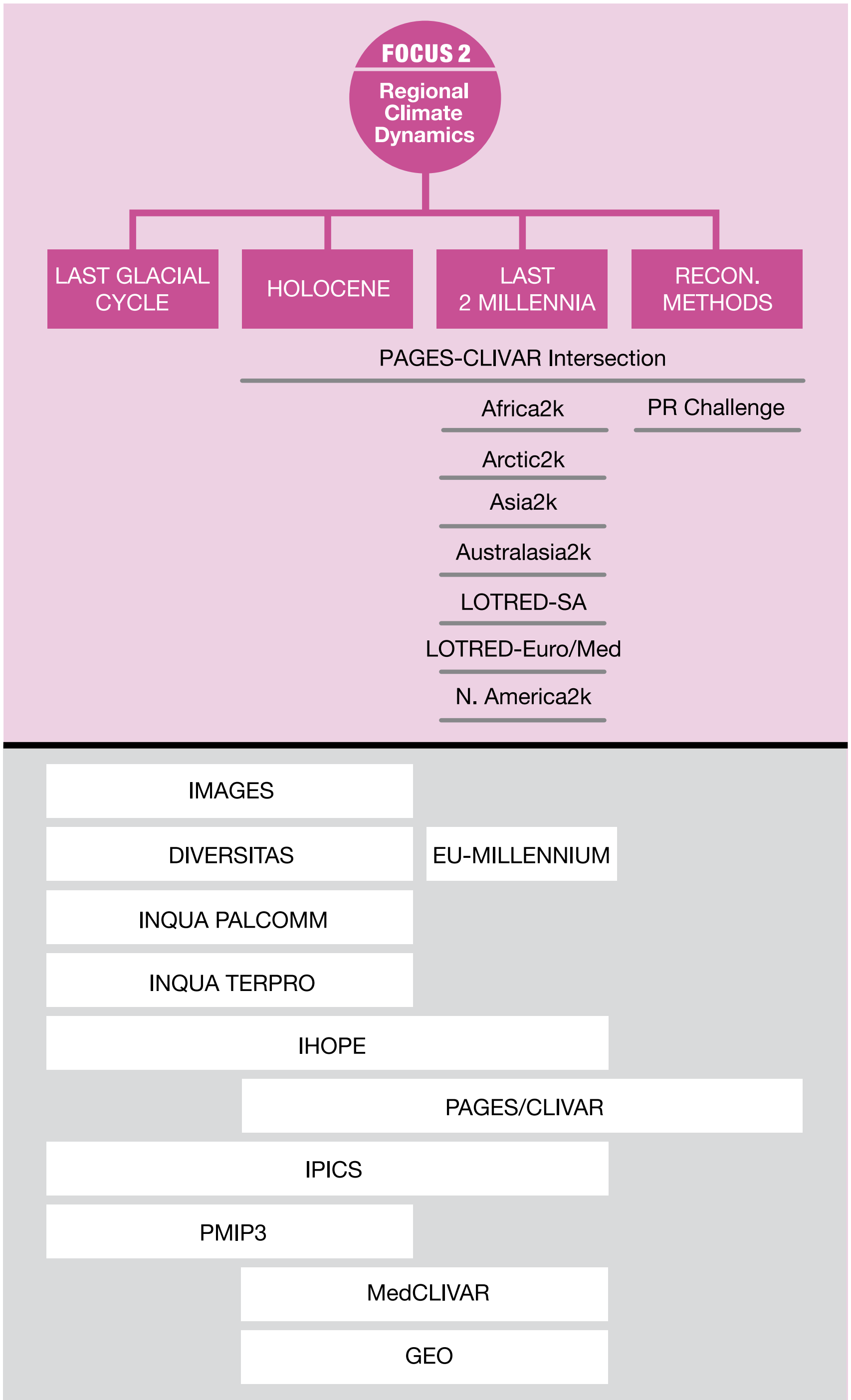

Figure 2.6: Structure of Focus 2. Top: Focus Themes (pink boxes) with their corresponding Working Groups below. Bottom: Overlap with external programmes and projects (white boxes). For explanation of acronyms, see Acronyms and Abbreviations List.

Overarching Questions

- How did regional climate and the Earth's natural environment change in the past?
- What are the main patterns and modes of climate variability on sub-decadal to orbital timescales?
- How do climate variability and extreme events relate to the mean state of the climate system?

Rationale

During the past three decades, the focus of palaeoclimatology has been to diagnose global and Northern Hemisphere climate variability, including teleconnections, rapid transitions, feedbacks and modes of operation of the climate system. The major issues of detection and attribution of present climate change have been largely settled. Now questions relate increasingly to the regional climatic and environmental responses to global change, as these affect societies and form the basis for efficient adaptation measures. Accordingly, the IPCC AR4 WG1 dedicated an entire chapter to regional climate projections (Chap. 11: Christensen et al., 2007) and a GCOS-WCRP-IGBP team evaluating the AR4 concluded that research that improves the performance of regional climate change models, for example, by more rigorous model validation (Bojinski and Doherty, 2008), was now a priority. Likewise, the U.S. National Research Council (2006) called for regional reconstructions of a range of relevant climatic variables.

Information on past climate dynamics at the regional scale allows us to characterise local amplitudes and rates of change. Furthermore, it allows us to better assess the consequences of current and future changes, by providing a context for observed climatic-environmental change, long-term records to analyse multi-decadal and slower processes, and benchmark scenarios for general circulation models. Consequently, Focus 2 places a strong emphasis on regional studies that consider past climate dynamics on seasonal to millennial timescales and (sub-)continental or ocean-basin spatial scales. Inclusion of a suite of climate parameters will overcome the hitherto overemphasis on temperature reconstruction, which is a rather poor diagnostic of climate system dynamics. Studies in this Focus include multi-proxy reconstructions of the key climate parameters, and transient palaeo-runs with models of different complexity and resolution.

This procedure allows us to investigate how the specific patterns, modes and regimes of climate variability have changed over time, and provides an opportunity to study how strongly regional patterns are dominated by internal variability of the climate system. In close coordination with Focus 1, Focus 2 addresses these questions by including regions that currently have low data density, such as the tropics and the Southern Hemisphere. In addition, Focus 2 provides regional-scale information that builds the basis for global-scale integrative studies within Focus 3, and for analysis of the climate-environment interaction with humans on historical timescales in Focus 4.

State of Science and Knowledge Gaps

Advances in modelling techniques, which now allow atmosphere-ocean-biosphere coupling, high spatial resolution, transient runs and representation of climate modes (Claussen et al., 2002; Braconnot et al., 2004; see also CCT 3), have increased the need for regional proxy datasets that are well-dated, of high resolution and carefully calibrated (Gladstone et al., 2005). New analytical techniques have increased the array of proxies and archives used for palaeoscientific studies (e.g., ice cores, corals, tree rings, speleothems, boreholes, documentary data, soils and landforms, and marine, lake and other sediments), forming an increasingly rich base for data synopsis and data-model comparisons (Jones et al., 2009). Improving chronologies (see CCT 1), proxy development (see CCT 2) and database infrastructure further advance our understanding of the climatic sensitivity and environmental response at the regional scale. However, reconstructions are biased towards the northern mid-latitudes, with tree ring chronologies being the dominant proxy for late Holocene studies. Furthermore, there is uncertainty about the performance of the various reconstruction techniques, and a lack of complete understanding of the dynamics that drive regional changes and their far-field teleconnections.

As a result of increased spatial coverage of palaeoclimatic data, new model experiments and iterative efforts to compare data and model results, past global to regional scale climate dynamics are becoming better understood for a variety of timescales (e.g., Rutherford et al., 2005; Mann et al., 2007 and references therein).

Focus 2 Structure

Focus 2 is structured into four Themes (Fig. 2.6):

- Last Glacial Cycle
- Holocene
- Last 2 Millennia
- Spatio-Temporal Reconstruction Methods

The first three are differentiated by their distinct temporal scope and associated temporal resolution, while the fourth is methodological in nature.

Theme: Last Glacial Cycle

Major advances have been made in reconstructing and understanding glacial-interglacial cycles. Knowledge of greenhouse gas forcing has been gained from ice core records, and climatic timeseries from both hemispheres (Fig. 2.7) have been better synchronised into consistent age models (Shackleton et al., 2000; Roucoux et al., 2005; Brauer et al., 2008). Together with the Paleoclimate Modelling Intercomparison Project Phase II (PMIP2) model experiments and the Multiproxy Approach for the Reconstruction of the Glacial Ocean Surface (MARGO) project's spatial time-slice reconstruction of the Last Glacial Maximum surface ocean (Kucera at al., 2005), these efforts have advanced our understanding of the sensitivity and response of the climate system to natural forcings and feedbacks, such as changes in insolation, greenhouse gases, ice cover and ocean circulation. However, we still lack comprehensive understanding of the causes of carbon cycle changes, the amplifiers of orbital forcing, and the inter-hemispheric coupling of glacial-interglacial and millennial-scale abrupt climate change. High- to low-latitude comparisons (e.g., the Pole-Equator-Pole (PEP) transects; Markgraf, 2001; Battarbee et al., 2004) have shown, for example, that the millennial Dansgaard-Oeschger cycles recorded in Greenland ice cores also occur at low latitudes (e.g., Cruz et al., 2005). However, it is not yet clear what drives them and how they are transmitted globally, or how ecosystems responded to the substantial and rapid climate fluctuations.

The primary emphasis of post-glacial studies has been on events of rapid change during deglaciation and the early Holocene, in particular the Younger Dryas cold event (12.9-11.6 ka) with its abrupt termination (Steffensen et al., 2008), and the 8.2 ka event. These episodes provide opportunities to study regional environmental dynamics associated with rapid climate change (e.g., Fig. 2.8).

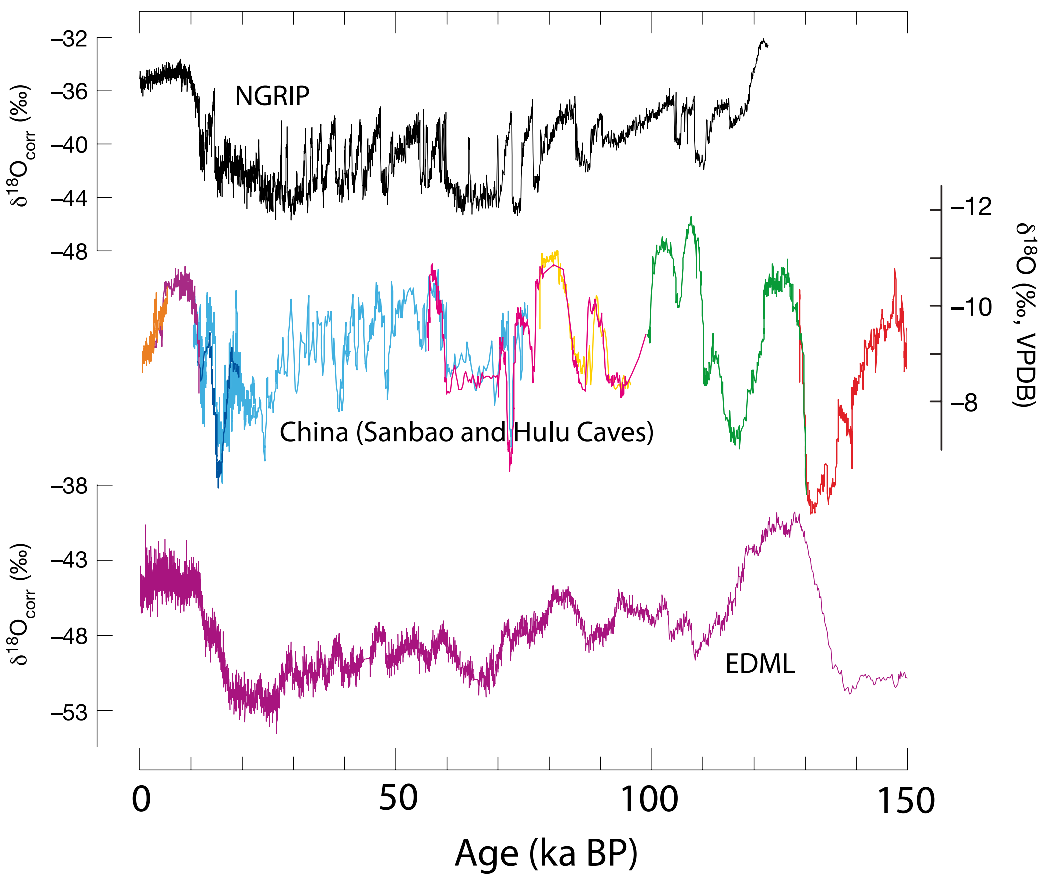

Figure 2.7: One-to-one coupling of glacial climate variability in Greenland (black; NorthGRIP, 2004), Antarctica (purple; EPICA Community Members, 2006) and the East Asian monsoon region (coloured; Wang et al., 2008).

Theme: Holocene

Holocene research has also focused on regional climate responses to slowly varying changes in the climate system, particularly the amplification of the seasonal insolation cycle. Proxy data, for example, record the influence of the Northern Hemisphere summer insolation maximum in the early Holocene on Arctic sea-ice cover, vegetation and fire regimes, mountain glacier size, and subtropical monsoon strength. In contrast, parts of the tropics appear to have been colder during the early Holocene than the pre-industrial era (Fig. 2.9, see summary in IPCC AR4 Chap. 6: Jansen et al., 2007). On multi-decadal to multi-centennial timescales, it remains ambiguous whether stationary climate cycles exist, and how climatic and environmental variability relate to solar and volcanic forcing, sea ice, and ocean thermohaline circulation changes (Wanner et al., 2008).

Theme: Last 2 Millennia

Research on the last 1 to 2 ka has resulted in several multi-proxy reconstructions of global or hemispheric temperature (e.g., Rutherford et al., 2005; Moberg et al., 2005; Mann et al., 2008, and references therein; see Jones et al. 2009 for a review). Many of these synthesis reconstruction studies differ from each other by applying different methodologies but are usually based on the same limited number of datasets. Regional activities to increase spatial coverage of individual datasets will be a major step towards a more appropriate data basis. In addition, first attempts have been made to reconstruct other climatic parameters at high spatial and temporal resolution (e.g., Luterbacher et al., 2004). For example, Figure 2.10 shows those seasonal patterns of 500 hPa geopotential height, temperature and precipitation that

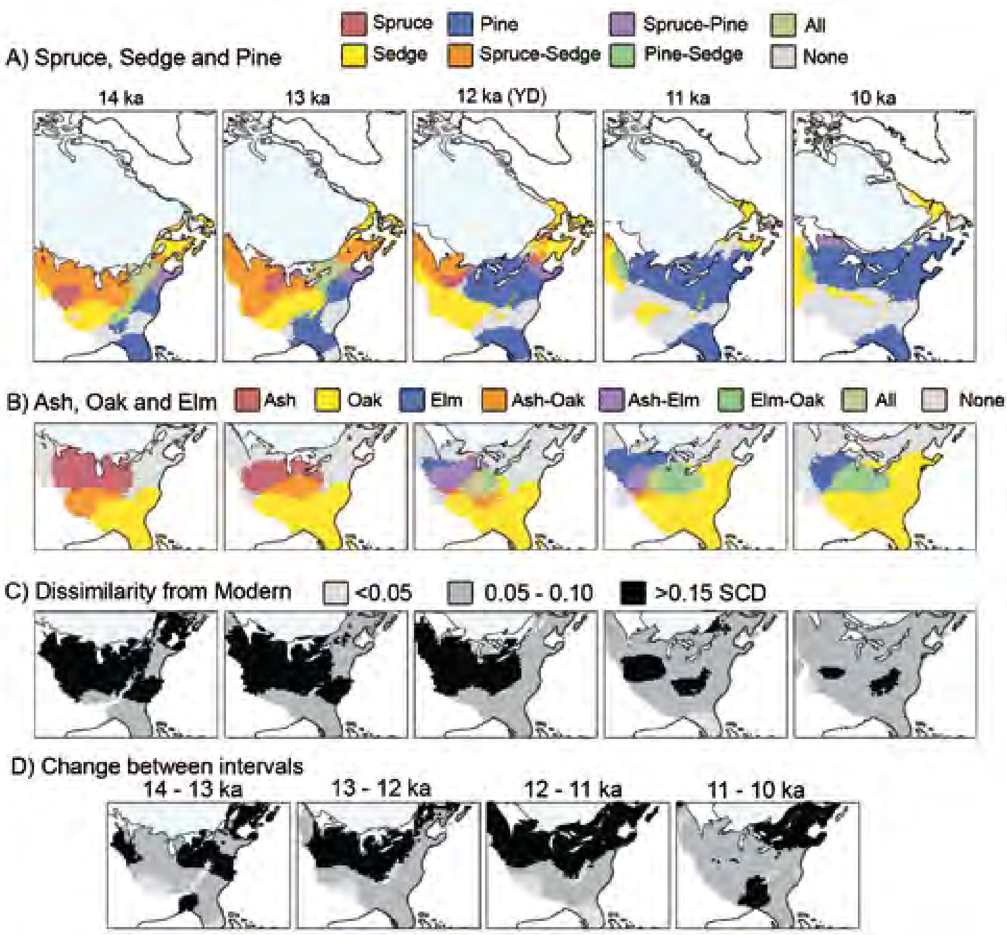

Figure 2.8: Example of a vegetation reconstruction during the last glacial-interglacial transition: Maps of plant associations and vegetation change at 1-cal-ka intervals between 14 and 10 cal ka BP. Colours illustrate different vegetation assemblages. Individual plant taxa are mapped as red, yellow or blue, with overlapping ranges represented by the combination of these colours to yield orange, purple, green or gold. Grey represents the absence of the mapped taxa, white represents regions with no data. Two combinations of three taxa are mapped: A) regions with greater than 20% spruce (*Picea*; red), 5% sedge (*Cyperaceae*; yellow), and 20% pine (*Pinus*; blue) pollen, and B) regions with greater than 5% ash (*Fraxinus*; red), 15% oak (*Quercus*; yellow), and 6% elm (*Ulmus*; blue) pollen. Maps of square chord distances (SCDs) represent the dissimilarity between fossil and modern pollen assemblages C). SCD values > 0.15 (black) represent pollen assemblages with no modern equivalent. Offset maps D) use SCDs to show the amount of change between 1-ka intervals. High SCDs document large changes (Shuman et al., 2002).

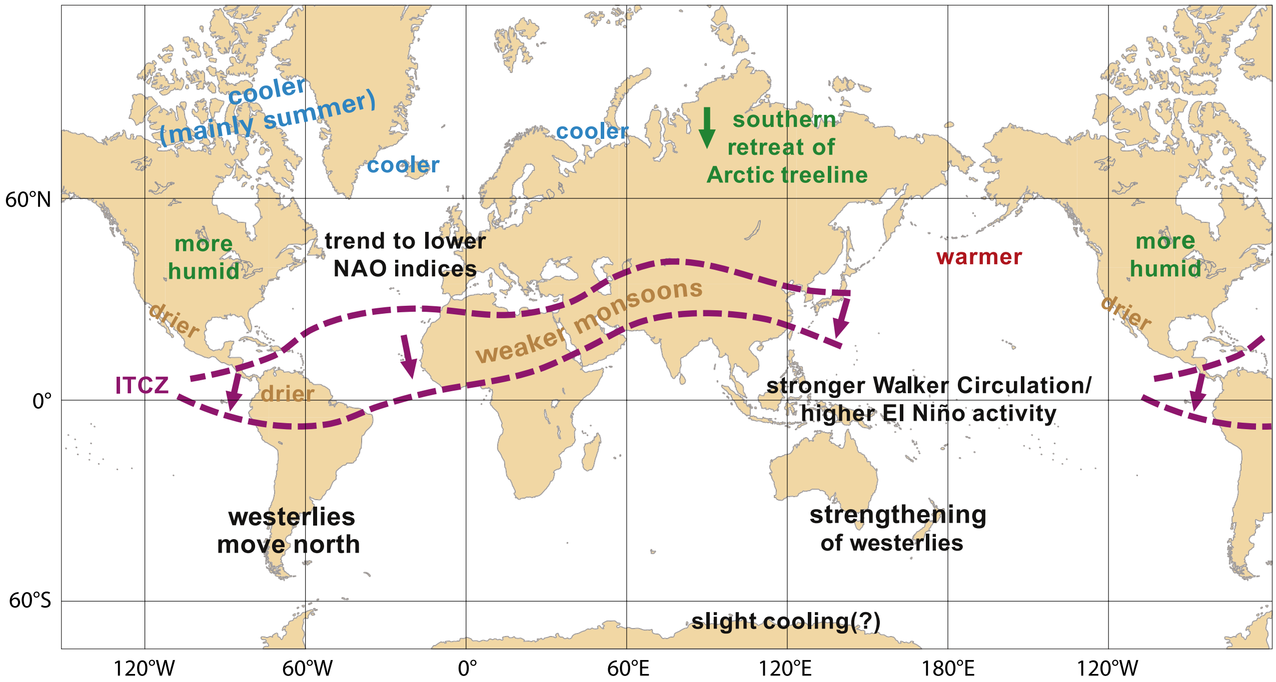

Figure 2.9: Spatial synthesis of Holocene climate trends from proxy evidence – global climate change for the pre-industrial period (ca. AD 1700) compared to the mid-Holocene (ca. 6 cal ka BP) (figure modified from Wanner et al., 2008).

explain the highest amount of combined variability over Europe during the time period AD 1766-2000. The study is based on the combined empirical orthogonal function (EOF) analysis of all three parameters using a gridded dataset, which was processed based on multi-proxy and instrumental data (Casty et al., 2007). The graphs in the bottom row represent the corresponding normalised principal components, which provide information about the strength of a certain pattern, for example, the remarkably positive trends for the NAO-like winter and spring patterns after the 1960s. This means very pronounced positive (red) or negative (blue) anomalies of 500 hPa geopotential, temperature and precipitation.

