# 40. Chronology and Climate Forcing of the Last Four Interglacials

Frank Sirocko, Martin Claussen, Thomas Litt, Maria Fernanda Sánchez Goñi, André Berger, Tatjana Boettger, Markus Diehl, Stéphanie Desprat, Barbara Delmonte, Detlev Degering, Manfred Frechen, Mebus A. Geyh, Matthias Groeger, Masa Kageyama, Frank Kaspar, Norbert Kühl, Claudia Kubatzki, Gerrit Lohmann, Marie-France Loutre, Ulrich Müller, Bert Rein, Wilfried Rosendahl, Katy Roucoux, Denis-Didier Rousseau, Klemens Seelos, Mark Siddall, Denis Scholz, Christoph Spötl, Brigitte Urban, Maryline Vautravers, Andrei Velichko, Stefan Wenzel, Martin Widmann and Bernd Wünnemann

The last four interglacials (intervals during which global ice volume was similar to, or less than, that of our current warm stage) correspond to the warmest parts of the marine oxygen isotope stages MIS 5, 7, 9, 11. These interglacials followed the 100-kyr rhythm of eccentricity, but each had different insolation regimes, different durations, different ice volumes and different sea-level heights, but atmospheric greenhouse gas concentrations were similar and reached values which, by and large, were close to those of the current interglacial (Holocene or MIS 1) before the industrial revolution led to the artificial enrichment of the atmosphere's greenhouse gas concentrations via the burning of fossil fuels. The Holocene is addressed in a few papers, but an intercomparison of the ongoing interglacial with the past interglacials is not the focus of this book.

This final paper of the book will summarize the evidence presented and discussed in the research articles. It is intended to be comprehensible to the lay reader and thus does not go into detail. Every paper is represented by a list of three statements which sum up the key findings. This is followed by a synthesis of the current state of knowledge on each of the climatic warm intervals discussed in the book. There is almost complete agreement on several themes, in particular on the subject of insolation forcing, while other topics, such as the correlation of sequences dated by different techniques, will need to be discussed and evaluated further before a consensus is reached. At the end of this paper, we make some suggestions for future research themes, which will need to be answered soon if the climate of the past is to be of use for the prediction of climatic and environmental evolution in the future when the natural forcing of climate has to interact with the human influence on the atmosphere and land surface.

## STATEMENTS BY FIRST AUTHORS OF RESEARCH ARTICLES

**Martin Claussen**, *University Hamburg and Max Planck Institute for Meteorology, Hamburg, Germany*

(1. Introduction to Climate Forcing and Climate Feedbacks)

1. Commonly, climate is defined as statistics (mean, variance, ...) of the atmosphere. In climate physics, however, a wider definition has proven to be useful in which climate is viewed as the state and statistics of the climate system which encompasses the atmosphere, the ocean, the ice and the land including the living world, i.e. the marine and terrestrial biosphere as well as carbon and nutrient cycles.
2. Climate varies on all timescales, not only because of changes in climate forcing, but also because of internal dynamics and feedbacks between the components of the climate system which are seemingly unrelated to variations in forcing.

3. Not all climate variations on timescales longer than 30 years are directly driven by oscillation forcing; some of these variations could arise because of the sluggish dynamics of the deep ocean or the ice sheets or because of a strongly nonlinear, disproportional response of the climate system to subtle variations in forcing.

**André Berger**, *Université catholique de Louvain, Belgium*

(2. Insolation During Interglacials)

1. The spectrum of the long-term variations of daily insolation is dominated by precession everywhere over the Earth and for any day except close to the polar night.
2. The energy received by the Earth over a given time slice during the year defined in terms of the longitude of the Sun (an astronomical season for example) is a function of obliquity only, the length of such astronomical seasons being a function of precession only.
3. The amplitude of the variations of insolation (in particular during the interglacials) is a function of the amplitude of the variations of precession.

**Martin Claussen**, *University Hamburg, and Max Planck Institute for Meteorology, Hamburg, Germany*

(3. A Survey of Hypotheses for the 100-kyr Cycle)

1. Even some 160 years after first geological evidence, the ice-age riddle is not yet fully solved. However, we have some clues on which elements should constitute a theory of Quaternary Earth system dynamics, regarding concepts and model structure.
2. It is certain that the ice-age riddle cannot be explained in terms of a single dominating process. Instead, a systems approach involving a number of feedback processes and the nonlinear nature of the climate system is expected to lead to a solution.
3. It is likely that changes in insolation caused by changes in orbital parameters trigger fast internal feedbacks such as the water vapour–temperature feedback and the snow–albedo feedback. Some feedbacks, like the snow–albedo feedback, amplify climate changes very rapidly once a certain threshold in the system is crossed. Initial changes are then further amplified by slower feedbacks such as biogeochemical and biogeophysical feedbacks and finally, the isostatic response of the lithosphere to icesheet loading.