Despite significant progress over the last few decades, we still do not sufficiently understand the precise sequence of changes related to regional climate forcings, internal variability, system feedbacks, and the responses of surface climate, land cover and bio- and hydrosphere. Furthermore, at the decadal to centennial timescale we do not understand how sensitive the climate is to changes in solar activity, frequency of volcanic eruptions, greenhouse gas and aerosol concentration, and land cover. At the continental to regional scale, it is understood that climate is strongly modulated by internal variability, such as the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO) in the Atlantic area, and the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) in the Pacific area. However, the interactions of key processes at different temporal and spatial scales are not fully understood (Bengtsson et al., 2006). Moreover, many parts of the globe lack adequate palaeorecords for comparison with model simulations, and high-resolution (spatially and temporally) instrumental datasets are sparse. This is particularly true for the Southern Hemisphere and the tropics.

Theme: Spatio-Temporal Reconstruction Methods

Climate reconstructions from different methods and proxy datasets over the last millennia show general similarity in their depiction of large-scale mean temperature evolution, particularly at the decadal to centennial timescale (Fig. 2.11; Mann et al., 2008). There are, however, important differences at the interannual and multi-centennial to millennial scale. It is unclear how much these differences result from the selection of specific proxy datasets, the potential inability of proxies to resolve information at all timescales, or from the algorithms themselves (National Research Council, 2006).

A better understanding of the strengths and weaknesses of reconstruction procedures is essential, and will reduce uncertainties and biases. More detailed climate field reconstructions will provide this crucial understanding and benefit studies of future climate, particularly those focusing on the regional level targeted within PAGES Focus 2. Reconstruction methods developed for the last millennia may ultimately also be employed on longer timescales during the Holocene and the last glacial cycle.

Focus Goals

Focus 2 sets six main goals:

- To develop datasets that describe the patterns of past climate change and climate variability at the regional scale, including the major climate state variables, such as air pressure, temperature, precipitation or precipitation minus evaporation (P-E), and atmospheric and oceanic circulation patterns, for the last 2 ka and wherever possible during the last glacial cycle (last 130 ka).
- To examine the regional response of marine and terrestrial ecosystems to large-scale changes in the climate system. Activities towards this goal are being coordinated with Focus 4 and offer links to the International Programme on Biodiversity Sciences (DIVERSITAS).
- To better understand the mechanisms (natural and anthropogenic forcing, internal variability, feedbacks, sensitivity) operating in the climate system that determined regional variations (including abrupt and extreme climate events) of climate and environment over the past 130 ka (Fig. 2.7).
- To understand the modes of variability (such as ENSO/PDO, NAO/AMO), the teleconnections between them (Fig. 2.9), and their influence on regional climate history.
- To carry out ensemble simulations of past climate variability with suitable climate models of different complexity, in close coordination with the recon-

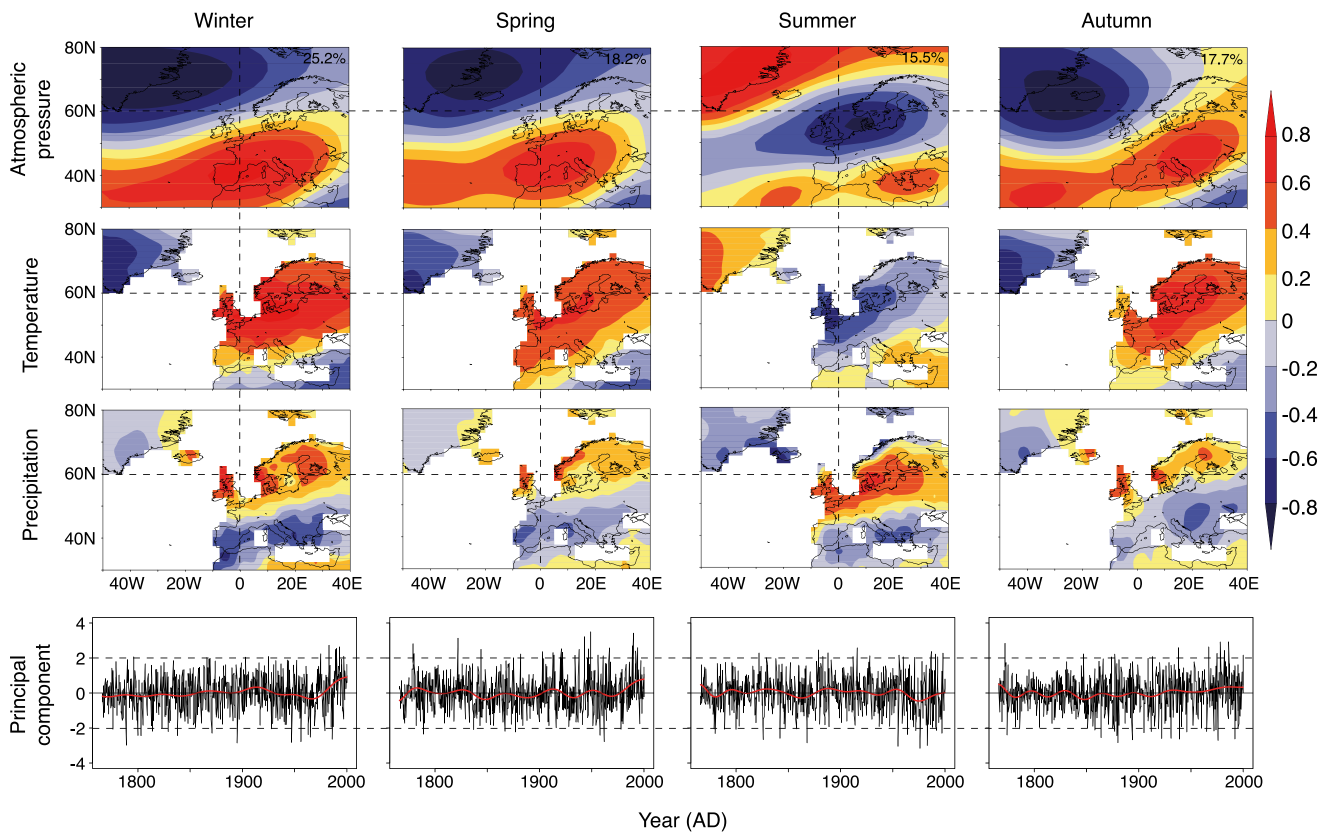

Figure 2.10: Example of a regional reconstruction (Europe) based on the LOTRED approach. Leading empirical orthogonal functions (EOF1) of the seasonal patterns of reconstructed 500 hPa geopotential height (top row), land surface temperature (second row) and land surface precipitation (third row), obtained from a combined linear EOF analysis of gridded multi-proxy and instrumental data for the period AD 1766-2000. Values indicate correlations. Bottom row shows graphs of the corresponding normalised principal components of the combined first EOFs for each year of the period AD 1766-2000 (black curves) and their multi-decadal trends obtained from a 31-year smoothing (red curves) (figure modified from Casty et al., 2007).

struction activities, and with Focus 1 and CCT 3.

- To support improvements in model development and data-model comparison approaches, to better constrain the drivers and mechanisms of regional climate change on different timescales.

Implementation

PAGES, together with other international projects (e.g., AIMES, CLIVAR, and IMAGES), focuses on an Earth System approach to understanding the long-term dynamics of the climate system (Alverson et al., 2003). Focus 2 addresses palaeoclimate studies at the regional scale, following, for example, the Long Term Reconstruction and Diagnostics (LOTRED) approach whenever the data density and quality allows it (Wanner and Luterbacher, 2002). Focus 2 envisages developing regional datasets and associated data synopsis and modelling studies, and archiving the datasets in leading data centres.

The activities of each Theme will be carried out by Working Groups (WGs) (Fig. 2.6). In particular, the Last 2 Millennia Theme has a large number of active WGs with a regional scope. These WGs aim to achieve a global network of regional synthesis of climate variability for the last 2 ka (Fig. 2.12). To this end, regional workshops will be organised. Meetings that then bring these regional groups together are envisioned, with the ultimate aim being to publish a global-scale synthesis.

The IGBP cross-programme Global Palaeofire WG is assigned to the Last Glacial Cycle Theme, as it specifically

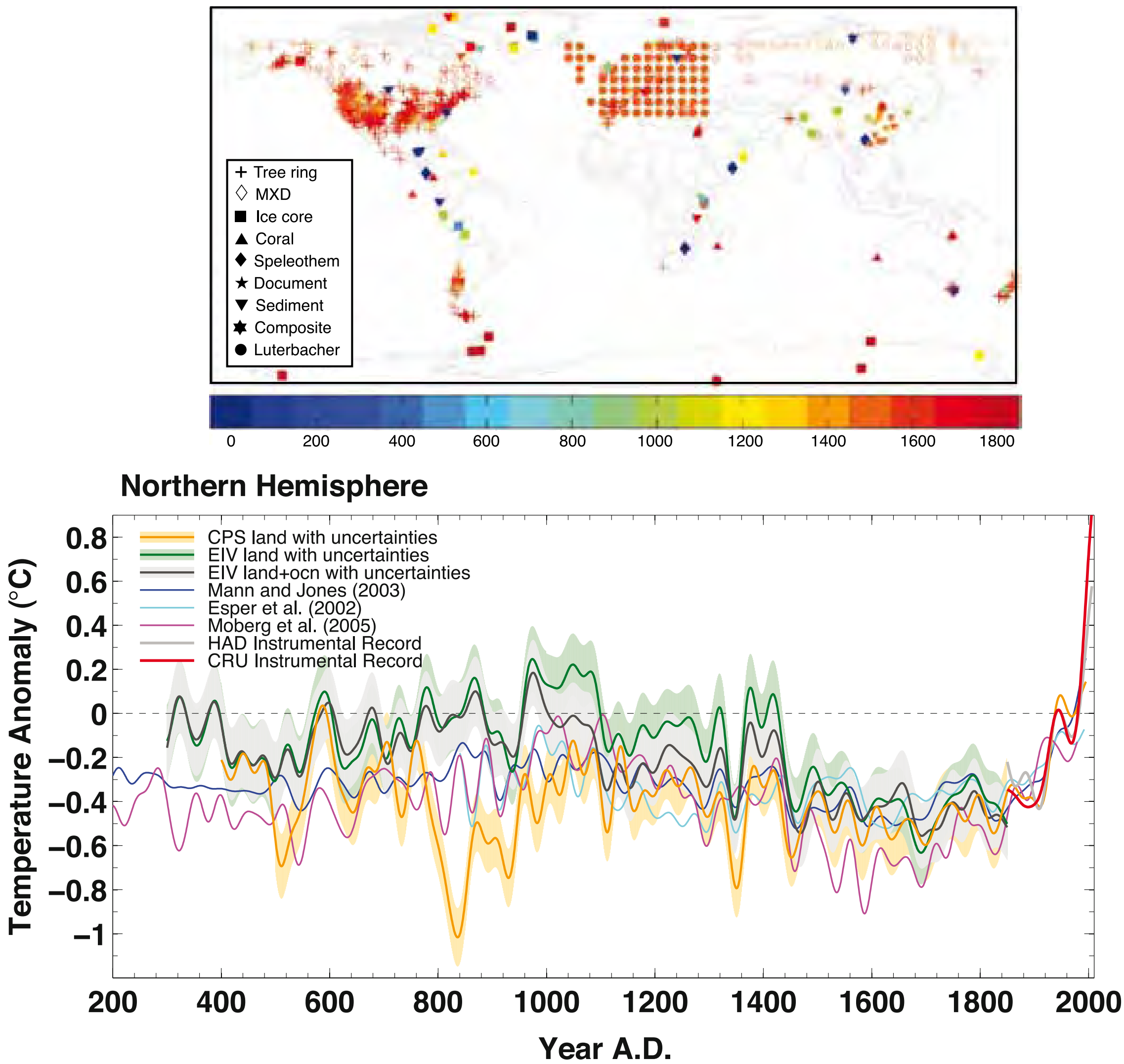

Figure 2.11: Spatial distribution of the proxy records (top; colour scale = starting dates of proxy records) used in the Northern Hemisphere surface temperature reconstructions (bottom), smoothed with a 40-year low-pass filter (figure from Mann et al., 2008; Copyright (2008) National Academy of Sciences, USA).

studies regional environmental dynamics over this period. Other WGs under the Holocene and Last Glacial Cycle Themes will be developed to bring together researchers currently working on these time periods. The Past Interglacials WG (see Focus 3) will contribute to both Themes through spatial studies of the last interglacial and the Holocene. Likewise, PMIP3 will contribute to an understanding of the last glacial cycle and the Holocene, with modelling of the mid-Holocene, the last interglacial and the Last Glacial Maximum, using Global Circulation Models (GCMs).

The Paleoclimate Reconstruction Challenge (PR Challenge) is a NOAA-supported project and PAGES WG under the Spatio-Temporal Reconstruction Methods Theme, and provides benchmarks for the reliability of proxy reconstructions (see www.pages-igbp.org/science/prchallenge/).

Linkages

Potential links with DIVERSITAS exist in the effort to understand the response of plant and animal communities to transient climate change during periods of rapid change, and will offer opportunities for stronger interaction between ecologists and palaeobiologists. For activities focusing on periods within the Holocene (including the last 2 ka) and on sub-millennial timescales, the well-established coordination with CLIVAR will continue, mainly through the PAGES/CLIVAR Intersection but also through the European Science Foundation's Med-CLIVAR project and the IPICS 2k Array. Cooperation with coordinated national and continental (e.g., European Union) programmes needs to be strengthened or established, respectively. Focus 2 science will contribute to IHOPE (see Focus 4) and to the Group on Earth Observations (GEO) Task CL-06-01 "Sustained Reprocessing and Reanalysis of Climate Data" and lead the Sub-Task "Extending the Record of Climate Variability at Global Scale". On longer (Pleistocene) timescales, Focus 2 will collaborate with IMAGES on palaeoceanography and with several IPICS groups on ice core research. Furthermore, goals overlap with those of the International Union for Quaternary Research (INQUA) Commissions on Terrestrial Processes, Deposits and History (TERPRO) and Palaeoclimate (PALCOMM). In particular, the activities of the INQUA Integration of Icecore, Marine and Terrestrial Records (INTIMATE) projects follow similar goals to the Last Glacial Cycle Theme, offering opportunities for cooperative activities.

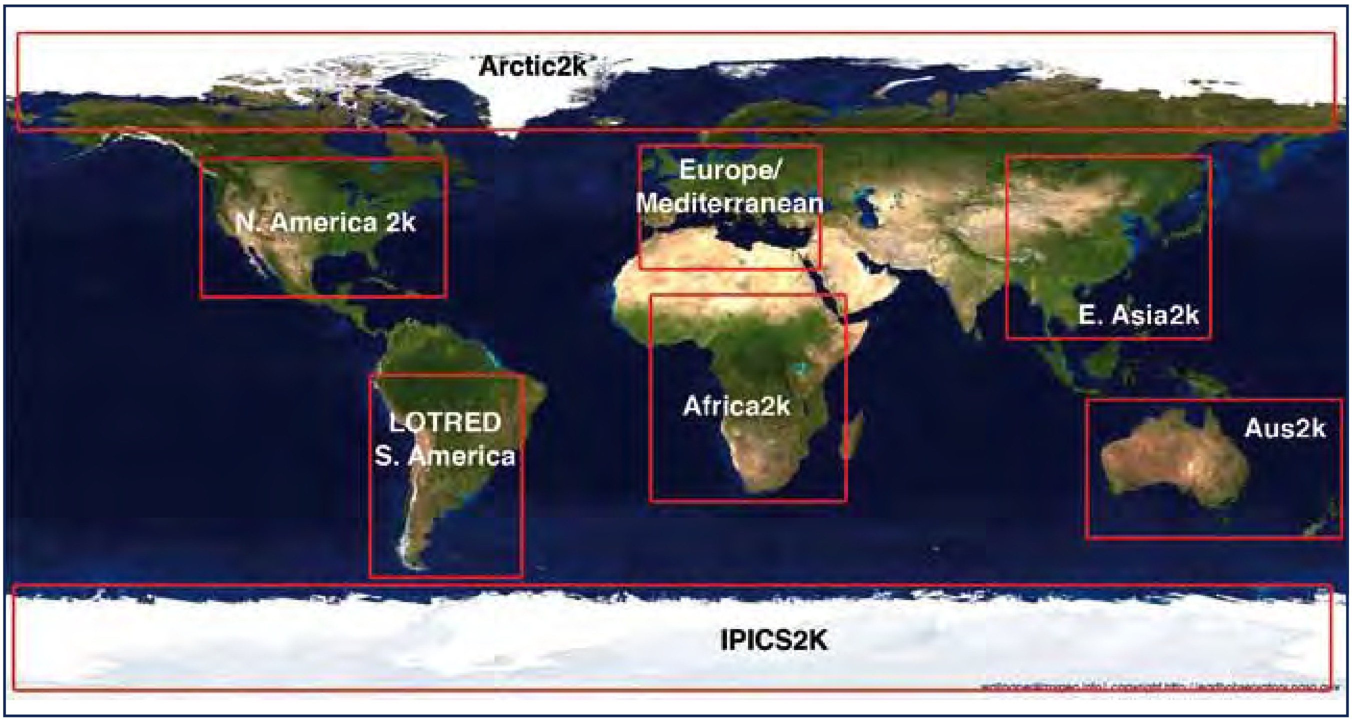

Figure 2.12: The distribution of the regional Working Groups that are active under the Last 2 Millennia Theme. Each regional group focuses on regional patterns, sensitivity and variability over the last 2 ka. The ultimate aim is to bring these results together into a global-scale synthesis (Map provided by NASA's Earth Observatory, 2009).

Focus 3: Global Earth-System Dynamics

This Focus looks at large-scale interactions between components of the Earth System (atmosphere, biosphere, cryosphere, hydrosphere) and the links between regional- and global-scale changes. It hosts activities to synthesise records at a global scale, acting as an umbrella for the regional studies of Focus 2 and as a link to the forcings addressed in Focus 1. Working Groups address global-scale abrupt and gradual Earth System changes and their underlying processes, including their response to changes in forcings, internal feedbacks and teleconnections.

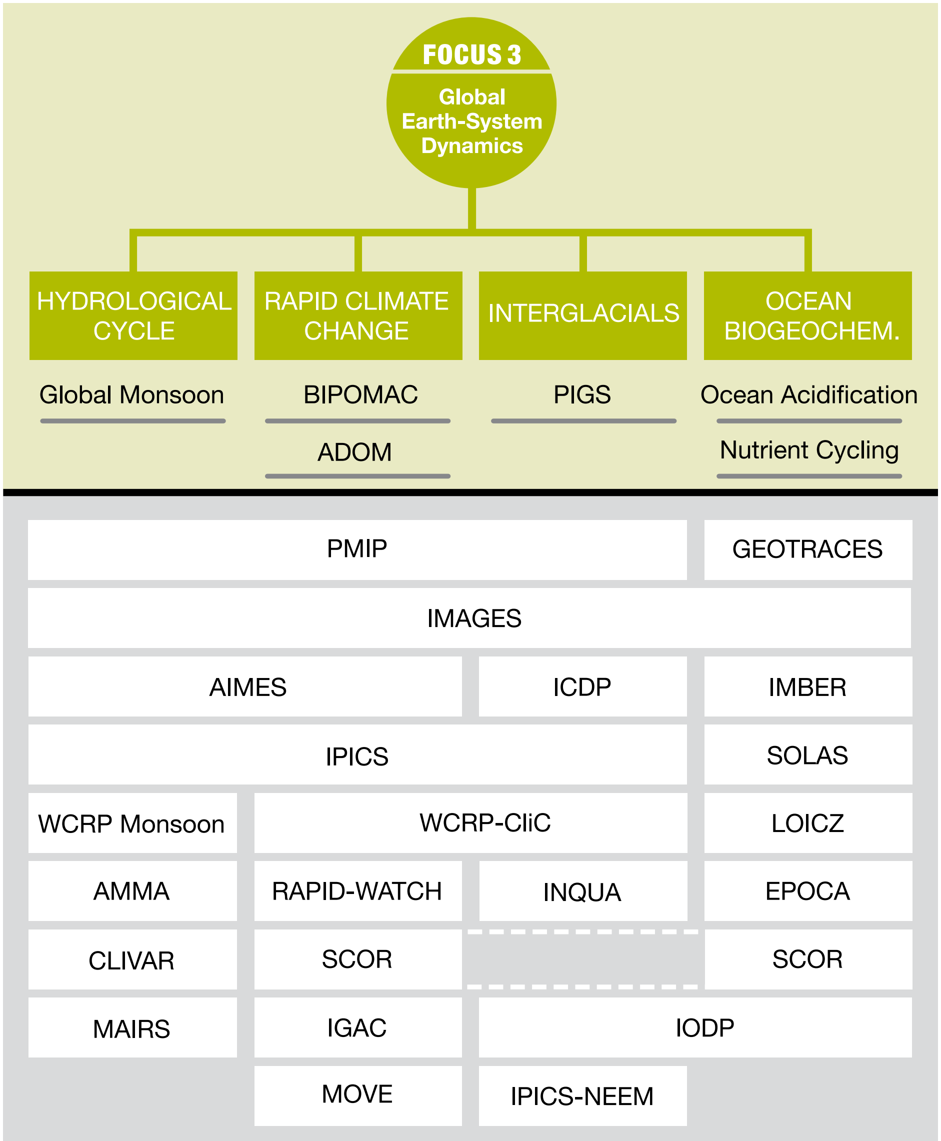

Figure 2.13: Structure of Focus 3. Top: Focus Themes (green boxes) with their corresponding Working Groups below. Bottom: Overlap with external programmes and projects (white boxes). For explanation of acronyms, see Acronyms and Abbreviations List.