**André Berger**, *Université catholique de Louvain, Belgium*

(4. Modelling the 100-kyr Cycle – An Example From LLN EMICs)

1. The LLN model is a model of intermediate complexity which takes into account, in a simplified way, the atmosphere, the hydrosphere, the cryosphere, the biosphere, the lithosphere, their mutual interactions and internal feedbacks. Under the forcing of insolation and a progressively decreasing atmospheric $CO_2$ concentration, it simulates the transition between the 41-kyr and the 100-kyr worlds around 850 kyr.
2. The model also simulates the spectrum of the northern hemisphere ice volume over the last 450 kyr, with the strongest period at 100 kyr.
3. It fails to reproduce the reduced amplitude of the 100-kyr cycles before 450 kyr with cool interglacials and cold glacials.

**Frank Sirocko**, *University of Mainz, Germany*

(5. Introduction: Palaeoclimate Reconstructions and Dating)

1. The beginning, end and duration of the past interglacials do not appear to be synchronous all over the world, i.e. parts of the climate system have been in an interglacial state for longer than others.

2. Beginning and end of interglacials in the low latitudes and in the Antarctic lead to respective changes on the northern hemisphere.
3. Time-transgressive climate shifts are also strong over Europe, where the sea-surface temperature (SST) changes of the North Atlantic drift were associated with a stepwise shift of the vegetation zones, at least at the end of the past interglacial, with interglacial conditions persisting for longer in southern Europe than in the north.

**Barbara Delmonte**, *DISAT, University Milano-Bicocca, Milano, Italy.*

(6. Late Quaternary Interglacials in East Antarctica from Ice-Core Dust Records)

1. Aeolian dust records from deep East Antarctic ice cores preserve evidence for extremely low dust fluxes during the last five interglacials (10 to 25 times lower than in glacial periods). This is related to reduced primary production and mobilization of dust on the Southern Hemisphere continents, and to changes in atmospheric transport and the hydrological cycle. The data show no evidence for pronounced cold events within the last five interglacials (back to MIS 11.3).
2. The Sr–Nd isotope fingerprint of aeolian dust in Antarctica suggests a dominant southern South American provenance during Quaternary glacial times, but the first geochemical data for stage 5.5 and the Holocene show significant differences and opens up the possibility for different provenance mixing.
3. Dust-size variability in the EPICA-Dome C ice core suggests shorter transport time for dust or more direct air mass penetration to the site during interglacials with respect to cold periods.

**Mark Siddall**, *University of Bern, Switzerland*

(7. Eustatic Sea Level During Past Interglacials)

1. The last nine interglacial periods differ not only in height and variability of sea level, but also in timing relative to northern summer insolation peaks.
2. Sea levels during MIS 5e, 9c and 11 were close to or slightly higher than modern sea level but sea level during MIS 7 may have been slightly lower than present day.
3. Some interglacials have a single peak close to modern sea level (MIS 5e, 9c) and others have several (MIS 7), while MIS 11 persisted with little variation for at least 30 kyr.

**Manfred Frechen**, *Leibniz Institute for Applied Geosciences (GGA-Institut) Hannover, Germany*

(8. Uranium-Series Dating of Peat from Central and Northern Europe)

1. Fen peat is suitable for uranium-series dating under the asumption of complete fractionation of uranium and thorium during formation and no gain or loss of U and Th since the time of formation.
2. Uranium-series dating provides more reliable and precise absolute dates of interstadial and interglacial peat layers in Central Europe. Examples of uranium dates for MIS 5, 7 and 9 are: $91 \pm 2$ kyr for lignite (MIS 5c) from Zell in Switzerland, $106 \pm 11$ kyr for the fen peat (MIS 5e) from Allt Odhar in Scotland, $214 \pm 8$ kyr for peat (MIS 7) from Groß-Rohrheim in Germany and $317 \pm 14$ kyr for fen peat from Tottenhill Quarry in Norfolk, England.
3. TIMS $^{230}Th/U$-dating results provide a chronological frame for terrestrial sediments such as fen peat, cave sinter and travertine covering the past 500 000 years.