Overarching Questions

- How do large-scale changes in the Earth System affect regional climatic and environmental conditions?
- How have regions or Earth System components interacted to produce climate and environmental variations on a global scale?
- What are the causes and thresholds of rapid transitions between quasi-stable climatic and environmental states, in particular on timescales that are relevant to society? How reversible are these changes?

Rationale

Humanity is currently carrying out a global-scale experiment in climate modification. By significantly and rapidly changing the forcing by greenhouse gases out of the envelope of late Quaternary conditions, we are testing the response of the system. The consequences of such an experiment will be the result of interactions between components of the Earth System. Therefore, we need to learn about these interactions, in particular about the non-linear and threshold responses that may exist. The impacts of the experiment will be felt as a result of regional changes in the pattern of precipitation, temperature and other climatic variables. We therefore have an urgent need to understand how global-scale changes are imprinted in individual regions and why.

The past provides numerous examples in which changes in forcing at the global scale have occurred, and others where a redistribution of climate patterns appears to have occurred in the absence of global-scale forcing, either because of a change in the spatial and seasonal pattern of forcing, or because of internal changes in the system. We can use the past to diagnose the patterns of change that occur under different scenarios. More specifically, by investigating how changes in different components of the Earth System and different regions were related in the past, we can test and improve the process understanding required for predictive models. Additionally, we can investigate whether the system has exhibited rapid changes, and possibly threshold behaviour.

Focus 3 Structure

Although processes that, by definition, involve the whole Earth System are difficult to divide into packets, the science of this Focus is considered under four Themes (Fig. 2.13):

- Variability of the Hydrological Cycle
- Rapid Climate Change
- Climate Variability within and between Interglacials
- Paleo-Perspectives on Ocean Biogeochemistry

This Focus can be seen as a global-scale umbrella and synthesis of Focus 2, and as the response to the forcings of Focus 1. Taken together, these aim to improve understanding of (mainly) natural processes that form the context for the human-induced issues of Focus 4.

Theme: Variability of the Hydrological Cycle

Rationale

The global hydrological cycle is of crucial importance for terrestrial ecosystems. Moreover, through the transport of large amounts of latent heat, cloud feedback processes and water vapour feedback, the hydrological cycle is also involved in the large-scale transfer of energy from low to high latitudes and partly controls climate sensitivity. Water availability is a key control of vegetation and, hence, faunal distributions. Observations suggest that the hydrological cycle varies on daily to inter-decadal timescales. Specifically, the detrimental effects associated with perturbations of the hydrological cycle (drought, flooding) are of major concern with respect to future climate change. Our current knowledge of the hydrological cycle and its sensitivity to changes in climate forcing, as well as its interactions with other components of the Earth System, is still incomplete. As a result, projections regarding, for example, future changes in precipitation, disagree not only in magnitude but also in the sign of the anticipated change in low-latitude terrestrial areas (IPCC AR4 WG1 Chap. 10: Meehl et al., 2007: Figs. 10.9, 10.12). Accordingly, there is an urgent need to better constrain the feedbacks associated with the hydrological cycle over a range of timescales.

State of Science and Knowledge Gaps

The largest natural variation of the hydrological cycle at a global scale is associated with the monsoon systems (Fig. 2.14). Palaeoclimatological data have been used successfully to demonstrate, for example, the variability of the Indian, East Asian and African monsoons at Milankovitch timescales (e.g., Wang et al., 2005a; Wang et al., 2008). At millennial to centennial timescales it has been shown that the monsoon systems varied in concert with rapid climate changes in the North Atlantic (e.g., An and Porter, 1997; Gupta et al., 2003; Mulitza et al., 2008.).

While the temporal evolutions of the regional monsoon systems are generally known, large uncertainties exist with respect to the sequence (phasing) of their response to global forcings. In addition, the potential interaction of interannual modes of climate variability (e.g., AMO, ENSO) and the global monsoon systems remains to be quantified.

Proxy data suggest major changes in the hydrological cycle at low latitudes during rapid climate changes (e.g., Schefuß et al., 2005). However, the potential role of feedbacks mediated by the hydrological cycle in rapid climate changes awaits quantification.

At millennial and shorter timescales, shifts in the position of the Intertropical Convergence Zone (ITCZ) have been linked to changes in the frequency of El Niño events (Haug et al., 2001), strength of the overturning circulation in the Atlantic Ocean (Stouffer et al., 2006) or high-latitude sea ice cover (Chiang and Bitz, 2005). Since some of the inferred triggers of ITCZ shifts are correlated with each other (e.g., sea ice cover and rate of meridional overturning), the underlying processes leading to the shifts are not fully understood.

Theme Goals

- To unravel the mechanisms causing variations in both the global and regional monsoon systems.
- To identify and understand teleconnections between global- and regional-scale monsoon variations and other components of the climate system.
- To disentangle the processes leading to shifts in the position and strength of the ITCZ at interdecadal to millennial timescales.

Implementation

Many activities defined within this Theme are carried out within the Global Monsoon Working Group. This WG includes both data producers and modellers, and integrates across all the regional monsoon systems, as well as across past and present timescales. Accordingly, activities within this WG involve cooperation with modern climatological projects of the WCRP cross-cutting Monsoon Initiative including regional components, such as the joint CLIVAR-GEWEX Asian Monsoon Experiment (GAME), and CLIVAR's Variability of the American Monsoon Systems (VAMOS) and Variability of the African Climate System (VACS), as well as the African Monsoon Multidisciplinary Analysis (AMMA) and links to the ESSP regional project Monsoon Asia Integrated Regional Study (MAIRS). The Global Monsoon WG constitutes a multi-year PAGES project that operates on the basis of cross-disciplinary, cross-timescale and cross-regional workshops, partly in collaboration with PMIP and CLIVAR modelling groups. A comprehensive synthesis publication is envisioned for 2011.

Theme: Rapid Climate Change

Rationale

The dominant climate feature of the last glacial period ca. 70-10 ka (and indeed of earlier ones) is the millennial-scale

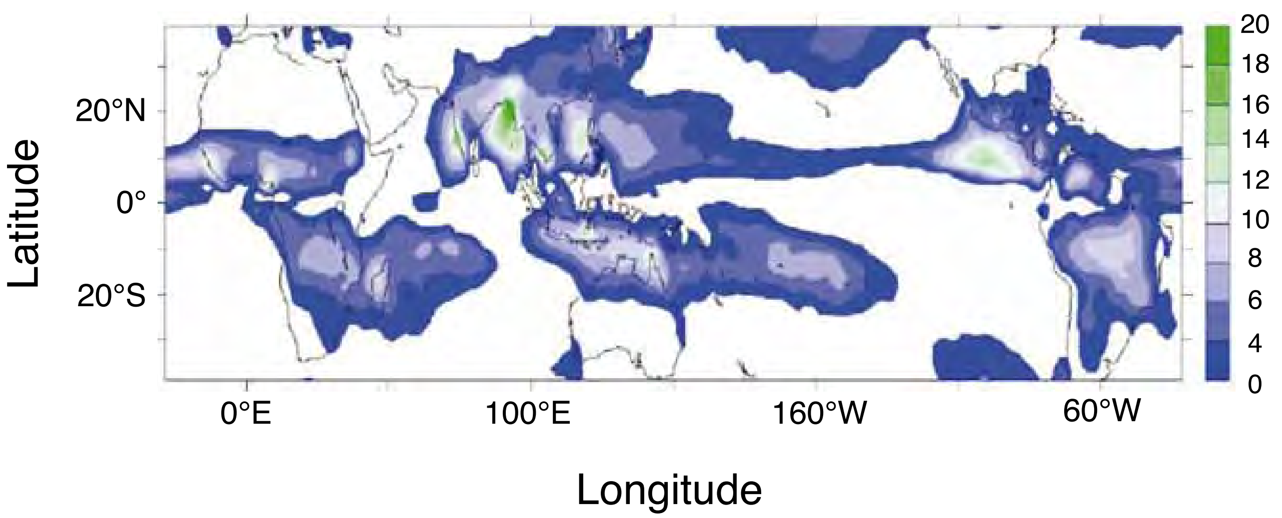

Figure 2.14: Observed difference between summer and winter precipitation (mm/day) showing the monsoon domains. Based on modern precipitation climatology of Xie and Arkin (1997).

changes most clearly observed as Dansgaard-Oeschger (DO) events and their counterparts, the Antarctic Isotopic Maxima (AIM) (Fig 2.15; EPICA Community Members, 2006). These events are widely believed to be due to changes in ocean heat transport, and they lead to extremely fast (years to decades) changes in atmospheric circulation and regional climate (e.g., Steffensen et al., 2008; Brauer et al., 2008). The question has been raised whether similar changes in ocean circulation could occur under future warming scenarios, and if so, what their effects on greenhouse gas concentrations and climate would be. By studying the magnitude and rate of past rapid climatic and oceanographic change and the relationship to associated forcings and feedbacks, we can assess the sensitivity of the Earth's oceanic and atmospheric circulation systems and associated climatic and environmental responses.

State of Science and Knowledge Gaps

The last glacial period includes numerous repetitions of rapid warmings and slower coolings (NorthGRIP Project Members, 2004). The Greenland ice cores indicate that warmings had amplitudes of up to 15°C (Masson-Delmotte et al., 2006) and were completed within decades. The warmings manifest themselves in many other Northern Hemisphere climate records, such as sea surface temperatures in the Atlantic (Shackleton et al., 2000), and in climate records as far afield as California (Behl and Kennett, 1996) and China (Wang et al., 2001). It has been shown that every DO oscillation has an AIM as a counterpart in Antarctica, and that Antarctica warms while Greenland is cold, and cools while Greenland is warm (EPICA Community Members, 2006) (Fig. 2.15). Furthermore, the ice core greenhouse gas record shows that atmospheric CO_2 concentrations correlate with climate changes in Antarctica (Lüthi et al., 2008). Atmospheric CH_4 concentrations show many of the millennial-scale features of Greenland climate records (EPICA Community Members, 2006).

The main hypothesis to explain these events is that they result from changes in ocean heat transport acting as a bipolar seesaw mechanism (e.g., Stocker and Johnsen, 2003; Knutti et al., 2004). Freshwater forcing in the north changes the location and rates of sinking of waters, and thus weakens or modifies the meridional overturning circulation (MOC), which spontaneously recovers to give a warming at a later stage. While this hypothesis has some explanatory power, there is not yet any agreement on whether the cycles are quasi-periodic. Furthermore, there is little direct evidence of the changes in MOC that are such an important part of the story (McManus et al., 2004). This makes it difficult to use these past abrupt events to test the effects of a given change in MOC on climate, and leaves room for alternative explanations (Partridge et al., 2004).

DO events are seen only under glacial conditions, including previous glacial periods (Jouzel et al., 2007; Loulergue et al., 2008). The only clear example of an event probably caused by changes in MOC in the Holocene is the 8.2 ka event (Thomas et al., 2007; Rohling and Pälike, 2005). This event was probably caused by the outburst of proglacial Lake Agassiz (Teller et al., 2002), and some palaeoceanographic evidence exists for MOC changes and their transmitting role in the causal chain (Ellison et al., 2006, Kleiven et al., 2008). For the rest of the Holocene, there is considerable controversy over the role of MOC changes in climate variability (Bond et al., 1997; Risebrobakken et al., 2003).

Possible future changes in MOC rely on a different direct causation to palaeo-events, and the likelihood of a significant slowdown in MOC is considered very small by the IPCC AR4 WG1 (2007). However, the underlying scenarios used to make this conclusion did not take into account the possible effect of enhanced meltwater input from the Greenland and Antarctic Ice Sheets into deepwater formation areas. Accordingly, there is a need to better synthesise the evidence on ocean circulation during past abrupt events and Holocene cycles. Data synthesis should be integrated with model simulations of ocean circulation perturbations and associated anomalies in climate, greenhouse gas and ocean tracers (e.g., Renssen et al., 2001; Legrande et al., 2006; Siddall et al., 2007; Schmittner et al., 2008), and include bipolar contrasts as well as responses radially within high- and low-latitude regions.

Theme Goals

- To combine well-dated records of centennial- to millennial-scale oceanographic and climatic change during the Holocene, the last glacial period and previous interglacials, using both bipolar and global comparisons of data with rigorous quality and age control.
- To characterise the rate of abrupt changes and their temporal relation to the underlying forcings and feedback processes.
- To use data compilations to assess hypotheses on the drivers and effects of past MOC changes, in order to inform assessments of the possibility of such changes in the future and of their potential impacts.

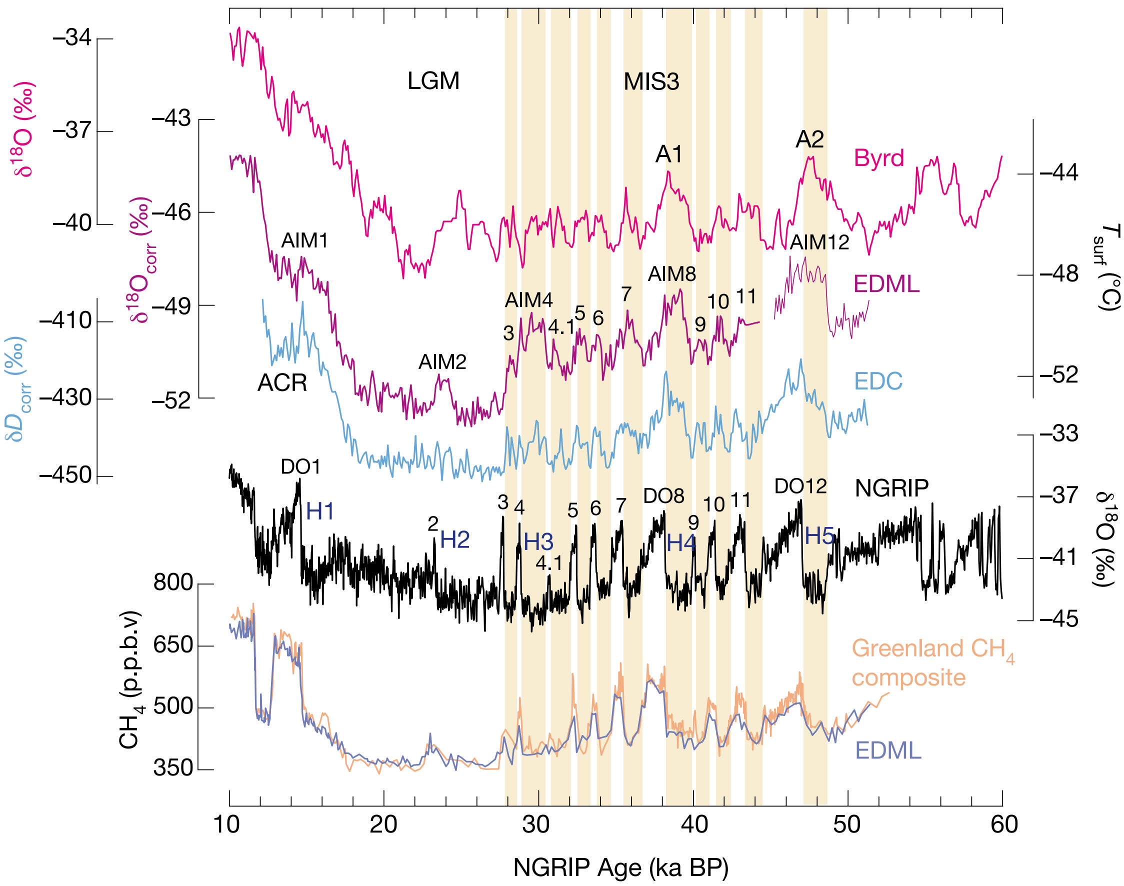

Figure 2.15: The bipolar seesaw, showing the sequence of Antarctic and Greenland warmings in DO and AIM events. (EPICA Community Members, 2006)

Implementation

Bipolar Machinery (BIPOMAC) is the leading WG for this Theme. BIPOMAC was initially a project of the International Polar Year and has subsequently been adopted as a WG by PAGES to pursue goals beyond the lifetime of the Year. The ADOM WG, which addresses atmospheric dynamics using aeolian deposits and modelling, will also provide a major contribution towards the Theme goals, as will the PIGS WG, by addressing whether abrupt events like the 8.2 ka event also occurred during previous interglacials. Instruments for synthesis within the Theme are special sessions at large conferences, aimed at bringing together marine, ice and terrestrial polar records of DO variability. Additionally, at least one workshop is required to synthesise signals of DO events and possible Holocene abrupt climate events around the world, and compare them with modelling results of abrupt changes. Activities in this Theme will seek close collaboration with IMAGES in order to obtain suitable palaeoceanographic records, particularly on ocean circulation, as well as with the IPICS 40,000 Year Network in order to synthesise ice core records of millennial-scale events around both polar regions. Research on rapid changes in the cryosphere (especially in sea ice, continental ice and permafrost) is now being addressed through scientific collaboration with the WCRP-CliC Intersection. Studies on past changes in the MOC will complement projects on monitoring of present-day Atlantic MOC changes, such as the U.K. Natural Environment Research Council's Rapid Climate Change (RAPID) and Will the Atlantic Thermohaline Circulation Halt (RAPID-WATCH) programmes, and the Meridional Overturning Variability Experiment (MOVE) of the SIO/NOAA Joint Institute of Marine Observations. These programmes may provide opportunities for cross-timescale collaboration in the future.

Theme: Climate Variability within and between Interglacials

Rationale

Both the ice core (e.g., Jouzel et al., 2007) and marine (e.g., Lisiecki and Raymo, 2005) records show that the most prominent climate signal of the last 800 ka is the alternation between long cold periods (with large ice sheets on the North American and Eurasian continents) and relatively short periods of interglacial warmth (Fig. 2.16). For the last ca. 1 Ma, these interglacials have recurred on average every 100 ka, with a dominant 40 ka periodicity prior to this. The interglacials are particularly compelling periods of interest because we live in such a period. Some earlier interglacials were warmer than the present one, at least in the polar regions, and probably associated with lower meridional temperature and pressure gradients. Although the cause of warmth was different from the cause we expect in the next century, they still offer the possibility to discover how the Earth behaved under a range of interglacial conditions. In particular, we can investigate whether increased warmth led to the loss of a significant part of either the Greenland or West Antarctic Ice Sheets, and whether warmer conditions and reduced meridional temperature and pressure gradients favoured certain feedbacks in the climate system.

State of Science and Knowledge Gaps

Investigations of glacial-interglacial change in the frequency domain show that seasonal and latitudinal variations in insolation due to changes in Earth's orbit drive the climatic changes seen (Hays et al., 1976), while the strength of major warmings implies that amplification, particularly through albedo and greenhouse gas changes (Siegenthaler et al., 2005; Lüthi et al., 2008), is essential. However the reason for the long period between interglacials, and the exact timing and sequence of events at major warmings, remains obscure (e.g., Shackleton, 2000).

Each interglacial is different; having a different amplitude, length and trajectory (Fig. 2.16). If we wish to understand the underlying drivers of interglacial climates, we need to compile the spatial pattern of each interglacial. While some interglacials appear to be clearly cooler than the present (EPICA community members, 2004), others appear significantly warmer. Marine isotope stage 5e was approx. 4°C warmer than present in the Antarctic (Jouzel et al., 2007) and probably 3-5°C warmer in the Arctic (NorthGRIP Project Members, 2004; Otto-Bliesner et al., 2006). Sea level was most likely 4-6 m higher than present, implying that one or both of the Greenland or West Antarctic Ice Sheets may have been significantly smaller than they are now (Overpeck et al., 2006). Understanding which ice sheet was reduced and by how much would place significant constraints on model estimates of the effects of warming on ice sheets (e.g., Gregory et al., 2004). Furthermore, it has been suggested that very fast sea level changes may have occurred during the last interglacial, marine isotope stage 5e (Rohling et al., 2008), and confirmation or denial of this is clearly important in view of recent concerns of

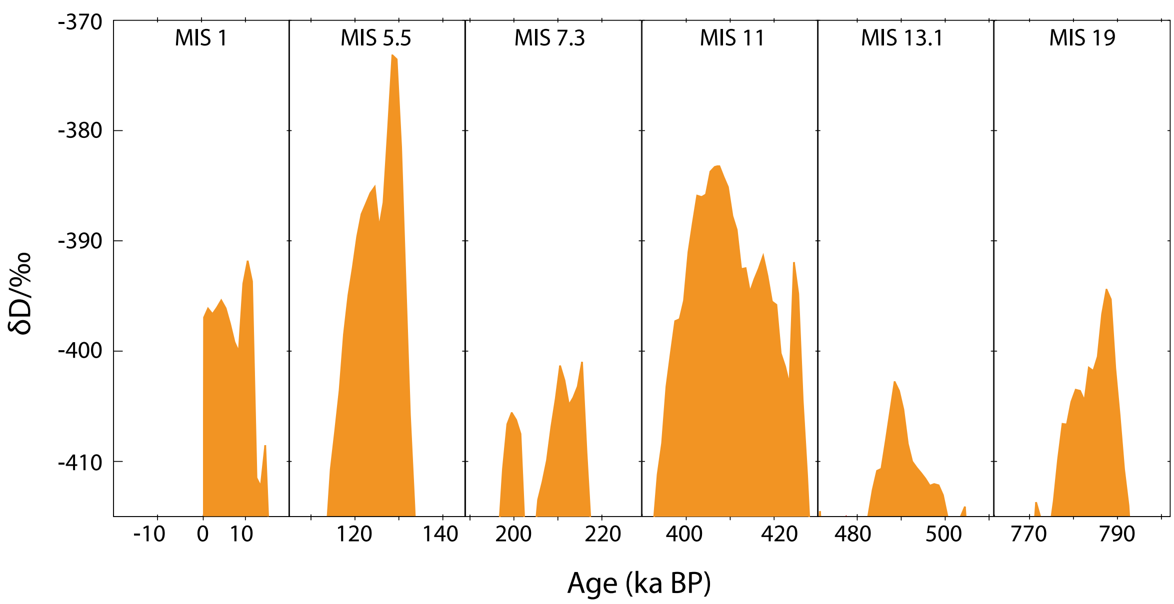

Figure 2.16: The evolution of Antarctic temperature (represented by deuterium content) across a selection of interglacials. Data are shown as 1 ka averages, based on Jouzel et al. (2007). Interglacials can be warm or cool, long or short, and vary in shape.

ice sheet stability. Other warm interglacials are also of interest in this context, particularly marine isotope stage 11, for which sea level estimates are highly uncertain, ranging from almost zero (McManus et al., 2005) to a 20-m rise (Hearty et al., 1999). A further interest of this Theme is to determine whether the high-frequency climate variability of past (especially warmer) interglacials was similar to that of the present interglacial, which is essentially unknown.

Theme Goals

- To combine well-dated records of multiple glacial cycles over at least the ice core era (800 ka), with the particular goal of understanding the spatial pattern and temporal trends within interglacials.
- To constrain the extent of changes in sea level and ice-sheet extent in past interglacials (link to Focus 1 and PALSEA).
- To determine the variability at multi-annual to millennial timescales within warmer interglacials of the last 800 ka.

Implementation

The Past Interglacials Theme will work with national and regional programmes that address the topic, and will provide an international coordination link between them. The Past Interglacials (PIGS) WG leads the implementation of scientific activities for this Theme. The Theme goals will be addressed in a series of workshops, some of them jointly organised with the sea level WG PALSEA and with the PMIP3 sub-group modelling the last interglacial period. This thematic overlap will maximise workshop output and benefit. Furthermore, formation of an intercomparison project on past interglacial ice sheet modelling with the aforementioned programmes, will be encouraged. Along the way, collection and archiving of well-dated and highly resolved records is envisioned and should eventually lead to spatial reconstructions of past interglacials. A workshop integrating results from across the entire Theme and a synthesis publication are planned for around 2012. Collection of long records that include several past interglacials requires specialised surveying and sampling strategies. Programmes dedicated to recovering long climatic records are obvious potential partners for this Theme, and include IMAGES, IODP, the International Continental Scientific Drilling Program (ICDP), and the deep drilling programmes of IPICS. Moreover, ample thematic overlap exists with INQUA.

Theme: Paleo-Perspectives on Ocean Biogeochemistry

Rationale

Marine biogeochemical dynamics can provide strong feedbacks on climate change. Global-scale variations in marine plankton productivity, ecosystem structures and nutrient cycling inevitably shift carbon and nitrogen budgets within the Earth System, and therefore are effective in modulating greenhouse gas concentrations in the atmosphere. Other more immediate economic aspects of marine ecosystems relate to their role as a food source, and their importance for biodiversity and protection of coastlines. Future global change is expected to greatly affect the ocean, for example, through the uptake of CO_2 and the resulting acidification, through changes in macro- and micronutrient inputs from land to ocean, and through global warming-induced water stratification and ocean circulation changes. This Theme therefore focuses specifically on past ocean biogeochemistry.

State of Science and Knowledge Gaps

While it is evident that the ocean plays a major role in the global carbon cycle, the various processes involved are difficult to quantify and their future trends hard to predict. Palaeodata provide benchmarks of past changes and constraints on possible future change, especially with respect to biogeochemical processes that take place over decades or centuries, such as ocean circulation or ecosystem adaptation. However, few datasets are comprehensive enough to inform on global-scale issues.

Marine biogeochemical processes act with physical oceanographic processes to control the exchange of carbon with the atmosphere and with the solid Earth. For example, sinking of biomass from the ocean surface layer or ecosystem shifts between carbonate and silica producers in response to seawater pH changes can impose feedbacks on the climate system at a magnitude relevant to global budgets.

A number of studies have reconstructed changes in oceanic phytoplankton productivity at regional or basin-wide scales (e.g., Sarnthein and Winn, 1990; Kohfeld et al., 2005). However, there is no consensus on the efficiency of carbon sequestration in the ocean by marine plankton, the so-called “biological pump”, at a global scale under climatic conditions different from today. Knowledge gaps exist at glacial-interglacial to multi-decadal timescales, in particular with respect to the availability of limiting macro- and micronutrients and associated changes in plankton productivity and community structures. A specific research need also exists to explore the operation of the nitrogen cycle in the past, for which N-isotope proxy data suggest major changes between glacials and interglacials (e.g., Galbraith et al., 2008; Fig. 2.17) and across rapid climate change events (e.g., Altabet et al., 2002).

Additionally, questions remain on the role of iron, an indispensable micronutrient for phytoplankton growth, in marine biogeochemistry. There is ongoing debate about the efficiency of iron fertilisation in sequestering carbon in ocean regions with excess macronutrients, and about the dominant processes of natural iron delivery to the surface ocean layer, with opinion split as to whether continental shelf sediment or aeolian mineral dust is the major source (e.g., Moore and Braucher, 2008). More subtle feedbacks can arise from the impact of, for example, iron on the shell structure of diatoms (Takeda, 1998) and, hence, the efficiency by which carbon can be transferred from the photic zone to the deep sea.

Ocean acidification (the lowering of seawater pH, e.g., due to increased uptake of atmospheric CO_2) affects the marine carbon system and ecosystems, and induces climate feedbacks. Acidification may reduce the ratio of calcifying to non-calcifying organisms and, through changing sea-

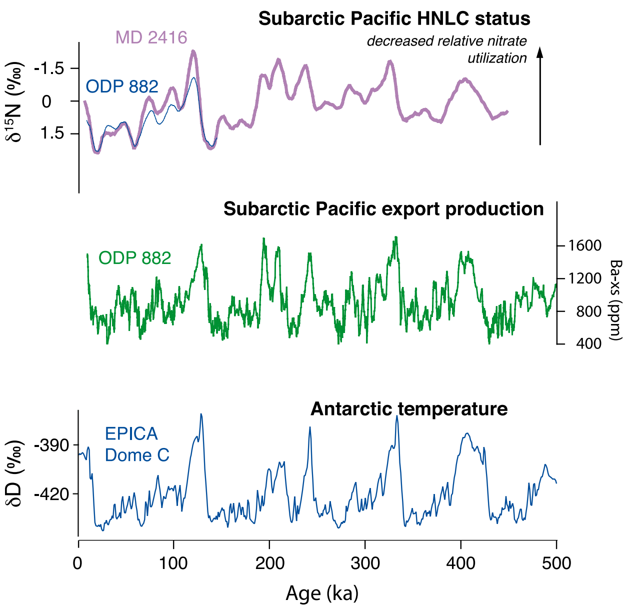

Figure 2.17: Subarctic Pacific relative nitrate utilisation ($\delta^{15}N$ difference records; purple) in the context of local export production (green) and global climate (blue). The Ba-xs is as published by Jaccard et al., 2005, the Antarctic Dome C temperature record is from Jouzel et al., 2007 (figure modified from Galbraith et al., 2008).

water carbon chemistry and particle sinking mechanisms (so-called "ballasting"; Armstrong et al., 2002), constitutes a negative feedback with regard to the oceanic uptake of CO_2 (Zondervan et al., 2001). However, it has also been proposed that calcification in some species might increase at lower pH (Iglesias-Rodriguez et al., 2008), thus implying a positive feedback on CO_2. Due to the complexity of the coupled chemistry-biology system, it is currently unclear what effect a high-CO_2 world will have on marine ecosystems at a global scale and how these will feed back on global climate. Palaeoceanographic studies of periods of past ocean acidification (e.g., Eocene Thermal Maxima; Fig. 2.18), atmospheric CO_2 change (at glacial terminations) and carbon-system reorganisation (e.g., mid-Brunhes), provide critical test cases for the response of global carbon cycle models on long timescales.

Theme Goals

- To compile proxy evidence for past global changes in the oceanic nitrogen and iron cycles during rapid climate transitions, and to unravel the mechanisms causing the variations.
- To quantify the response of marine organisms and ecosystems to acidification and their feedback on atmospheric CO_2 using palaeoceanographic records of historical acidification, as well as examples from high-CO_2 worlds in Earth history.
- To compile proxy data on marine productivity at glacial-interglacial and shorter timescales to assess the overall efficiency of the marine biological pump under different climatic boundary conditions.

Implementation

Achieving the goals will require an approach that combines global Earth-System modelling with proxy-based reconstructions and modern observational studies. Specifically, the models will include biogeochemical as well as ecological modules. Working Groups on marine nutrient cycling and on ocean acidification will pursue the Theme goals, with the involvement and collaboration of other international marine programmes. Potential exists for the development of a WG on the global carbon cycle, together with Focus 1.

Linkages

Focus 3 activities have direct linkages to the programmes and activities under both Focus 1 and Focus 2. In particular, Focus 1 is relevant with respect to CO_2 and CH_4 as diagnostics for biogeochemistry and as forcings for, for example, interglacial response. Furthermore, Focus 2 pro-

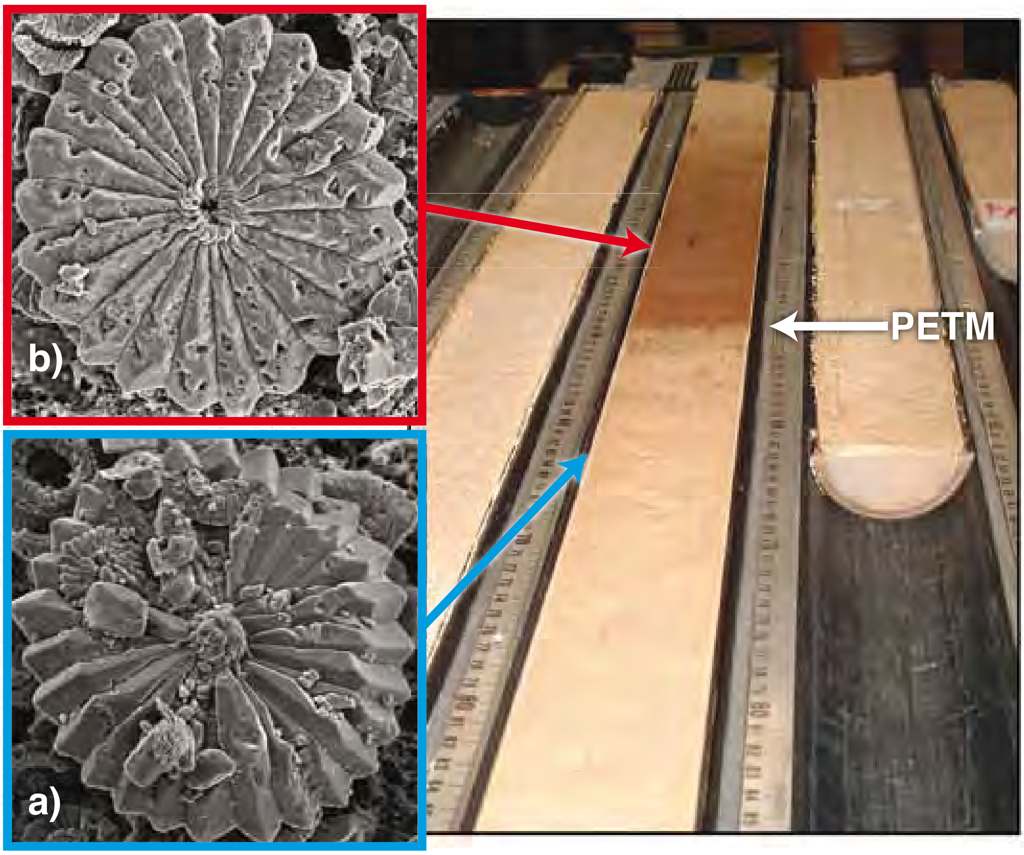

Figure 2.18: Core photo from Walvis Ridge (ODP Leg 208) with dark carbonate-free sediment representing the Palaeocene-Eocene Thermal Maximum (PETM), and calcareous nannofossils of *Discoaster multiradiatus* (Site 1263); a) Relatively well-preserved, pre-PETM specimen; b) Corroded specimen from an acidification event during PETM. Scanning electron microscope images from Mascha Dedert, Vrije Universiteit Amsterdam (figure from Kiefer et al., 2008).

vides the regional-scale data to the global-scale syntheses. PAGES Cross-Cutting Themes are also of great relevance for any global-scale activities. Activities within Focus 3 generally have significant overlap of interest with INQUA and hence potential for joint activities.

The Variability of the Hydrological Cycle Theme encompasses the research efforts of many programmes. Linkages will be sought with programmes such as WCRP-GEWEX, CLIVAR-VAMOS and CLIVAR-VACS, with the IPICS ice core community, and with regional monsoon projects such as MAIRS and AMMA.

Many international programmes have recognised interglacial periods as being key to our understanding of current and future climate. The PIGS WG thus has many linkages to external international programmes and projects, including IMAGES, IODP, ICDP (all on palaeoclimate data), WCRP-CliC (on cryosphere processes) and PMIP (on modelling the last interglacial), and with numerous national projects.

The activities of IMAGES are also linked with those of the Rapid Climate Change Theme, as are the future plans of the IPICS 40,000 Year Network to spatially cover the last 40 ka with ice core records from both hemispheres.

Central ideas of the IGBP-SCOR Fast Track Initiative on Ocean Acidification will find a continuation as a PAGES WG under the Paleo-Perspectives on Ocean Biogeochemistry Theme. As a direct result of its initiation within the IGBP and SCOR spheres, this WG incorporates close links with the marine IGBP Core Projects, SOLAS and IMBER, and cross-programme links with SCOR. IMAGES and IODP will contribute with palaeoceanographic expertise and research. Similar collaborations, especially with SOLAS and IMBER, will be sought by other WGs under the Ocean Biogeochemistry Theme. Potential for collaboration and data exchange also exists with the Global Marine Biogeochemical Cycles of Trace Elements and their Isotopes (GEOTRACES) programme.

Focus 4: Past Human-Climate-Ecosystem Interactions

This Focus addresses the long-term interactions among past climate conditions, ecological processes and human activities during the Holocene. Emphasis lies in comparing regional-scale reconstructions of environmental and climatic processes using natural archives, documentary and instrumental data, with evidence of past human activity obtained from historical, palaeoecological and archaeological records. The Focus promotes regional integration of records and dynamic modelling to: 1) Understand better the nature of climate-human-ecosystem interactions, 2) Quantify the roles of different natural and anthropogenic drivers in forcing environmental change, 3) Examine the feedbacks between anthropogenic activity and the natural system, and 4) Provide integrated datasets for model development and data-model comparisons.

This Focus has taken the name "PHAROS" from Alexander the Great's iconic lighthouse that served to warn travellers of danger, and illuminated their past and future directions.

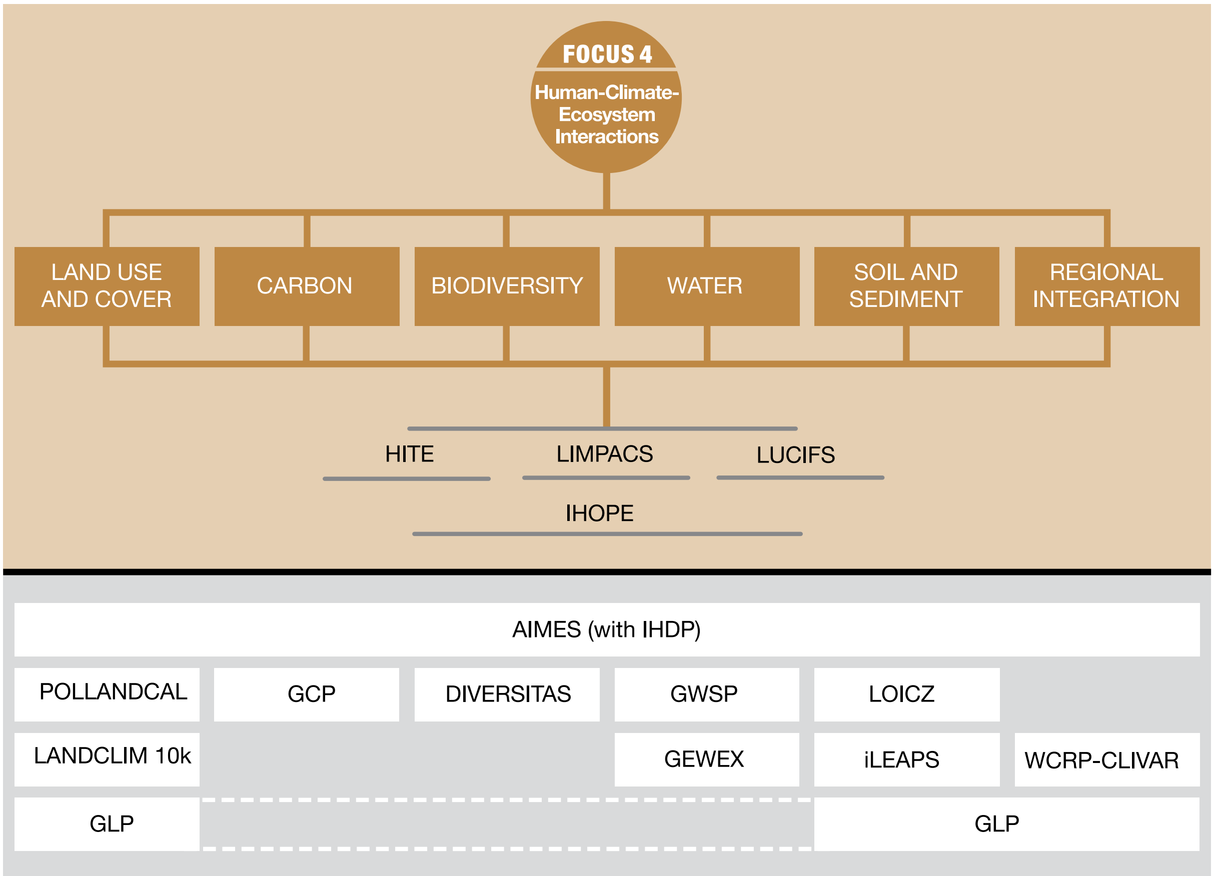

Figure 2.19: Structure of Focus 4. Top: Focus Themes (brown boxes) with their corresponding Working Groups below. Bottom: Overlap with external programmes and projects (white boxes). For explanation of acronyms, see Acronyms and Abbreviations List.

Overarching Questions

- What are the historical patterns of human interactions with climate change and ecological processes?
- How can we learn from past patterns and interactions in order to better understand and manage natural ecosystems at present and in the future?

Rationale

The current phase of IGBP (IGBP, 2006) tasks PAGES with providing regional and global information on the past behaviour of the Earth System. Efforts to reconstruct, systemically analyse and model past system behaviour help contribute to the assessment of future sustainability scenarios. The scope includes the physical climate system, biogeochemical cycles, ecological processes and human activities. Knowledge of the history of interactions between these elements is essential for a full understanding of the functioning of the Earth System and in providing the necessary perspective for addressing current issues of how modern systems may respond to future impacts.