**Denis Scholz**, *Heidelberger Akademie der Wissenschaften, Germany*

(9. U-Redistribution in Fossil Reef Corals from Barbados, West Indies, and Sea-Level Reconstruction for MIS 6.5)

1. Postdepositional remobilisation produces significantly wrong U-series ages of fossil reef corals and may, therefore, have consequences for the precise determination of the timing and duration of past interglacials.
2. A small degree of U-redistribution can only be detected by analysis of a large number of samples but not by the conventional reliability criteria.
3. MIS 6.5 sea level was between $-50 \pm 11$ and $-47 \pm 11$ m relative to the present sea level from $176.1 \pm 2.8$ to $168.9 \pm 1.4$ kyr BP.

**Bert Rein**, *Johannes Gutenberg-University, Mainz, Germany*

(10. Holocene and Eemian Varve Types of Eifel Maar Lake Sediments)

1. During the last interglacial, multicentennial periods of increased dust storm activity and aeolian dust deposition occurred at ~126, ~118 and ~112 kyr BP. So far, no evidence exists for comparable extreme, multicentennial dry periods within the Holocene as observed in the deposits of the last interglacial palaeolake.
2. Besides the Younger Dryas sediments, which where deposited immediately before the Holocene period, no indication could be found for climatically induced dust storm activity during the Holocene.
3. The lithic maximum in the sediments of the Little Ice Age (290–630 yr BP) does not necessarily require a climatological explanation since it can be explained by anthropogenically induced soil erosion due to increasing population density around the lake when medieval villages on the surrounding plateau deserted.

**Detlev Degering**, *Saxon Academy of Sciences, TU Freiberg, Germany*

(11. Dating of Interglacial Sediments by Luminescence Methods)

1. Luminescence methods were successfully applied in the age determination of interglacial sediments. The dated event is the last optical bleaching of the sediment and the maximum determinable ages are currently of the order of some hundred thousands of years, depending on sediment properties and the luminescence technique applied. A sufficiently long exposure to sunlight prior to sedimentation is essential for correct age determination; an incomplete reset of the luminescence signal will lead to age overestimation.
2. Eemian deposits can be dated with adequate precision by conventional luminescence methods. These include multiple aliquot infrared stimulated (IRSL) techniques (using polymineral fine-grain and coarse-grain potassium feldpar samples) and, in some cases (of low radioactivity), quartz optically stimulated luminescence (OSL) single-aliquot regeneration techniques. However, higher precision is reached by the infrared radiofluorescence method (IR-RF). Reliable luminescence dating of older interglacials (MIS 7 and 9) is only possible by the IR-RF method.
3. Dating of interglacial sediments requires, furthermore, the consideration of special dose rate-related problems: (i) the occurrence of radioactive disequilibria and (ii) layered sediments with varying radioisotope content. In both cases, high analytical effort and model calculations are necessary to minimize the influence of these sources of errors.

**Stefan Wenzel**, *Schloß Monrepos, Neuwied, Germany*

(12. Neanderthal Presence and Behaviour in Central and Northwestern Europe During MIS 5e)

1. The majority of the few archaeological sites of Central and Northwestern Europe which can be dated more precisely within MIS 5e are attributed to the first third of this interglacial (up to the *Quercetum mixtum*–*Corylus* phase).

2. So far, there is no evidence of hominid occupation in the *Carpinus* phase of the Eemian, and only a few archaeological sites are known from younger biozones of the Eemian.
3. In contrast to the rarity of archaeological sites from the last two-thirds of the last interglacial, which could indicate a deterioration of living conditions, the early Eemian sites and the sites solely attributed to the Eemian evidence that the lifeways of the Neanderthals living then differed little from those of their ancestors and their successors occupying a more open landscape: they hunted big game; they used a similar lithic technology, they practised long-distance transport of lithic artefacts (perhaps indicative of social networks) and they performed symbolic behaviour.