The majority of the Earth's surface has a history of human impact that is significant in terms of duration and/or intensity. Therefore, formulation of integrated strategies for preservation, conservation or sustainable management of ecosystems demands information about how human activities have interacted with natural ecosystems in the long term (Dearing, 2006). Where instrumental records are either too short or inadequate to capture the important timescales of change, or where they are deficient or absent, the time perspective is provided by palaeoclimatic, palaeoenvironmental, archaeological and environmental history communities who reconstruct past environments.

Thus, PHAROS is the PAGES Focus that addresses the long-term interactions between past climate, ecological processes and human activities. Emphasis is on comparing regional-scale reconstructions of ecological and climatic processes, from natural archives, documentary and instrumental data, with evidence on past human activity derived from historical and archaeological records (Oldfield and Dearing, 2003). Focus 4 research encompasses the Holocene period, with particular emphasis on the period of significant human activity, which varies from region to region. It also promotes process modelling efforts to: 1) Better understand the processes that dominate human-climate-ecosystem interactions, 2) Quantify the relative roles of different natural and anthropogenic drivers of change, and 3) Provide integrated datasets of palaeoenvironmental information for model comparison and verification. The research enhances the use of palaeorecords and other archives to provide past perspectives of environmental change that may be used to understand the functioning of present and future ecosystems (Dearing et al., 2006a; 2006b). In this respect, the Focus is forward-looking, with the ultimate goal of delivering tools and strategies for the sustainable management of ecosystems and landscapes.

State of Science and Knowledge Gaps

In recent decades, there have been rapid advances in our ability to reconstruct past ecological change, especially from peat and lake sediment records (Last and Smol, 2001a; 2001b; Smol et al., 2001a; 2001b). New and improved palaeoenvironmental methodologies have been used to address a range of global environmental change problems that are both systemic and cumulative in nature (see Turner et al., 1990). Research has shown that the timescales of significant human impact extend throughout much of the Holocene in many regions of the world, varying in intensity both spatially and with respect to the nature of the activity (Oldfield and Dearing, 2003). For example, studies concerned with agriculturally linked changes in land cover (e.g., Berglund, 1991; Foster et al., 2003), fire (e.g., Swetnam et al., 1999; Marlon et al., 2008), soil stability and sediment transport (e.g., Dearing and Jones, 2003; Hoffman et al., 2007; Page and Trustrum, 1997) and biodiversity (e.g., Berglund et al., 2007; Froyd and Willis, 2008) require a centennial to millennial time frame (Fig. 2.20). Issues related to pollution, for example, surface water acidification (Battarbee et al., 1985), eutrophication (Bennion et al., 2004), and air quality (Bindler et al., in press) associated with rapid global industrialisation processes tend to concern changes of the last few decades to centuries, although notable exceptions include the long timescales of pollution caused by smelting (Martínez-Cortizas et al., 1999) and agricultural eutrophication during the late Holocene (e.g., Fritz, 1989).

Increasingly, reconstructions reveal the complexity of coupled human-climate-ecology systems. In this respect, some attempts have been made to demonstrate the value of nonlinear systems and resilience theories in palaeoenvironmental studies (e.g., Dearing and Zolitschka, 1999; Dearing et al., 2008; Dearing, 2008: Fig. 2.21; Gomez et al., 2002). There is also a focus on feedback mechanisms

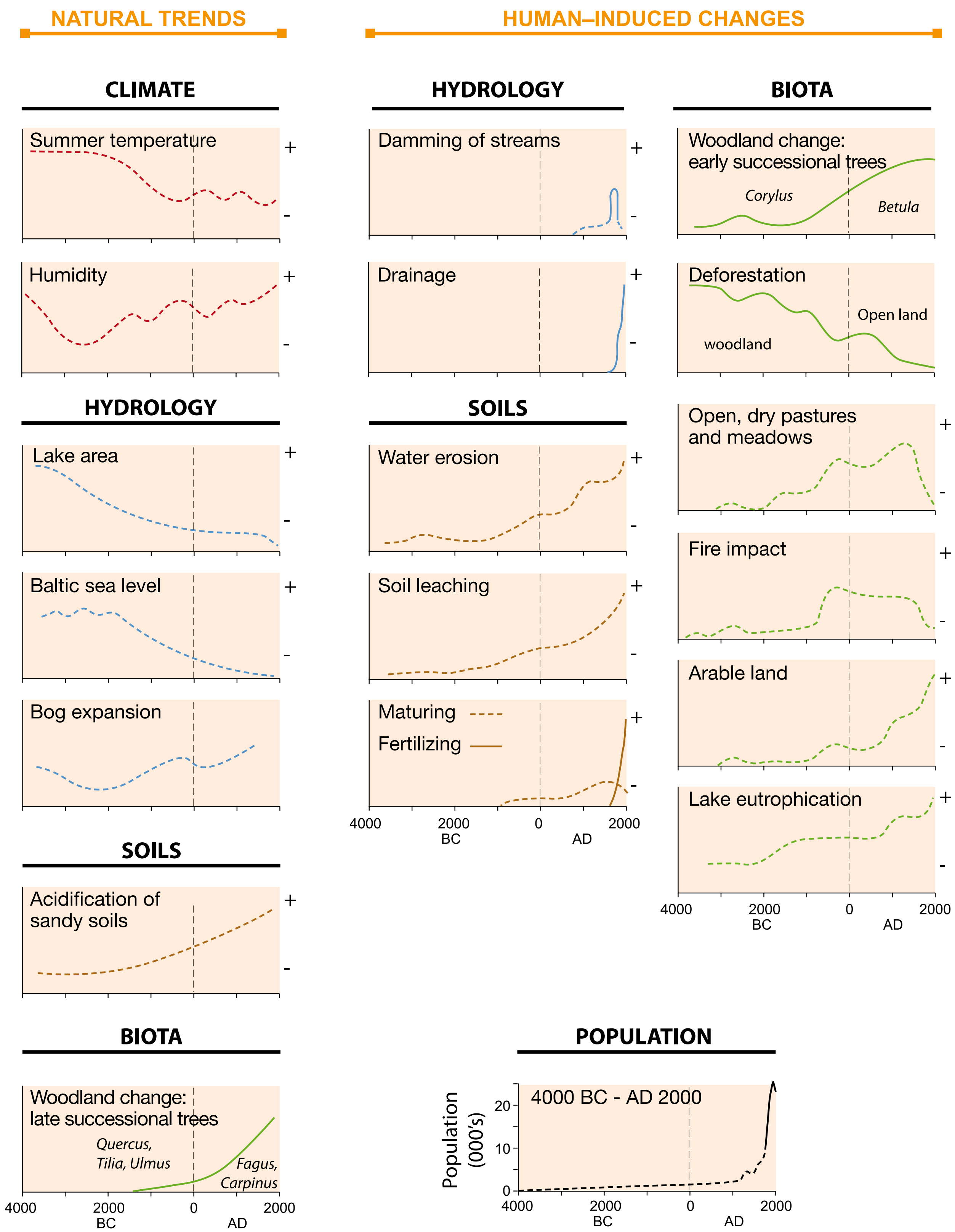

Figure 2.20: Centennial and millennial trajectories of human actions and environmental conditions for southern Sweden; one of the first studies to integrate multiple archives of palaeoecological, archaeological and documentary information. This work still comprises one of the most comprehensive human-environment data compilations for any region (figure modified from Berglund, 1991).

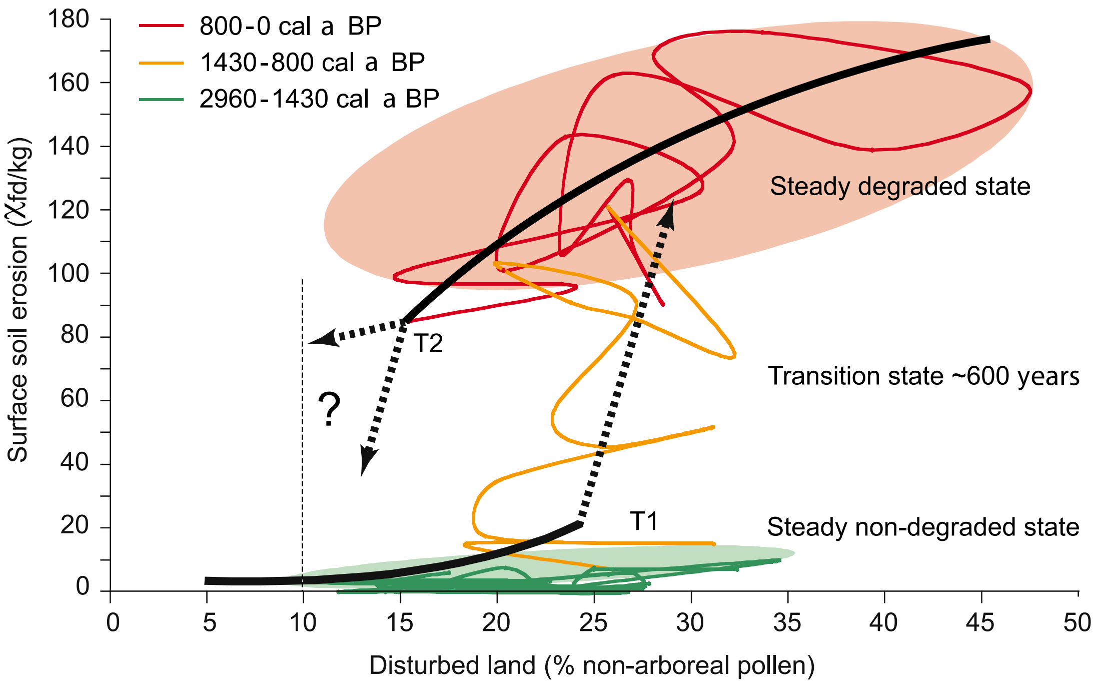

Figure 2.21: Reconstructed landscape stability in the Lake Erhai catchment, SW China, showing possible alternative steady states of the coupled soil-land cover system. The timeseries for "disturbed land" and "soil erosion" from 2960 cal a BP to present are plotted together in phase space. The stable "steady state" before 1433 cal a BP (green), progresses through a 600-year transition period before settling into the modern degraded "steady state" (red) after 800 cal a BP. T1 and T2 represent likely positions of major thresholds in the system. The dashed arrows from T2 show possible future trajectories of landscape recovery depending on land management but demonstrate the essentially irreversible state of the modern system (Dearing, 2008).

within past human-climate-ecosystem interactions. Recent evidence and models argue that prehistoric humans not only responded to past climates but may also have significantly contributed to local climate variability (e.g., Brovkin et al., 2006). Greenhouse gas records from ice cores have been used to argue for anthropogenic warming as a result of early but extensive agriculture and deforestation since the mid-Holocene (Ruddiman, 2003, 2005).

In many instances, palaeoenvironmental research has been critical in addressing environmental problems of societal concern. It is often the only means of understanding the complex synergies that exist between human activity and the naturally varying processes of environmental change. For a detailed review of the current state of this science, see Oldfield and Dearing (2003), Dearing et al. (2006a; 2006b), Dearing (2006) and Oldfield (2008).

New syntheses of data records are required at global to continental scales to test theories of climate forcing, to provide new quantitative data for biogeochemical cycles, to provide driving mechanisms of predictive models, to strengthen the knowledge basis of human-environment interactions, and to search for nonlinear behaviour that may have implications for future earth trajectories. At regional to local scales, new syntheses are needed to provide long-term perspectives on ecosystem response to climate and human activities, to help define reference conditions, conservation goals and restoration targets, to help define the spatial variability of ecosystem trajectories, and to provide the means to drive and validate local process-based predictive models.

Current concerns regarding global warming and its impacts, resource depletion, and societal and technological change place increasing emphasis on the accuracy of regional climate projections and our ability to construct suitable strategies for mitigation, adaptation and sustainable management (e.g., IPCC AR4, 2007). Consequently, we need to incorporate knowledge of the past over decades to millennia in all areas of environmental management and forecasting (e.g., Dearing et al., 2006a; 2006b), using both empirical and modelling approaches. By interrogating past records we can close gaps in our knowledge, for example:

- Comprehensive understanding of the modern climate system requires improved knowledge of the evolution of the land-atmospheric interactions that affect the carbon cycle, albedo and moisture states, particularly since the beginning of agriculture. There is a need for comprehensive regional to global reviews of palaeodata, including land use/land cover changes, biomass burning and fluxes of soil/sediments.
- Validation of numerical models that project future climate, vegetation, hydrological regimes, environmental impacts and socio-ecological change at regional to global scales over decadal timescales require testing against long-term time-series (Fig. 2.22). Palaeoenvironmental datasets are required for current models simulating regional climates, hydro-geomorphological change, water acidification and eutrophication, biogeochemical cycling and weathering, dynamic ecological change, and socio-ecological systems (Sellers et al., 1997; Prentice et al., 1992; Anderson et al., 2006; Gaillard, 2007; Hellman et al., 2008).

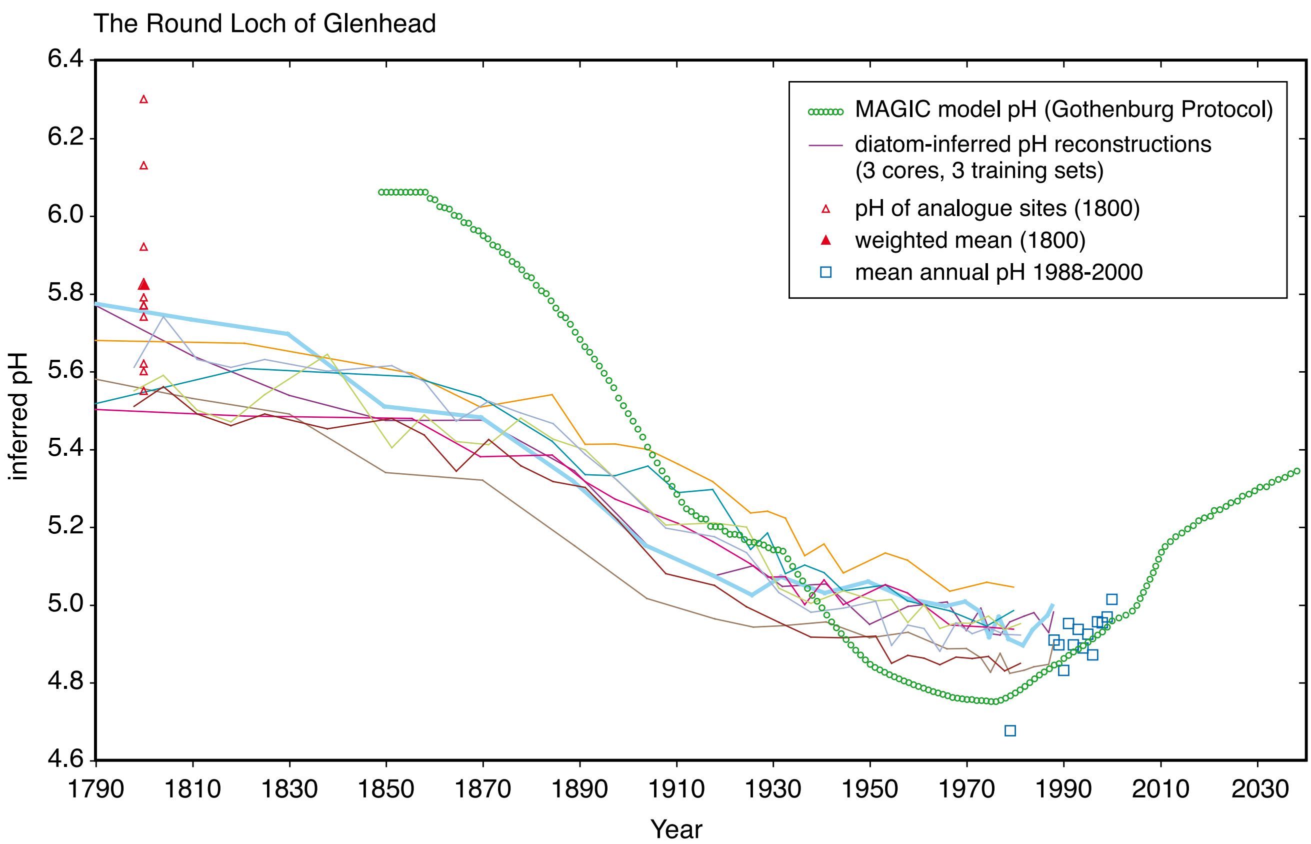

Figure 2.22: Data-simulation model comparisons. Comparison of measured, reconstructed and modelled lake pH data since AD 1800 at Round Loch, Scotland. Chronology of diatom-inferred pH (nine solid lines) according to SWAP, U.K. and EDDI models for ^{210}Pb-dated samples from three sediment cores using three different training sets. Modern annual pH of nine local lakes providing the strongest biological analogues for a pre-acidification (ca. 1800) sediment sample (open red triangles) and the weighted average of these (filled red triangles), Model for Acidification of Groundwater In Catchments (MAGIC) reconstruction (open green circles) and mean annual average pH for the period 1988-2000 and the year 1979 at Round Loch (open blue squares) (Battarbee et al., 2005).

Focus 4 Structure

To address the abovementioned issues and knowledge gaps, Focus 4 is divided into six topical Themes (Fig. 2.19):

- Land Use and Cover
- Carbon
- Biodiversity
- Water
- Soil and Sediment
- Regional Integration

Theme: Land Use and Cover

Climate modellers increasingly focus on processes governing changes in the land surface and their coupling to the atmosphere. Thus, there is a growing need for past land use/cover records at global to continental/regional scales (e.g., Dearing et al., 2006b; Denman et al., 2007). The major goal of this Theme is to produce land cover records based on fossil pollen records during the Holocene. The nonlinear nature of the pollen-vegetation relationship has previously made it difficult to quantify past land cover changes using fossil pollen records (e.g., Sugita et al., 1999). One promising approach is to apply the Landscape Reconstruction Algorithm, developed in order to overcome these difficulties (Sugita, 2007a; 2007b). It opens up the possibility of achieving a considerably more robust assessment of human land-use throughout the Holocene (Anderson et al., 2006; Gaillard, 2007). It is intended that this Theme will produce land cover reconstructions at global and continental to regional scale for the entire Holocene in various formats relevant for modellers—curves and trends (site curves, regional syntheses), figures (absolute numbers in percentage cover, biomass, plant functional types, biomes), maps, databases, open vs. forested land, extent and nature of permanent agriculture, and extent of grazing. Land cover reconstructions are also needed to understand and model terrestrial processes, like soil erosion, the direct focus of other PHAROS Themes and Working Groups.

Theme: Carbon

The carbon cycle lies at the heart of Earth System Science, providing the key contribution to climatic-environmental changes by the redistribution of carbon between terrestrial, oceanic and atmospheric systems. Quantifying carbon fluxes, sources, sinks and stores, and understanding the nature of interactions and feedbacks are essential to climate change research and carbon management. However, the temporal patterns of the major carbon fluxes and their consequences for carbon stores are poorly understood at timescales greater than a few years. Therefore, this Theme provides the historical perspective to these issues, complementing the work of international programmes like the Global Carbon Project (GCP). The focus is on reconstruction of decadal to millennial carbon dynamics in anthropogenic and pre-anthropogenic systems, long-term changes in carbon stores, particularly through burial in lakes (Kortelainen et al., 2004; Downing et al., 2008) and terrestrial sediments, and spatial syntheses at regional to global scales. The Theme will overlap with the Water, Soil and Sediment, and Land Use and Cover Themes.

Theme: Biodiversity

The 2005 Millennium Ecosystem Assessment recently highlighted critical gaps in our knowledge of biodiversity. The gaps address our understanding of:

- Responses of ecosystems to changes in the availability of nutrients and carbon dioxide.
- Non-linear changes and structural and dynamic characteristics of ecosystems that lead to thresholds and irreversible biodiversity changes.
- Nature of interactions among drivers of changes in biodiversity at regional scales.

The Millennium Ecosystem Assessment argues that such information is essential in order to design interventions that maximise positive impacts on biodiversity. Yet the majority of biodiversity records currently used to try and fill the current gaps in our knowledge cover less than 50 years (Willis et al., 2005). While this length of record may be acceptable for some short-lived organisms, it is often inadequate for larger species that have long-generation times (e.g., trees and large mammals) and for examining biodiversity changes at larger spatial scales (e.g., landscape and biome scales). The key is to understand the nature of interactions across all relevant spatial and temporal scales. This Theme will focus on the compilation of longer-term ecological records at a range of spatial and temporal scales, in order to complement the use of existing shorter-term observational records identified by DIVERSITAS. Specifically, it will aim to synthesise long-term records that can provide information on: 1) Drivers of biodiversity change, 2) Determination of baselines and natural ecosystem variability, 3) Biodiversity thresholds and resilience, 4) Migrations, invasions and extinctions, 5) Conservation of cultural landscapes, and 6) Wilderness conservation. This Theme will also address the need to improve our recognition of biological remains in natural archives, maintain and expand taxonomic expertise, and improve interpretation of fossil records through fundamental work on representativity and congruence.