**Maria Fernanda Sánchez Goñi**, *Université Bordeaux 1, France*

(13. Introduction to Climate and Vegetation in Europe During MIS 5)

1. The complexity, both temporal leads and lags and geographical variability, of the nonlinear climatic signal in response to insolation changes during the penultimate deglaciation, last interglacial and last glacial inception is clearly shown by the collection of papers presented in this chapter.
2. Problems of nomenclature and stratigraphy for the last interglacial, reflecting the history of the discipline, are on the way to being solved, although uncertainties in the chronology of a number of MIS 5 records require further investigation.
3. Our scientific community should concentrate its efforts in accurately correlating the available records. It is only through this approach that we will be able to document the climatic variability of MIS 5 in an integrated way, link the processes reflected in different parts of the Earth system and propose reliable scenarios for the mechanisms underlying the climatic variability of the last interglacial.

**Klemens Seelos**, *Johannes Gutenberg-University, Mainz, Germany*

(14. Aprupt Cooling Events at the Very End of the Last Interglacial)

1. The LEAP (late Eemian aridity pulse) is detectable in loess records of the Eifel region and in the northern German record of Rederstall.
2. Taiga vegetation characterizes Rederstall in the first phase after the LEAP (after 118 kyr) and develops gradually into tundra after 115 kyr. At the same time, *Carpinus*-dominated temperate forest spread in the Eifel region and in France, and finally deteriorated at 111 kyr.
3. Loess and pollen records in the Eifel region and northern Germany show the first drastic and fast cooling, associated with widespread aridity, during the C24 cold event (111 kyr).

**Denis-Didier Rousseau**, *Université Montpellier II, France*

(15. Estimates of Temperature and Precipitation Variations During the Eemian Interglacial: New Data From the Grande Pile Record (GP XXI))

1. We applied a new method on new pollen data from Grande Pile, the inverse mode to the Biome4 vegetation model. The method utilizes $\delta^{13}$C, measured in parallel to the pollen samples as a constraint for the model. First the biomes and the $\delta^{13}$C simulated by the model are compared with the biome allocation of the pollen data. The $\delta^{13}$C to be simulated takes into account the degradation effect on the preserved organic matter.
2. This study highlights variation ranges of annual precipitation and/or temperature narrower using an inverse modelling procedure with $\delta^{13}$C than without. These

narrow ranges allow to reveal expected climatic trends that were noticed in marine sediments but not precisely reconstructed on the continent.

3. The variations in temperature appear to be related to SST oscillations in the North Atlantic region and are also in agreement with the timing of ice-sheet build-up in the Northern Hemisphere. Seasonal variations are also identified in the estimated temperatures of the warmest and coldest months.

**Norbert Kühl**, *University of Bonn, Germany*

(16. Quantitative Time-Series Reconstructions of Holsteinian and Eemian Temperatures Using Botanical Data)

1. Reconstruction of Eemian and Holsteinian temperatures shows uninterrupted interglacial conditions for both intervals. However, the Holsteinian seems to be less stable than the Eemian with some intra-interglacial coolings.
2. The course of temperature change within the Eemian and Holsteinian interglacial stages differs. Holsteinian January and July temperatures were higher in the later part of the interglacial, while the Eemian had its temperature optimum during the early phase.
3. The temperature decline at the very end of the Holsteinian interglacial resembles in magnitude the decrease at the end of the Eemian. Reconstructions reveal a drop in mean January temperature by 10–15°C and in mean July temperature by about 3°C.

**Andrei Velichko**, *Institute of Geography RAS, Moscow, Russia*

(17. Comparative Analysis of Vegetation and Climate Changes During the Eemian Interglacial in Central and Eastern Europe)

1. As follows from comparison of pollen data, the main phases in the evolution of vegetation during the Eemian Interglacial were similar in the Central and Eastern Europe.
2. We demonstrate the regional pattern of vegetation in the Eemian and Early Weichselian. Mixed broad-leaved forests in Central Europe included species that characteristically require a certain oceanicity of climate (e.g. *Ilex aquifolium, Hedera helix and Taxus baccata*). The participation of these plants decreased eastward. Of those species, only *Tilia platyphyllos* and *Viscum album* are found in the Eemian pollen assemblages in the East European Plain. Plant communities also differed noticeably from west to east during the cooler intervals at the beginning and end of the interglacial, primarily in the proportion of broad-leaved species in zonal vegetation formations.
3. Significant contrasts in environmental and climatic fluctuations mark the Saalian/Eemian boundary (transition from MIS 6 to MIS 5e). Two substages of vegetation development can be identified in the pollen diagram. Pine and spruce forest with shrubs occurred in the earliest phase. Then open birch woodlands and steppe-like communities occupied the area. Vegetation dynamics at this boundary resemble those detected at the transition from Weichselian to Holocene (Allerød and Younger Dryas).