Theme: Water

The quality and quantity of water resources increasingly impose constraints on human societies and ecosystem health in most regions of the Earth. This is particularly so in regions where intense catchment change has altered the hydrological balance and reduced the quality of water supplies and wetlands, and where past and projected climate change shifts the availability of surface water for consumptive and ecosystem needs. Studies of changes in past water quality and quantities, notably of lake acidification and eutrophication, have been essential in identifying the trajectory of change and establishing the range of natural variation that existed prior to intense human modifications of catchments. Such approaches have the capacity to quantify natural baseline conditions, identify drivers and rates of past change, and assess the degree of departure from baseline on a broad range of contexts (Bennion and Battarbee, 2007). Through integration of evidence on land surface, climate and watershed change, the Water Theme will compile and integrate records to gauge: 1) Sensitivity or resilience of waterways to catchment development, 2) Points of initiation and trajectories of change that are detrimental to sustainable societal development, 3) Interactions between climate, surface cover and stability changes, and aquatic ecosystems over time, and 4) Future water resource availability and condition, and the state of aquatic ecosystems (using dynamic models to generate and test scenarios).

Theme: Soil and Sediment

Sediment archives (alluvial, colluvial, limnic) provide records of changing soil erosion and the transport/deposition of sediment by fluvial processes. The degree of soil erosion and the extent and volume of sedimentary deposits provide information on the nature and timing of past human impacts, and the impact of environmental variability (particularly climate) on human society (e.g., Brown, 2002; Dearing and Jones, 2003; Gregory et al., 2006; Wasson, 1994). This Theme will integrate soil/sediment records to provide spatially distributed patterns through time and across different regions. The results may be used for interpreting past levels of landscape disturbance, past human-environment interactions, describing trajectories of soil/sediment movements up to the present, defining baselines, reconstructing past sediment budgets, and developing and validating process models. Through interpretation of catchment behaviour (hydrological and sediment cycles) within the LUCIFS WG (see Implementation section below), this Theme will make an important contribution to other PHAROS Themes, PAGES Foci (e.g., Focus 2), IHOPE and the Global Land Project (GLP).

Theme: Regional Integration

Integrating palaeoenvironmental records can provide comprehensive environmental profiles of socio-environment interactions at regional scales. Such profiles are especially important to the development of policies and strategies in regions where successful management of key environmental processes, ecological services and their interaction is critical, for example, within natural wildernesses, biodiversity hotspots, climate change hotspots or regions projected to be particularly vulnerable to combinations of stressors. This Theme will initially integrate past evidence for environmental processes and ecological services for selected regions that are projected by the IPCC (Fig. 2.23) and others (e.g., Giorgi, 2006) to be climate change “hotspots”. It will compile and integrate records in order to: 1) Identify drivers of change, 2) Track socio-environmental trajectories, 3) Establish levels of modern resilience and vulnerability, and 4) Provide the basis for the development and validation of dynamic models for scenario production. This Theme will develop particular links to other PAGES Foci (e.g., Focus 2), GLP and IHOPE.

Focus Goals

Focus 4 seeks to understand ecosystem change on different timescales and at spatial scales ranging from local to global, with five specific goals:

- To understand and quantify the nature of human activities that have influenced the functioning of ecological systems. For example, the historical links between climate, human activities (such as irrigation practices) and soil erosion in different world regions.
- To elucidate feedbacks from human activities to the climate system. For example, determining the impact (local to global) of deforestation on climate.
- To describe how human and climate impacts have interacted with internal system dynamics. For example, the extent to which river channel changes are a consequence of external forces, such as land use and climate, or internal forces, such as hydraulic dynamics and system configuration.

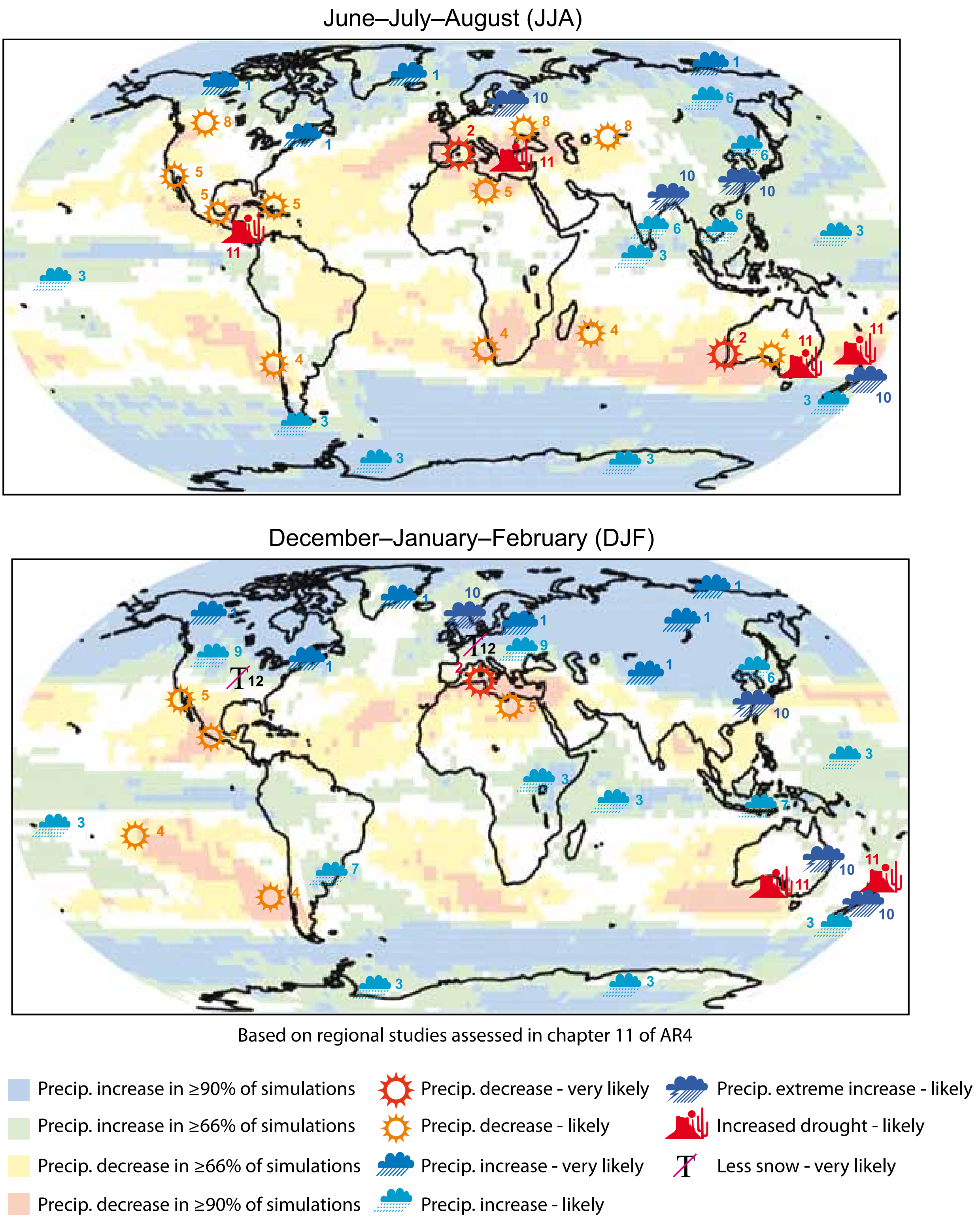

Figure 2.23: Robust findings on regional climate change for mean and extreme precipitation, drought and snow. This regional assessment is based on atmosphere-ocean general circulation models (AOGCMs), regional climate models, statistical downscaling and process understanding. The background map indicates the degree of consistency between AR4 AOGCM simulations (21 simulations used) in the direction of simulated precipitation change (IPCC AR4 WG1 Chap. 11: Christensen et al., 2007).

- To explore the sensitivity and resilience of modern ecological systems to new or increased stresses from human activities and climate change. For example, to identify those ecological processes that have been the most responsive to past rapid climate change and which may be sensitive to projected climate change in the future.
- To synthesise and integrate findings on past human-climate-ecosystem interactions in order to help develop appropriate sustainable management strategies. For example, determining the historical range of variability in natural disturbance regimes, the reference conditions that are most relevant for ecosystem restoration, or the land use that appears most appropriate in the face of projected change.

Implementation

The Themes of Focus 4 will be addressed by specialists from one or more of three Working Groups: Human-Climate Interactions with the Terrestrial Environment (HITE), Human-Climate Interactions with Lake Ecosystems (LIMPACS), and Land Use-Climate Interactions with Fluvial Systems (LUCIFS). These WGs are comprised of large, well-established scientific communities with national and international identities, and continue on from WGs that were active under PAGES previous science structure. They will focus on the synthesis and integration of data, and the dynamic modelling of processes within a specific interdisciplinary topic.

Working Group: HITE – Human-Climate Interactions with the Terrestrial Environment

HITE studies palaeorecords and other ecological archives to document and understand the interactions between human activities and terrestrial ecosystems through time. This improves the scientific basis of procedures that ensure the security and services of terrestrial ecosystems for the future.

Working Group: LIMPACS – Human-Climate Interactions with Lake Ecosystems

LIMPACS is concerned with understanding how and why lake ecosystems have changed, are changing and might change in the future, especially on decadal timescales. Additionally, LIMPACS seeks to understand the role of lakes in Earth System processes through time, especially with respect to biogeochemical processes (e.g., in transforming and storing carbon) and as centres of biodiversity.

Working Group: LUCIFS – Land Use-Climate Interactions with Fluvial Systems

LUCIFS applies a strong focus on a whole-catchment, systems-based understanding and analysis of the relationship between the external drivers of land use and climate change, and the internal working of multi-component catchments on timescales that encompass the period of agriculture. Anticipating change in fluxes of materials in river catchments as a consequence of global change requires this understanding.

Linkages

Themes and WGs in Focus 4 link explicitly to all PAGES Foci and CCTs. Particularly close links exist with Focus 1 activities on reconstructing and understanding climate forcings during historical times, with Focus 2 WGs on regional climate reconstructions of the last 2 ka and the Holocene, and with the Focus 3 Variability of the Hydrological Cycle Theme.

As the Focus 4 topics and timescales specifically include the human component, this Focus has close thematic affinity with a number of Core Projects in IGBP, and with programmes and cross-cutting projects in ESSP. For example, the Land Use and Cover, and Soil and Sediment Themes offer ample opportunities for collaboration with GLP, and in the case of Soil and Sediment, with iLEAPS and LOICZ. Specific plans to link the Land Use and Cover Theme to the NordForsk Pollen-Landscape Calibration (POLLANDCAL) and LANDCLIM 10 000 networks are already in place. The Water Theme will develop links to the ESSP Global Water System Project (GWSP) and potentially also to the WCRP Global Energy and Water Cycle Experiment (GEWEX). The Carbon Theme will establish collaborations with GCP and work closely together with carbon system modelling groups C4MIP and PCMIP, carried out under the AIMES banner. Further collaboration of Focus 4 with AIMES (and with the International Human Dimensions Programme on Global Environmental Change (IHDP)) has been institutionalised through IHOPE (see below). Through the Biodiversity Theme, PAGES will contribute the long-term biodiversity perspective to DIVERSITAS science and form the basis for future collaboration. Links with IHDP and WCRP (mostly through CLIVAR) will be sought through the activities of the Regional Integration Theme.

Cross-Programme Initiative: IHOPE – Integrated History and Future of People on Earth

IHOPE is a joint research initiative of PAGES and AIMES with IHDP (Costanza et al., 2007a; 2007b). IHOPE seeks to better understand the dynamic interactions between all aspects of human behaviour and the environment by connecting the histories of humans, climate and environment at multiple temporal scales (millennial, centennial, decadal and future scenarios). It builds on studies of past regional changes (as addressed specifically by PAGES Focus 4 and Focus 2). IHOPE extends beyond this by integrating the social science elements into Earth System understanding.

The goals of IHOPE are:

- To map the integrated record of natural and human system changes on the Earth over historical and prehistorical times. The timeframe depends on the availability of palaeoenvironmental and historical/archaeological data, and the history of the region itself. For example, Australian history might cover the last 60 ka, whereas in southern Europe, the last 20 ka would capture initial colonisation since the Last Glacial Maximum. In principle, IHOPE extends over approx. the last 100 ka, the period of spread of modern humans. However, the last millennia and the last century are studied with higher temporal and spatial resolution.
- To understand the socio-ecological dynamics of human history by testing human-environment system models against the integrated history. For example, how well do various models of the relationships between climate, agriculture, technology, disease, language, culture, war and other variables explain the historical patterns of human settlement, population, energy use and Earth System cycles (e.g., certain biogeochemical cycles)?
- To project with more confidence and skill options for the future of humanity and Earth System dynamics, based on models and understanding that have been tested against the integrated history and with participation from stakeholders.

Specific questions addressed by IHOPE include:

- What are the resilience characteristics of socio-ecological systems that lead to either sustainability or collapse? What makes socio-ecological systems resilient, brittle or vulnerable at various points in their evolution?
- How do societies respond to the closing of frontiers? Can technology create new frontiers indefinitely?
- What is the role and path of technology and substitution in the evolution of socio-ecological systems?
- What causes socio-ecological systems to be more or less successful in perceiving and adapting to decadal and longer changes (e.g., land use, climate, disease)? Are some types of environmental stress inherently more likely to cause collapse than others?
- What might have been the long-term human contributions to changes in the rates and composition of Earth processes?
- Historically, what are the effects of humans on the dispersal of other species (i.e., diseases, invasive species) and vice versa?
- How and where have human systems successively created dynamic connections with the environmental system, so that the latter is now dependent on human “disturbance” for its stability/instability?

Cross-Cutting Themes

PAGES has identified four Cross-Cutting Themes that are more general in scope than the Foci but are of fundamental relevance to all Foci and to palaeoscience in general.

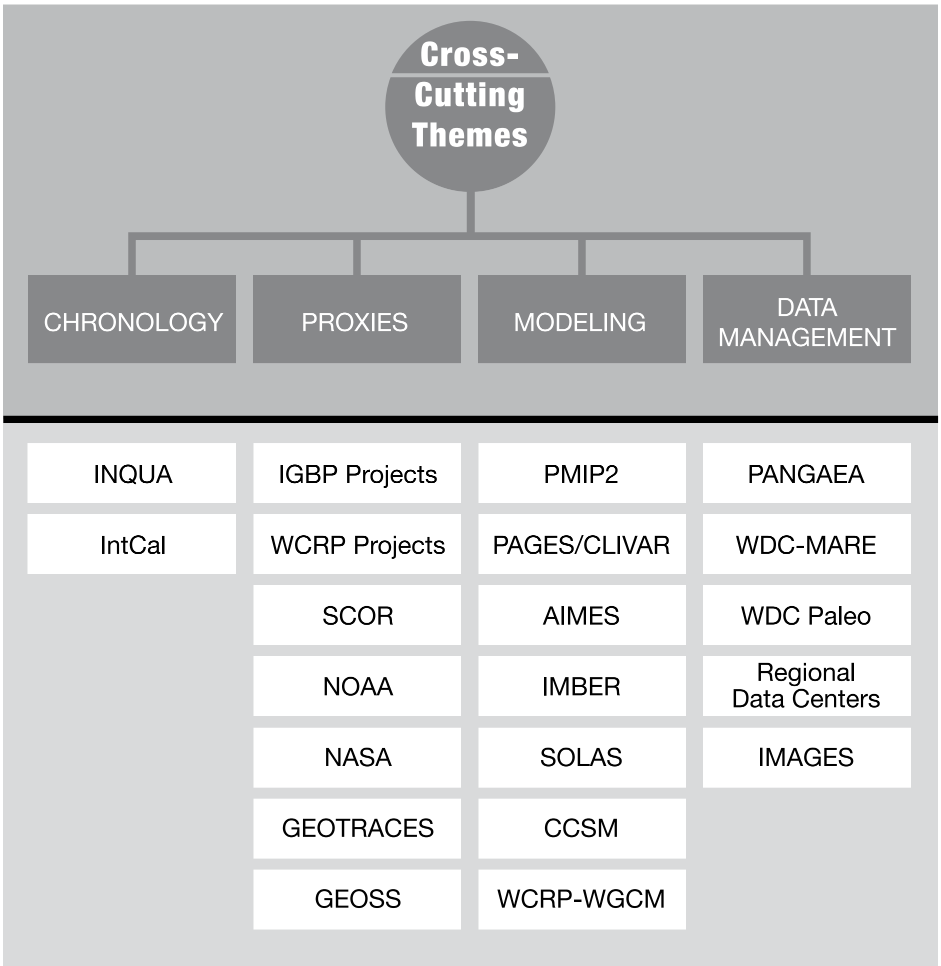

Figure 2.24: Organisation of PAGES four Cross-Cutting Themes (top; grey boxes) showing overlap with external programmes and projects (bottom; white boxes). For explanation of acronyms, see Acronyms and Abbreviations List.

Cross-Cutting Theme 1: Chronology

Chronology is crucial to palaeoresearch and often constrains the strength of conclusions from palaeoenvironmental reconstructions. This Theme supports efforts to improve tools for absolute and relative dating, and to enhance the reliability of reference timescales. It also encourages creative new approaches to solving chronology issues.

Rationale

Accurate chronologies of palaeoenvironmental and palaeoclimatic records are necessary in many aspects of palaeoscience (Fig. 2.25). Firstly, detailed comparisons between different land, ocean and ice archives require that records are brought onto a common absolute or relative timescale that resolves (at least) the timescale of interest. Secondly, a meaningful comparison of palaeoenvironmental datasets from different locations with modelling results requires high-resolution and accurate dating, as well as accurate and systematic reporting of chronological uncertainties. In particular, the trend towards transient model simulations (with EMICs and fast GCMs) and the associated shift from "snap shots" of climate reconstructions to a dynamical approach require chronological strategies that allow the sequences of events to be characterised and constantly updated. Finally, a growing interest in abrupt changes and Earth System variability on centennial, decadal and interannual timescales requires that the quality of chronological tools for palaeoresearch keeps pace with this demand and is systematically assessed and reported.

An age model of a palaeorecord can be derived from a set of absolute (e.g., radiometric or layer counting) dates, or from the stratigraphic comparison with a well-dated master record using events not directly linked to climate (i.e., volcanic ashes, pollution peak, palaeomagnetic variations) or climatic events detected in the proxy records (e.g., event stratigraphy). The major events of climate change are globally teleconnected but with leads and lags between regions and in the environmental response. Therefore, any common master chronology that contains age references for these events needs to include the complexity of Earth System dynamics while at the same time providing satisfactory reliability. In all cases, age models must be based on approaches that are clearly defined and established in international conventions. Accurate chronologies often rely on a combination of the above-mentioned approaches.

PAGES strongly supports the numerous national and international projects, groups and commissions already working on solutions to the above issues, while recognising the need to integrate the different efforts.

Goals

Specific goals for CCT 1 include:

To improve absolute dating

- To reduce the uncertainty of existing radiometric dating methods (i.e., ^{14}C, $^{40}K/^{40}Ar$, $^{40}Ar/^{39}Ar$, Uranium-series).
- To improve calibration techniques, particularly for ^{14}C calibration curves and luminescence ages using tree rings, sediment varves, etc.
- To develop new dating methods (e.g., for the time beyond the range of U/Th dating) (before ca. 300 ka).
- To promote laboratory dating intercomparisons (e.g., Ar constants).

To improve chronostratigraphic dating

- To synthesise correlations of regionally occurring well-dated tephra on land and in the ocean with the ice core record.
- To compile palaeomagnetic master curves for all parts of the globe, including their centennial- and millennial-scale variations.

To improve event stratigraphy

- To establish regional event stratigraphy master curves such as the GICC05 coordinated effort by the INTIMATE group of the North Atlantic (Lowe et al., 2008) based on the NorthGRIP ice core.
- To develop a global network of high-resolution climate records from different regions and archives, with timescales consistent between records and relative to orbital solar insolation over at least the mid- and late Pleistocene.
- To establish a high-resolution master curve of past global mean sea level change and spatial synopses of local changes.