**Tatjana Boettger**, *UFZ Centre for Environmental Research Leipzig-Halle, Germany*

(18. Indications of Short-Term Climate Warming at the Very End of the Eemian in Terrestrial Records of Central and Eastern Europe)

1. Geochemical and palynological investigations of lacustrine sediments from Central and Eastern Europe document at least two warming events during the transition from the Eemian to the Early Weichselian on a broad European transect.

2. The first pronounced warming phase takes place towards the very end of the Eemian. The second climatic amelioration was detected within the first Weichselian Stadial (Herning).
3. Correlations between Eemian European terrestrial sequences and their possible connection to the NGRIP record are discussed. Generally, it appears that warming phases towards the end of the last interglacial preceded the final transition to glacial conditions.

**Ulrich Müller**, *Johann Wolfgang Goethe University Frankfurt, Germany*

(19. Vegetation Dynamics in Southern Germany During Marine Isotope Stage 5 (∼130 to 70 kyr Ago))

1. The Eemian interglacial in southern Germany is characterized by dense thermophilous deciduous forests during the early and middle part and coniferous forests in the late part of the interglacial.
2. The exact timing and persistence of Eemian forests in southern Germany is a matter of debate. Varve chronologies suggest a duration of Eemian forests from ∼126 to 115 kyr BP in northern Germany and from ∼127 to 109 kyr BP in southern Italy. Possibly, Eemian forests existed in southern Germany from ∼126 to 110 kyr BP.
3. A comparison of vegetation reconstructions across Europe points to a steepening of meridional vegetation gradients during the declining stage (∼115 to 109 kyr BP) of the last interglacial. Presumably, the steepening of vegetation gradients was associated with a southward displacement of the warm North Atlantic current.

**Maryline Vautravers**, *University of Cambridge and British Antarctic Survey, Cambridge, UK*

(20. Subtropical NW Atlantic Surface Water Variability During the Last Interglacial)

1. In the Gulf Stream area, eight periods can be recognized between 108 and 134 kyr related to changes in the intensity of summer stratification and late winter mixing.
2. At the end of MIS 5e (122–116 kyr), winter SST are at their maximum while summer SST start to decrease. Superimposed on this trend, we found several high-frequency cooling events.
3. Most of these small coolings are associated with lithics peaks testifying for iceberg incursions in the subtropical area during the last interglacial.

**Bert Rein**, *Johannes Gutenberg University, Mainz, Germany*

(21. Abrupt Changes of El Niño Activity off Peru During Stage MIS 5e-d)

1. El Niño activity sharply dropped during the last interglacial, as it did uring the middle of the Holocene when perihelion occurred in late summer. However, during MIS 5d, the strength of El Niño activity did not recover with more favourable insolation conditions as was observed during the late Holocene.
2. The strong El Niño activity that was indicated by the Zebiak and Cane ENSO model according to orbital forcing did not occur in Peru at the beginning of the last glaciation. The transition into a glacial world apparently changed critical boundary conditions, which are linearized around a current mean climatology in the ZC ENSO model.

**Bernd Wünnemann**, *Freie Universität Berlin, Germany*

(22. Interglacial and Glacial Fingerprints from Lake Deposits in the Gobi Desert, NW China)

1. Hydrological changes in the Chinese Gobi Desert are strongly interlinked with climate dynamics on the Tibetan Plateau during the last interglacial–glacial cycle

2. The Eemian interglacial stage between 129 and 119 kyr appears to have been a period of positive water balance within the Gaxun Nur Basin as a result of warm and moist climate conditions with enhanced summer monsoon moisture.
3. The subsequent rapid increase of climate instability with phases of colder and drier conditions coincides with strong shrinkages of lake size and enhanced aeolian transport, frequently influenced by the extra-tropical westerlies and the winter monsoon.

**Katy Roucoux**, *University of Leeds, UK*

(24. Fine Tuning the Land–Ocean Correlation for the Late Middle Pleistocene of Southern Europe)

1. There are pronounced phase offsets between forested intervals in Portugal and marine isotope-defined warm intervals. For example, MIS 7e lasts from 246 to 229 kyr, while the forested interval associated with it lasts from 243.2 to 237 kyr.
2. Forested intervals varied in length from one warm stage to the next, and correlation of marine and terrestrial pollen sequences indicates that this pattern applies across southern Europe. In the marine pollen record of MD01-2443, the shortest forested period, at 3.5 kyr long, is the Lisboa forest interval associated with MIS 9e, while the longest uninterrupted forested period, at 10 kyr long, is the Cascais forest interval associated with MIS 7c.
3. Forested intervals also varied in floristic character across southern Europe as a result of local climatic, geological and biogeographical factors. For example, it appears that while tree populations were replaced by Ericaceous heath in Portugal at the end of the forested intervals associated with MIS 7e and MIS 9e, coniferous forest thrived elsewhere in southern Europe. Hence, we cannot assume that periods of interglacial conditions necessarily resulted in forest vegetation everywhere for their whole duration.

**Stéphanie Desprat**, *Université Bordeaux1, France*

(25. Climate Variability of the Last Five Isotopic Interglacials: Direct Land–Sea–Ice Correlation from the Multiproxy Analysis of North-western Iberian Margin Deep Sea Cores)

1. The last five isotopic interglacials (MIS 1, 5, 7, 9 and 11) were investigated in NW Iberian margin deep-sea cores, using terrestrial (pollen) and marine (planktic foraminifera, benthic and planktic foraminifera oxygen isotopes) climatic indicators.
2. This work shows that the climatic variability detected on the continent is contemporaneously recorded in the ocean. Although minima and maxima of ice volume and marine and terrestrial temperatures in the NW Iberian region appear synchronous, temperature changes are not in phase with ice volume variations. Particularly, substantial ice accumulation at high latitudes, associated with the glacial inception of these past interglacials, generally lags NW Iberian temperature decrease by some millennia.
3. The comparison of the different marine isotope stages highlights a common pattern of climatic dynamics within these isotopic interglacials, which is characterized by three major climatic cycles, related to orbital cyclicity, on which suborbital climatic fluctuations are superimposed.

**Mebus A. Geyh**, *Leibniz Research Institute of Geosciences, Hannover, Germany*

(26. Palynological and Geochronological Study of the Holsteinian/Hoxnian/Landos Interglacial)

1. Based on new TIMS $^{230}$Th/U dates from two fen peat layers of the Holsteinian reference site at Bossel, from several Holsteinian and non-Holsteinian profiles in northern Germany as well as on re-evaluated numerical $^{230}$Th/U dates from two sites with Hoxnian deposits in England, the Holsteinian Interglacial has an $^{230}$Th/U age of about 320 kyr and therefore is correlated with MIS 9.
2. There is palynological evidence for a reliable correlation between precisely analysed Holsteinian and Hoxnian deposits in Poland, Germany, England, SW-Ireland and France.
3. It became obvious that the Holsteinian interglacial is correlated with the Landos interglacial rather than with the Praclaux interglacial. The latter belongs to MIS 11 and is linked with the Rhume interglacial.

**Markus Diehl**, *Johannes Gutenberg-University, Mainz, Germany*

(27. A New Holsteinian Pollen Record from the Dry Maar at Döttingen (Eifel))

1. The Döttingen pollen sequence is the first Holsteinian pollen profile from middle-southern Germany. It represents a ‘low mountain range-type’ Holsteinian vegetation succession, to correlate with that of the north German lowlands, but with different pollen percentage values, showing that the pine-birch dominance of the north German profiles cannot be seen as a overregional, typical Holsteinian signature.
2. The first spike of pine-birch dominance (sometimes interpreted in Northern Germany as a cooling event) is also visible at Döttingen, but is preceded by a volcanic ash layer. The Döttingen sequence thus points towards a causal connection between volcanic activity and the Holsteinian vegetation development.
3. The transition of the Holsteinian to the subsequent cold stage is characterized by a change from a temperate forest to an open boreal forest within centuries.