The ultimate goal should be to establish a set of regional master curves that are accurately dated with high-resolution age models that cover the Holocene, the last glacial cycle, and the mid- and late Pleistocene using the three types of dating techniques (absolute, chronostratigraphy

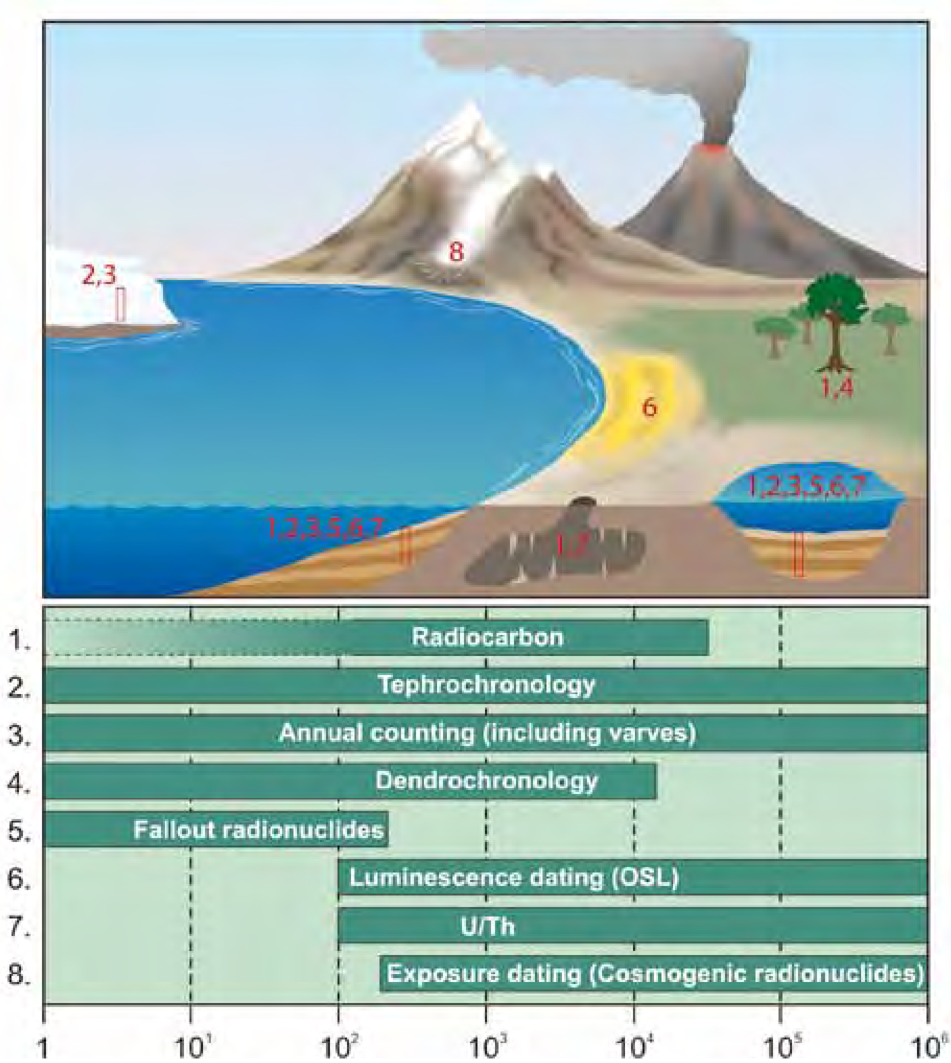

Figure 2.25: Late Quaternary depositional environments (ice caps, glacial moraine deposits, loess and sand dunes, trees, marine sediments, speleothems, lake sediments) and associated dating techniques. The lower part of the figure shows the effective dating ranges of the different techniques (Bertrand et al., 2008).

and event stratigraphy). These master curves should ideally be of annual resolution wherever possible, contain a good palaeomagnetic and tephra record, be sensitive to climate variations to enable event stratigraphic correlations, and report the age uncertainties for each datum.

Implementation

In an attempt to integrate the chronological efforts being carried out by different groups, CCT 1 will organize:

- Side-events at workshops that have a broader scope but with a chronostratigraphic aspect, to harvest results as a by-product of the main workshop.
- Special sessions or symposia at large international conferences (e.g., PAGES, AGU, EGU, INQUA, ICP) to stimulate discussion between the larger groups of the land, ice and ocean communities.
- Small stand-alone workshops, to address specific major chronostratigraphic problems.

In addition, CCT 1 in collaboration with regional groups will define datasets that are potentially eligible to become regional master curves.

The webpages for this CCT will serve as a coordination hub, providing information such as data quality requirements, reports and abstracts of all CCT 1-related workshops supported by PAGES, and a list of the major publications dealing with the chronological issues. A "PAGES Table of Paleo-Chronology", showing Heinrich layers, ice-rafted debris events, dust spikes, methane outbursts, super El Niños, etc, will also be established online and will be continuously updated with events and results.

Linkages

Since every palaeoscience organisation, project or group addresses chronology in one form or another, opportunities for cooperation abound. Primary partners for exchange (Fig. 2.24) include the INQUA Commission on Stratigraphy and Chronology (SACCOM) and PAL-COMM INTIMATE projects, who have a long tradition in research on the subject, as well as groups such as the IntCal Working Group, who address aspects of radiocarbon dating.

Cross-Cutting Theme 2: Proxy Development, Calibration and Validation

This Theme supports improvement of the precision and accuracy of palaeo-proxies as a basis for high-quality reconstructions of past global change to complement instrumental data. It includes efforts on proxy interpretation and development, analytical innovation, inter-laboratory comparisons, and calibration refinement, with the aim to reduce uncertainty in proxy-based reconstructions.

Rationale

Widespread, reliable instrumental records are only available for the past 150 years and then only for parts of the globe. Climate and environment variations in the more distant past can be estimated by analysing proxy data from sources such as tree rings, corals, ocean and lake sediments, cave deposits, ice cores, boreholes, glaciers, and historical documents.

Considerable advances in the quality of proxy-based reconstructions have been made over recent decades. However, the demand for accuracy, precision, resolution and quantitative interpretation is increasing as the questions asked in global change research become more detailed, for example, the refinement of the scale of interest down to seasonal to interannual, or local to regional variability. In addition, quantitative reconstructions of climate parameters other than temperature are being called for. It is important to meet these demands in order to maximise the usefulness of palaeoscience in complementing observational and projection studies.

Proxy data are the products of a series of steps (Fig. 2.26), each with their inherent pitfalls and limitations, which add up to the proxy data uncertainties that limit the interpretation of proxy records and reconstructions. Some of the most common factors that complicate the quantitative interpretation of climatic and environmental reconstructions are as follows:

- Most proxy records are influenced by a variety of parameters that are difficult to separate.
- The relationship between proxy sensitivity and ambient conditions can vary over time.
- Proxy signals are often biased towards seasons or extreme periods.
- Proxy-record sensitivities are sometimes frequency dependent.
- Extended and homogeneous instrumental records to calibrate and validate the reconstructions are absent for many regions and parameters.

This CCT promotes efforts to identify and reduce the shortcomings and pitfalls in proxy-record generation and interpretation.

Goals

The overarching goal of this CCT is to support advances in the precision and accuracy of palaeo-proxies in order to generate high-quality records of past global change that can complement instrumental data and modelling efforts. To this end, specific aims include improvement in proxy interpretation and development, refinement of analysis and calibration, and encouragement/facilitation of inter-laboratory comparisons.

To improve the quality of proxy records and the resulting reconstructions, the following key objectives have been identified in the steps from site selection to reconstruction (Fig. 2.26):

- To discover new proxies – In order to arrive at a comprehensive reconstruction of Earth's environmental history, it is necessary to expand the available range of proxies to include environmental parameters, for which we have basically no (e.g., cloud formation) or only poor (e.g., ocean salinity, sea ice cover, ice sheet thickness, dimethyl sulfide) proxies at hand. PAGES paves the way for this by facilitating knowledge exchange between researchers studying past records and those interested in modern processes (e.g., biologists, geophysicists, geochemists, glaciologists, oceanographers and climatologists).
- To optimise site selection – Observational data (e.g., results from IGBP sister Core Projects and WCRP)

and model runs with simulated proxies can assist site selection by identifying sites sensitive to environmental change and proxy response. CCT 2 provides a platform for communication with these groups and supports campaigns to study key locations and undersampled regions.

- To improve sample analysis – Progress in the ever-increasing quality of field and laboratory measurements usually results from innovations, often of a technical nature, by specialist scientists. CCT 2 can contribute to analytical improvement by organising group efforts such as inter-laboratory comparison/calibration studies.

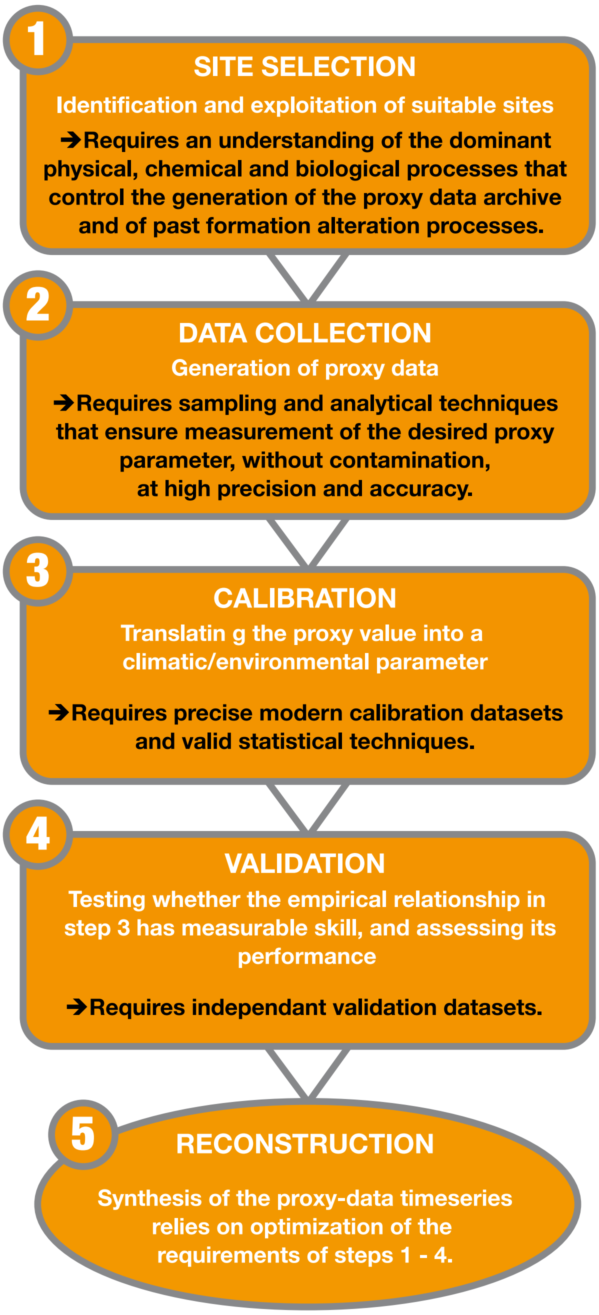

Figure 2.26: General methodology for using proxies in reconstructing past climate and environment (figure modified from Committee on Surface Temperature Reconstructions for the Last 2000 Years, National Research Council, 2006).

- To provide calibration datasets – The calibration of proxy data requires large sets of samples or proxy datasets from the (quasi-modern) calibration period, as well as optimal datasets of instrumental measurements. Collaboration with other projects in IGBP, WCRP, and the broader ESSP community can help to identify and provide datasets for calibration.

- To validate proxy interpretation – A deeper understanding of the biological, physical and chemical controls on the formation of proxies and proxy archives, and of their post-depositional history (alteration, transport, etc.) is necessary to reliably and quantitatively interpret the proxy data with respect to their representation of environmental and climatic parameters. To this end, PAGES encourages a cross-disciplinary, integrative approach (see PAGES Objectives & Approach in the Introduction). As a complementary approach to increase confidence in reconstructions, CCT 2 promotes the combination of multiple independent lines of evidence, for example, multi-proxy strategies and data-model comparisons.

- To quantify and express proxy-data uncertainties – Beyond efforts to reduce uncertainties in general, the coherent and quantitative expression of uncertainties is a major task within CCT 2. This is addressed according to the requirements of modelling studies and in close collaboration with statisticians, and with Working Groups of Focus 1, Focus 2 and Focus 3.

Implementation

Detailed research on proxy issues will mostly be carried out by individual research groups. However, some of the objectives listed above will require the coordinated efforts of WGs within CCT 2. In addition, WGs will communicate with other relevant projects in IGBP and the wider ESSP community (see Linkages section below). Here, the role of this CCT will be to facilitate cross-disciplinary communication and concerted efforts through workshops, meeting sessions and summary publications.

Linkages

A solid understanding of the modern physical and biogeochemical processes that determine the formation of proxy archives is essential to improving our interpretation of proxies. In this regard, CCT 2 will seek the specific expertise in modern process studies from Core Projects in IGBP and WCRP, SCOR, NOAA, NASA and other Earth Science organisations (Fig. 2.24). The crucial access to calibration data will be sought through groups specialised in Earth observation and monitoring, such as GEOTRACES and the Global Earth Observation System of Systems (GEOSS), as well as again from groups within IGBP and WCRP (Fig. 2.24).

Cross-Cutting Theme 3: Modelling

Numerical models provide a comprehensive, quantitative and physically coherent framework for exploring couplings and feedbacks between the various components of the Earth System. As such, modelling is a key element of all the PAGES Foci. Some palaeo-specific modelling issues are generally not as relevant to the communities developing Earth System models for future projections. Accordingly, this Theme supports efforts to improve model components specific for palaeoresearch requirements.

Rationale

Over the past years, Earth System modelling has become increasingly important in the area of palaeoscience. Physically based Earth System models (ESMs) provide a valuable tool to assess conceptual models of past climate changes derived from palaeodata. Conversely, data-based reconstructions of past climate variations provide critical testbeds for ESMs, which are usually optimised to capture present-day climate. Hence, combining data-based reconstructions and palaeo-modelling offers a promising way to fully comprehend past climate dynamics (Fig. 2.27) and accordingly benefit forecasting simulations through improved model skill.

A benefit of the joint utilisation of palaeo-reconstructions and palaeo-modelling is a means for formulating and testing hypotheses, for example, by quantifying the response of the Earth System to different forcings. Moreover, ESMs provide a comprehensive, quantitative and physically consistent framework for exploring couplings and feedbacks between the various components of the Earth System. This type of analysis is of specific relevance for detecting thresholds, especially if ESMs of different degrees of complexity are considered. In addition, ESMs provide a powerful link between past climate changes and projections of future climate, which are assessed by the same type of models.

Numerical modelling plays a crucial role in the research underlying all PAGES Foci. The models employed not only include ESMs but also those for interpreting proxies at a local scale (e.g., hydrological lake-level models), as well as human-climate interaction models. The models in use are frequently developed outside the palaeoscience community and are optimised for capturing modern processes. Accordingly, ESMs do not typically deal with a number of issues that are important to palaeo-modelling, and which will therefore be promoted by CCT 3:

- Forward modelling of proxies.
- Objective comparison of proxy data and modelling results (including upscaling/downscaling techniques, regional modelling, assimilation of sparse data).
- Optimising selection of sampling locations.
- Requirement for modules of reduced complexity allowing for longer integration times (including the physical climate, ecosystem and biogeochemistry modules).
- Modules for Earth System components operating at geological timescales (e.g., the weathering-carbonate burial cycle).

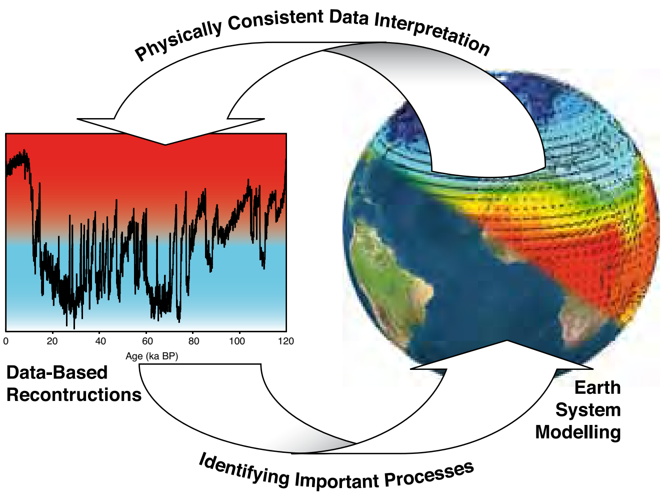

Figure 2.27: Combined approach of palaeo-reconstruction and Earth System modelling to decipher the dynamics of past environmental changes (data from NorthGRIP Project Members, 2004; figure from M. Schulz).

These topics are best addressed in a palaeo-framework that includes modellers as well as specialists dealing with the intricacies of palaeo-proxies and proxy-based reconstructions.

Goals

CCT 3 has three specific goals:

To foster the development of strategies for proxy modelling.

- To maximise the anticipated synergy, focus will be on proxies with wide spatial coverage and for which large data collections already exist (e.g., stable isotopes reflecting the physical and biogeochemical processes in the Earth System).
- Strategies for including proxies such as aerosols or pollen will also be developed.

To devise methods for the objective comparison of proxy data and modelling results.

- In present-day climatology, data assimilation has become an important tool for quantifying the state of the climate system based on observations. However, these methods are not readily available for the sparsely distributed palaeodata. Successful strategies for assimilation of palaeodata could also help scientists working on proxy-based reconstructions to optimise the selection of sampling locations and will be promoted by this CCT.
- Proxy-based reconstructions are often widely spaced and associated with uncertainties that are not well constrained. The lack of suitable statistical methods for comparing such data with model output will be addressed by CCT 3. This includes strategies for downscaling the output of global models to regional scales (e.g., for lake level, ice sheet, fire, coastal upwelling, or aerosol transport models).
- This CCT will stimulate the development of coupling techniques for two-way nesting of coupled regional and global climate models.

To promote the development of comprehensive ESM families.

- The long timescales associated with geological processes often require integration times that are significantly longer than those used for generating future climate scenarios. To meet this requirement and also rely on the same type of models used in the IPCC community, models should be offered with a range of resolutions and system components suitable for long palaeoclimate experiments.

Implementation

The goals above will be addressed with a series of workshops, under the lead or with the participation of CCT 3, on the following topics:

- Inclusion of proxies within climate models (forward modelling) – Emphasis on proxies for the hydrological cycle (e.g., stable isotopes of water), ocean circulation ($\delta^{13}C$, $\delta^{18}O$, $\Delta^{14}C$, Pa/Th) and biogeochemical processes ($\delta^{13}C$, Cd/Ca, $\delta^{15}N$).
- Data-assimilation and regionalisation techniques for palaeodata – Emphasis on various strategies for state estimation (i.e., finding the state of a model that optimally fits the reconstructions), as well as techniques for embedding regional models in global models.
- Development of comprehensive model families for palaeoclimate simulations – Emphasis on comparison of different strategies in developing model families with respect to resolution-dependent parameterisations of physical, chemical and biological processes.

Linkages

See Figure 2.24 for the overlap of CCT 3 with external programmes. Of particular importance is the link with PMIP2, which has a complementary thematic focus on the model output of defined palaeo-scenarios, and with the PAGES/CLIVAR Intersection, which addresses data-model comparison and forward modelling issues with a focus on the late Holocene and abrupt events. Within IGBP, CCT 3 shares many of its goals regarding model physics with the AIMES project, which does not however specifically deal with palaeoscience issues. Cooperation with IMBER and SOLAS will benefit the improvement of the representation of biogeochemical processes in models. Other important partners include long-standing working groups addressing aspects of climate modelling, such as the Community Climate System Model (CCSM) Paleoclimate WG and the CLIVAR WG on Coupled Modelling (WGCM).

Cross-Cutting Theme 4: Data Management

This Theme provides an umbrella for activities that support availability and access to palaeoscience data, as well as creative ways for their scientifically fruitful utilisation. It aims to mediate between the scientific community and international data centres such as WDC and PANGAEA, as well as the regional, national and thematic databases.

Rationale

Future progress in understanding climate linkages and their impact on environment is dependent on the provision of well-documented data. The palaeoscience community has developed an impressive mix of databases of various sizes and concepts. This mix includes the large data centres, mostly organised in the World Data Center (WDC) network, which provides nearly inexhaustible storage capacities and long-term constancy (e.g., WDC for Paleoclimatology at NOAA/National Climate Data Center in Boulder, USA and PANGAEA/WDC for Marine Environmental Sciences in Bremen, Germany). It also includes the smaller national and regional proxy- or archive-specific databases, which offer close contact with the specialist communities in addition to the scientific expertise to service data exchange, guarantee data quality standards and encourage scientific projects.

Despite widespread acknowledgement of the importance of data availability, many scientists place a low priority on contributing data to data centres and are often reluctant to share data. Thus, data acquisition is a continuous struggle for database curators, and the amount of relevant, high-quality palaeodata that is not internet-accessible is unacceptably high and is impeding progress in palaeoscience. Another challenge is to ensure that the flow of data, information and technology in data repositories is not just a curatorial exercise but also a usable tool for a diverse scientific community.

Goals

CCT 4 has three goals for the coming years:

- To support scientific data collection and synthesis activities, in particular, encouraging data collection on PAGES relevant themes.
- To ensure the availability of and access to (palaeo) science data by: 1) Providing a Paleodata Portal for coordinated data searches, 2) Optimising the flow of data, information and technology between the mix of larger and smaller databases, 3) Supporting the archiving of and access to standard datasets (e.g., for modellers), 4) Including model run outputs, 5) Serving the observing community (e.g., extending glacier observations back in time), and 6) Facilitating palaeoscientists access to modern data.
- To encourage data submission and expansion of the archive of internet-accessible palaeodata by: 1) Increasing the merit of data contribution and recognition of datasets as a form of official publication (e.g., assigning a Digital Object Identifier (DOI)), and 2) Fostering data submission practices in coordination with funding organisations and publishers.

Implementation

Early in its history, PAGES was an important player in the creation of the NOAA/NCDC World Data Center for Paleoclimatology. Building on this effort, PAGES has established a Data Management Working Group, the "PAGES Databoard" (www.pages-igbp.org/resources/data/databoard.html), which includes representatives from all of the major data centres, as well as representatives from thematic data collection efforts. Databoard meetings are held once every 2-3 years. The Databoard will coordinate activities under CCT 4.

The role of CCT 4 is that of a mediator between scientists and data centres, as well as between the different databases. PAGES media (e.g., website and publications) play an important role in communicating data management issues to the scientists. For the data centres, PAGES provides the users' perspective and a link to the research community.

Compilation, quality control and archiving of palaeodata are to be an integral part of activities in the PAGES Foci. Data cited in PAGES publications (including special journal issues and the PAGES newsletter) will show the location where the data are stored.

Linkages

Well-established links (Fig. 2.24) already exist with World Data Centres, most importantly with WDC for Paleoclimatology at NOAA/National Climate Data Center in Boulder, USA and PANGAEA/WDC for Marine Environmental Sciences in Bremen, Germany. In addition, strong links exist with several regional and thematic data centres (e.g., the Mediterranean Basin and Subtropical Africa (MEDIAS) database, and the African, European and North American pollen databases). On CCT 4 issues, PAGES will also work closely with IMAGES Data Management.

Implementation Strategy

Organisational Structure and Management

PAGES is in essence a community of palaeoclimate and palaeoenvironmental scientists with an International Project Office (IPO) as its central hub. Overall scientific direction for the project is the responsibility of the Scientific Steering Committee (SSC). Leaders of the Foci and Cross-Cutting Themes (CCTs), and the underlying Working Groups, direct activities at a finer level. Membership to PAGES is open to all and does not require an affiliation to a Focus or CCT. As such, PAGES includes a proportion of scientists from the wider Earth System Science community and interested members of the general public.

The organisational structure of the PAGES community of currently around 4750 members is as follows (Fig. 3.1):

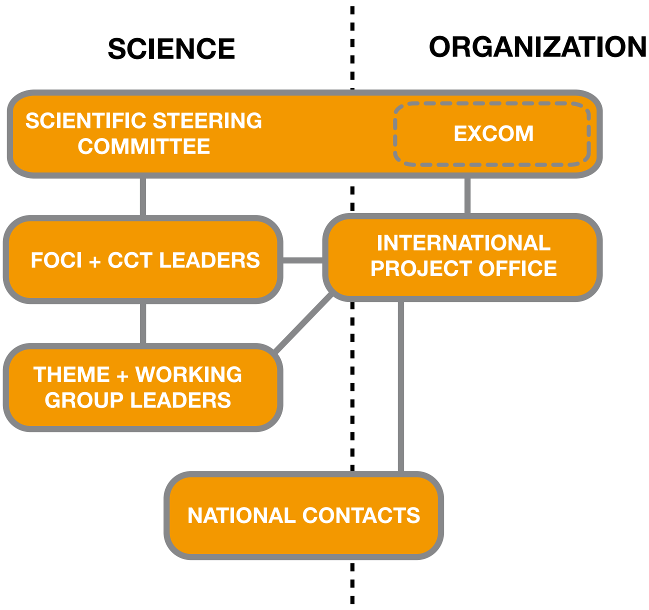

Figure 3.1: Organisational structure of PAGES. Connecting lines illustrate the main communication pathways.

Scientific Steering Committee

The SSC identifies the scientific emphasis of PAGES based on input from scientists from their respective communities and from national research programmes. It develops science plans for PAGES activities and recommends mechanisms for implementation and integration. SSC members act as liaisons to groups within the PAGES community and serve as spokespersons for PAGES at scientific meetings. In addition, the activities and responsibilities of the IPO are under the direction and review of the SSC.

Membership of the SSC is decided upon by a process of open nomination, followed by consideration by the current SSC and final approval by IGBP. Membership is on a voluntary basis and is usually for a three-year term, renewable once. The 15-20 SSC members represent a variety of nations and all major disciplines in palaeoscience. The SSC convenes an annual meeting, sponsored by IGBP.

The SSC is headed by an Executive Committee (EXCOM), a subgroup of five SSC members, including the elected Chair or Co-Chairs. A Memorandum of Agreement between the Swiss and U.S. National Science Foundations dictates that a Swiss and a U.S. scientist must hold principal positions within PAGES. For the Swiss representative, this was traditionally as Swiss Director (a supervisory position, above IPO Executive Director) but has more recently been as SSC Co-Chair. For the U.S. position, this was previously as Executive Director or SSC Chair but has more recently been as Co-Chair. The Chair or Co-Chairs work directly with the IPO to assist with decision making. Other EXCOM members are also in regular contact with the IPO for important decisions that arise between SSC meetings. The EXCOM convenes twice a year, once alongside the SSC meeting and once in between.

International Project Office

The PAGES IPO, based at the University of Bern, Switzerland, carries out the day-to-day operation of the PAGES project as a whole, and serves as the primary communication and information hub for the various project elements and other global change organisations. Activities include maintaining the PAGES website and databases, organising meetings and workshops, and writing and editing PAGES publications. Office staff are also engaged in the planning and execution of PAGES science plans.

The IPO is currently staffed with five people who share the equivalent of just over 3 full-time positions: Executive Director (100%) and Science Officer (80%), both PhD level; Project Officer/Communicator (60%); Finance/Office Administrator (30%); and a Webmaster/IT Coordinator (50%). In addition, a Graphic Designer supports the IPO in a freelance capacity.

Foci and CCT Leaders

Each Focus and CCT is overseen by a small number of SSC members who guide the scientific activities. Themes and Working Groups also have one or more Leaders who come from the wider PAGES community, as well as a PAGES liaison from the SSC or IPO.

National Contacts

Currently, 50 countries have one or two PAGES National Contacts. These are scientists with a history of involvement in PAGES and scientists who have taken the initiative to form a National PAGES group. National Contacts are appointed or approved by the IPO and serve as the first point of contact for other researchers in their countries wishing to inform themselves about PAGES and become involved.

Funding

PAGES was founded in 1991 and has been jointly supported by the Swiss National Science Foundation (SNF) and the U.S. National Science Foundation (NSF), with a contribution from the National Oceanic and Atmospheric Administration (NOAA) since 1992. This support covers the costs of the IPO (approx. 60%) and of scientific activities such as meetings, workshops and publications (approx. 40%). Since the end of 2008, PAGES has also received in-kind support from the University of Bern, Switzerland, where the PAGES IPO is located. In addition, IGBP provides a block grant towards the costs of the annual SSC and EXCOM meetings. Beyond PAGES core funding, the IPO and SSC pursue external sources of additional funding for specific purposes, such as PAGES workshops and the PAGES Open Science Meetings.

Research Approaches

Since PAGES is science-driven but not itself a hands-on research project, the research approaches of PAGES are general, overarching practices that facilitate coordinated, community-driven palaeoresearch, rather than specific scientific methods. PAGES supports international and interdisciplinary activities, with the aim to building a worldwide, integrative past global change community with active links to other global change communities. The creation of such a community provides individual researchers and groups better access to data and workshops, and to other geographical regions and topics of interest. The bundling of research institutions and scientists within an international network leads to more robust, balanced and globally relevant palaeoscience—a whole that is greater than the sum of its parts. An example of such a network is that of the International Marine Past Global Changes Study (IMAGES), which currently consists of scientists from more then 50 institutions in 26 countries.

In its current phase, PAGES sees workshops complemented by conference sessions and larger meetings as its central means to fostering integrative palaeoscience. Each year, PAGES provides partial support for 10-15 international workshops that target PAGES scientific objectives. A proportion of the supported workshops are planning meetings. This funding is top-down in nature, aimed at furthering specific PAGES activities and developing new scientific directions. The remainder of the workshop support is bottom-up in nature, granted in response to requests from meeting organisers within the palaeoscience community. PAGES has 1-2 open calls for workshop proposals each year for support in this form.

Recognition of PAGES Research

Research carried out under the PAGES umbrella is endorsed by PAGES. Projects can apply for PAGES recognition by contacting the Foci or CCT Leaders, members of the SSC or the IPO. Endorsed projects may become integrated within PAGES as a Working Group, or remain independent from PAGES with official recognition of their immediate relevance to PAGES goals. The advantages of association with PAGES include enhanced visibility, validation of the project in the eyes of the community, a platform for dissemination of news and results through print and online publications, and potential strengthening of outside funding proposals.

Since PAGES is not itself a research project, the majority of its results are not of the traditional kind. Therefore, PAGES publications, that is, products arising from PAGES-supported workshops and groups, tend to be special journal issues, synthesis papers and books, rather than individual research articles.

Collaboration and Linkages

As outlined in the Introduction, PAGES plays a central role in integrating the themes of the other IGBP core Projects. This is achieved within the formal context of IGBP joint meetings, such as Scientific Committee meetings (held each year and attended by the Chairs and Executive Officers of each of the projects) and Congresses or Open Science Conferences (held every four years and attended by all the SSC members of each of the projects), as well as through project SSC meetings. For example, PAGES and AIMES currently share a common SSC member, and additional representatives of both projects attend each other's SSC meetings. Direct scientific inter-project collaboration occurs very effectively through IGBP Fast-Track Initiatives (FTIs), such as the 2005-2008 FTI on Ocean Acidification. Integration is also achieved outside the formal IGBP structure through scientific collaborations, invitations to workshops and reciprocal newsletter contributions.

Collaboration between the palaeoscience community and groups representing neighbouring disciplines that can benefit from or complement past global change research is considered essential to fulfilling PAGES mission and is actively sought. Within the Earth System Science Partnership (ESSP), active collaboration on climate change research exists in particular with the projects Climate Variability and Predictability (CLIVAR) and Climate and Cryosphere (CliC) of the World Climate Research Programme (WCRP). Beyond ESSP, PAGES is linked to large programmes and organisations, such as the U.S. National Oceanic and Atmospheric Administration (NOAA), the International Union for Quaternary Research (INQUA), the Integrated Ocean Drilling Program (IODP) and the International Continental Scientific Drilling Program (ICDP), as well as the American Geophysical Union (AGU) and European Geosciences Union (EGU).

PAGES also has links to numerous smaller groups with a more narrow focus, such as the Antarctic Climate Evolution (ACE) programme of the Scientific Committee on Antarctic Research (SCAR), the International Partnerships in Ice Core Sciences (IPICS), which is a PAGES endorsed project, the European Union's Millennium Project, and the abovementioned FTI on Ocean Acidification, which was a joint collaboration between IGBP and the Scientific Committee on Oceanic Research (SCOR), and coordinated by PAGES. More detail on scientific linkages is provided under each of the Foci and CCT sections in the Science Plan.

Data Policy and Management

PAGES supports the free and open exchange of data, and has strong policies on the availability and accessibility of data (www.pages-igbp.org/resources/data/policies.html). A Paleodata Portal—a single, coordinated palaeodata search engine—has been set up on the PAGES website (www.pages-igbp.org/dataportal) to speed up and simplify the way in which users search for relevant data. Data issues are managed under CCT 4 through the PAGES Databoard, which includes members from most major data centres. See Cross-Cutting Theme 4: Data Management for more details.

Capacity Building, Education and Outreach

Capacity building, education and outreach are an integral part of PAGES philosophy. Capacity-building efforts, including regional workshops, young scientists meetings and summer schools, are aimed at increasing palaeoscience expertise for young and developing-country scientists. In addition, the online National PAGES (www.pages-igbp.org/about/national/) and the PAGES National Contacts provide nuclei for community building on a national level and a format for their integration within the international palaeoscience community. As well as travel support for workshops, PAGES provides editorial publishing support for the PAGES newsletter and special journal issue publications, and assists with the establishment of personal connections.

PAGES priority in terms of outreach is to enhance the visibility of palaeoscience and to communicate the relevance of palaeoresearch results to the wider scientific community, policy makers and the educated public. PAGES offers a wide range of educational and outreach resources, most of which are available in digital form to download free of charge from the PAGES website (www.pages-igbp.org/resources/). PAGES primary publication, *PAGES news*, is produced 2-4 times a year, and contains short palaeoscience articles, programme news and workshop reports. In its print version, the newsletter reaches large numbers of researchers and institutions in developing countries that do not have access to the internet or funds for journal subscriptions. In addition to the newsletter, PAGES offers photos, posters, PowerPoint slides, Info Sheets, reports, newsletters, scientific articles, special journal issues and books (Fig. 3.2).

Figure 3.2: PAGES produces a range of outreach products, including books (left), a palaeoscience newsletter, *PAGES news* (centre), and special issues in peer-reviewed journals (right).

PAGES will continue to consider and implement new capacity building, education and outreach ideas as demands for information and support change in the future.

Outcomes

The major outcomes that PAGES envisions as a result of the activities outlined in this Science Plan and Implementation Strategy include:

- Research results that address the major scientific issues in palaeoscience and come closer to answering the key overarching questions that PAGES has posed.
- Closing of critical knowledge gaps described in the Fourth IPCC Assessment Report.
- Support of innovative scientific approaches and new data acquisition in areas that will lead to a better understanding of the Earth System.
- Development of standardised reference datasets, such as on palaeoclimate forcings and chronology.
- Further synthesis and dissemination of palaeoscience research results.
- Establishment of a more interdisciplinary and internationally inclusive palaeoscience research framework.
- Better integration of palaeoscience into other global change research agendas.

Project Timeline

The timeline in Fig. 3.3 shows milestones in the history and framework of PAGES, from its inception in 1991, through the present and into the future. As in the past, major meetings such as the PAGES Open Science Meetings will be held at regular intervals to provide an overview of the state of the science and the progress of the project in general. The PAGES scientific agenda is interlinked with the IPCC assessment process and with the scientific framework provided by IGBP. The Open Science Meetings, IPCC assessment reports and IGBP scientific developments provide input for re-evaluations of the scientific agenda of PAGES. Regular evaluations are considered necessary for PAGES to adapt to new developments in Earth System Science and to the needs of the palaeoscience community.

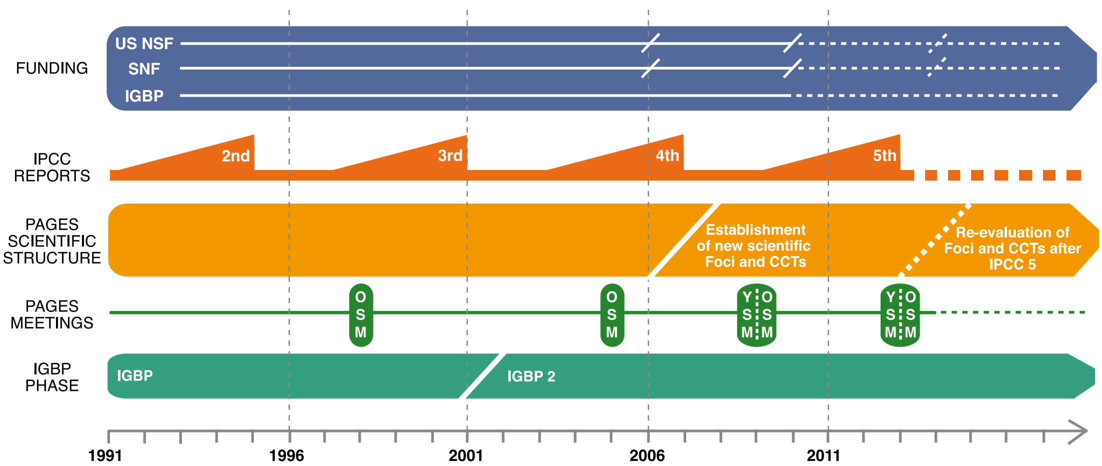

Figure 3.3: Timeline of the history and anticipated milestones of PAGES alongside the associated developments in IGBP and the IPCC assessment process.

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Acronyms and Abbreviations

ACE	Antarctic Climate Evolution
ADOM	Past Atmospheric Dynamics
AGU	American Geophysical Union
AIM	Antarctic Isotopic Maxima
AIMES	Analysis, Integration and Modeling of the Earth System
AMMA	African Monsoon Multidisciplinary Analysis
AMO	Atlantic Multidecadal Oscillation
AOGCM	Atmosphere-Ocean General Circulation Model
BIPOMAC	Bipolar Climate Machinery
C4MIP	Coupled Carbon Cycle Climate Model Intercomparison Project
CCSM	Community Climate System Model
CCT	Cross-Cutting Theme
CliC	Climate and Cryosphere
CLIVAR	Climate Variability and Predictability
DIVERSITAS	International Programme on Biodiversity Sciences
DO	Dansgaard-Oeschger
DOI	Digital Object Identifier
EDDI	European Diatom Database
EGU	European Geosciences Union
EMIC	Earth System Model of Intermediate Complexity
ENSO	El Niño-Southern Oscillation
EOF	Empirical Orthogonal Function
EPICA	European Project for Ice Coring in Antarctica
EPOCA	European Project on Ocean Acidification
ESM	Earth System Model
ESSP	Earth System Science Partnership
EXCOM	Executive Committee
FTI	Fast Track Initiative
GAME	GEWEX Asian Monsoon Experiment
GCM	General Circulation Model
GCP	Global Carbon Project
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GEOTRACES	Global Marine Biogeochemical Cycles of Trace Elements and their Isotopes
GEWEX	Global Energy and Water Cycle Experiment
GICC05	Greenland Ice Core Chronology 2005
GLOBEC	Global Ocean Ecosystem Dynamics
GLP	Global Land Project
GWSP	Global Water System Project
HITE	Human-Climate Interactions with the Terrestrial Environment
ICDP	International Continental Scientific Drilling Program
ICP	International Conference on Paleoceanography

IGAC	International Global Atmospheric Chemistry
IGBP	International Geosphere-Biosphere Programme
IHDP	International Human Dimensions Programme on Global Environmental Change
IHOPE	Integrated History and Future of People on Earth
iLEAPS	Integrated Land Ecosystem-Atmosphere Processes Study
IMAGES	International Marine Past Global Changes Study
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
INQUA	International Union for Quaternary Research
IntCal	International Radiocarbon Calibration
INTIMATE	Integration of Icecore, Marine and Terrestrial Records
IODP	Integrated Ocean Drilling Program
IPCC	Intergovernmental Panel on Climate Change
IPICS	International Partnerships in Ice Core Sciences
IPO	International Project Office
ISI	Institute for Scientific Information
ITASE	International Trans-Antarctic Scientific Expedition
ITCZ	Intertropical Convergence Zone
LANDCLIM 10 000	Past Land-Climate Interactions in Europe over the Last 10 000 Years
LIMPACS	Human-Climate Interactions with Lake Ecosystems
LOICZ	Land-Ocean Interactions in the Coastal Zone
LOTRED(-SA)	Long Term Climate Reconstruction and Dynamics (of Southern South America)
LUCIFS	Land Use-Climate Interactions with Fluvial Systems
MAGIC	Model for Acidification of Groundwater In Catchments
MAIRS	Monsoon Asia Integrated Regional Study
MARGO	Multiproxy Approach for the Reconstruction of the Glacial Ocean Surface
MedCLIVAR	Mediterranean Climate Variability and Predictability
MEDIAS	Mediterranean Basin and Subtropical Africa
MOC	Meridional Overturning Circulation
MOVE	Meridional Overturning Variability Experiment
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NEEM	North Greenland Eemian Ice Core Drilling
NOAA	National Oceanic and Atmospheric Administration
NorthGRIP; NGRIP	North Greenland Ice Core Project
NSF	U.S. National Science Foundation
PAGES	Past Global Changes
PALCOMM	Palaeoclimate Commission
PALSEA	Paleo-Constraints on Sea Level Rise

PANGAEA	Publishing Network for Geoscientific and Environmental Data
PCMIP	PalaeoCarbon Modelling Intercomparison Project
PDO	Pacific Decadal Oscillation
PEP	Pole-Equator-Pole
PETM	Palaeocene-Eocene Thermal Maximum
PIGS	Past Interglacials
PMIP (PMIP2, PMIP3)	Paleoclimate Modelling Intercomparison Project (Phase II, Phase III)
POLLANDCAL	Pollen-Landscape Calibration
PR Challenge	Paleoclimate Reconstruction Challenge
QUEST	Quantifying and Understanding the Earth System
RAPID (-WATCH)	Rapid Climate Change (–Will the Atlantic Thermohaline Circulation Halt)
SACCOM	Commission on Stratigraphy and Chronology
SCAR	Scientific Committee on Antarctic Research
SCOR	Scientific Committee on Oceanic Research
SIO	Scripps Institution of Oceanography
SNF	Swiss National Science Foundation
SOLAS	Surface Ocean-Lower Atmosphere Study
SPECMAP	Mapping Spectral Variability in Global Climate Project
SSC	Scientific Steering Committee
SWAP	Surface Water Acidification Programme
TERPRO	Terrestrial Processes, Deposits and History
VACS	Variability of the African Climate System
VAMOS	Variability of the American Monsoon Systems
WCRP	World Climate Research Programme
WDC (-Paleo, -MARE)	World Data Center (for Paleoclimatology, for Marine Environmental Sciences)
WG	Working Group
WGCM	Working Group on Coupled Modelling

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