**Brigitte Urban**, *University of Lüneburg, Germany*

(28. Interglacial Pollen Records from Schöningen, North Germany)

1. The complex Pleistocene sequence of the Schöningen browncoal mine, Germany, contains six major cycles (I–VI) providing biostratigraphical evidence of four interglacials (Holsteinian, Cycle I, Reinsdorf, Cycle II, Schöningen Cycle III, Eemian, Cycle V) and a number of interstadials younger than the Elsterian glaciation and preceding the Holocene (Cycle VI) being tentatively correlated with MIS 5, 7, 9 and 11 respectively.
2. The position of the Lower Palaeolithic spruce throwing spears of Schöningen can be assigned to the ultimate and already cool and dry Reinsdorf interstadial B of Cycle II (MIS 9/8?), characterized by a pine-birch open forest.
3. MIS 7 and MIS 9 (tentatively correlated with the Schöningen and Reinsdorf interglacials, respectively) differ strongly in their moisture regime as shown by the low presence of fir (*Abies*) in terminal phases of the Reinsdorf and its total lack in the Schöningen interglacial, pointing to an increasing dryness of the forested periods (interglacials) following the Holsteinian in northern Germany.

**Wighart von Koenigswald**, *University of Bonn, Germany*

(29. Mammalian Faunas From the Interglacial Periods in Central Europe and Their Stratigraphic Correlation)

1. The MIS 5e, 7, and 9 can be distinguished only vaguely by the mammalian fauna. Their diversity in insectivores and rodents is smaller than in the pre-Elsterian faunas. The only taxon showing an evolutionary trend is large vole *Arvicola* changing from *cantianus* to *terrestris* at about the Eemian.

2. The multiple climatic changes during the middle and upper Pleistocene caused an almost complete exchange of the mammalian fauna. In each interglacial period, the *Mammuthus* assemblage adapted to the cold climate disappeared and the *Elephas* assemblage immigrated from the Mediterranean region. Most mammalian lineages do not show a continuous evolution in Central Europe. Immigration and local extinction is the normal pattern.
3. The occurrence of the exotic *Hippopotamus amphibius*, known in recent times only from Africa, does not indicate very high temperatures or during the Eemian, but more likely a high maritime influence with mild winters.

**Wilfried Rosendahl**, *Reiss-Engelhorn-Museen, Mannheim, Germany.*

(30. MIS 5 to MIS 8 – Numerically Dated Palaeontological Cave Sites of Central Europe)

1. The numerical dates (MIS 5 - MIS 8) now available for palaeontological cave sites in Central Europe (12 sites with 31 dated strata) do not allow a critical discussion of their faunal assemblages with regard to their ecological-climatic distribution, with the exception of two sites. But even these two sites are not without contradicting faunal elements, and it remains uncertain whether they represent glacial or interglacial faunas.
2. In spite of all these problems, palaeontological cave sites represent a rich archive that can deliver important contributions to the reconstruction of the Middle and Upper Pleistocene palaeoclimate of Central Europe, provided many additional dates can be obtained to verify results obtained from other terrestrial archives.

**Christoph Spötl**, *Leopold-Franzens-Universität Innsbruck, Austria*

(31. The Last and the Penultimate Interglacial as Recorded by Speleothems From a Climatically Sensitive High-Elevation Cave Site in the Alps)

1. Changes in climate during MIS 5 to 7 identified by speleothem growth periods and oxygen isotope data are synchronous within the precision of the U/Th method with coral records of sea-level changes.
2. During MIS 7, the climate in the Alps was cooler, glaciers were larger and the timberline was lower than during MIS 5e. Speleothem growth during MIS 7 commenced ~236 kyr and ended ~190 kyr ago.
3. Full interglacial conditions during MIS 5e were reached 130 kyr ago and terminated 118–119 kyr ago.

**Martin Claussen**, *University Hamburg and Max Planck Institute for Meteorology, Hamburg, Germany*

(32. Climate System Models – A Brief Introduction)

1. In climate physics, climate models are a set of mathematical equations which are derived from physical principles and which are used in a prognostic mode to predict climate variations as function of some external forcing or which are tuned to data to interpolate between sparse data in time and space in a physically consistent manner.
2. When comparing data and model results, it is important to realize that climate is regarded as stochastic processes; therefore, it is not possible to predict all climate variations such as the precise course of a glacial interception in a deterministic way.
3. Only the interpretation of past climate variations by using mathematical climate models, which are validated against palaeoclimate evidence, will lead to picture of climate which is consistent with the physical understanding of our world.
4. In this chapter, models of different complexity are used. In chapters 33, 34

and 35, results of a comprehensive atmosphere ocean model or even an atmosphere ocean–vegetation model (in chapter 37) are discussed. In chapters 36, 38 and 39, models of intermediate complexity are used which interactively simulate the dynamics of the atmosphere, the oceans, vegetation and ice sheets.

**Frank Kaspar**, *Max Planck Institute for Meteorology, Hamburg, Germany*

(33. Simulations of the Eemian Interglacial and the Subsequent Glacial Inception with a Coupled Ocean-Atmosphere General Circulation Model)

1. European seasonal patterns of pollen-based temperature reconstructions for the early Eemian (at ~125 kyr) are in good agreement with simulation results of a state-of-the-art coupled ocean atmosphere general circulation model (ECHO-G) which was driven by orbitally induced changes in insolation.
2. When the same model is driven with insolation patterns of the last glacial inception at 115 kyr, the significantly reduced summer insolation of the northern latitudes leads to a distinct cooling of the northern hemisphere and the occurrence of a perennial snow cover over parts of North America.
3. The snow cover initially occurs in the region of the Canadian Archipelago, where cool southward winds from the Arctic prevail, and it is continuously expanding into the continent during the simulated period of several millennia.

**Martin Widmann**, *GKSS Research Centre, Geesthacht, Germany, and University of Birmingham, UK*

(34. Simulated Teleconnections During the Eemian, the Last Glacial Inception and the Preindustrial Period)

1. Simulations with a coupled atmosphere–ocean general circulation model (the same as used in the previous section) indicate that orbital forcing can change relationships between different climate variables.
2. Simulated temperature signals of multidecadal variations in the Arctic oscillation index are weaker in Europe and stronger in Siberia during the Eemian compared to the preindustrial period.
3. Simulated teleconnections between annual to decadal temperature variability at different locations are related to the Arctic Oscillation temperature signal, and can be somewhat different in the Eemian and in the preindustrial period.

**Gerrit Lohmann**, *Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany.*

(35. Orbital Forcing on Atmospheric Dynamics During the Last Interglacial and Glacial Inception)

1. Atmospheric dynamics plays an important role on orbital timescales, e.g. the modulation of the Icelandic Low.
2. The atmospheric teleconnections provide a bridge between low and high latitudes and transport the precessional forcing to high latitudes.
3. The related atmospheric circulation patterns induce nonuniform temperature anomalies which can have a greater amplitude than those resulting from direct solar insolation forcing.
4. Transient simulations are performed using the coupled atmosphere–ocean–sea ice general circulation model ECHO-G by applying a novel acceleration technique.

**André Berger**, *Université catholique de Louvain, Belgium*

(36. Interglacials as Simulated by MOBIDIC and the LLN 2-D Climate Models)

1. The LLN models succeed to reproduce the interglacials of the last 450 kyr as a response to insolation and $CO_2$ provided

feedbacks are correctly taken into account, in particular those related to water vapour, surface albedo and isostatic rebound. Sensitivity analyses show that glacial–interglacial cycles cannot be simulated under $CO_2$ forcing alone. Using the insolation forcing alone, glacial–interglacial cycles are simulated but only under low constant $CO_2$ values (under 230 ppmv).
2. Prediction for the next hundreds of thousands of years leads to a very long interglacial MIS 1. This length is similar to what was simulated for MIS 11. In both cases, these extremely long interglacials seem to be related to the very low eccentricity value which prevails during these times, the orbit of the Earth being almost circular.
3. In mid- and high latitudes during MIS 5e, sea-surface temperature in summer starts to decrease 11 kyr before the ice sheets start to grow over the continents.

**Matthias Groeger**, *Max-Planck-Institut für Meteorologie, Hamburg, Germany*

(37. Vegetation – Climate Feedbacks in Transient Simulations Over the Last Interglacial (128 000–113 000 yr BP))

1. During the Eemian, considerable changes in the land surface properties are simulated with a coupled ocean atmosphere vegetation marine biogeochemistry model (ECHAM3.6 – LSG2 – LPJ – HAMOCC); among these the northward expansion of boreal forests, and the greening of the Sahara desert are the most pronounced ones.
2. On land, the areas most sensitive to insolation are the northern high latitudes and the northern hemisphere monsoon belt.
3. In these regions, vegetation feedbacks can amplify the insolation-forced climate change by a factor of 2.

**Masa Kageyama**, *Laboratoire des Sciences du Climat et de l'Environnement, Gif sur Yvette Cedex, France*

(38. Mechanisms Leading to the Last Glacial Inception over North America: Results From the CLIMBER-GREMLINS Atmosphere-Ocean-Vegetation-Northern Hemisphere Ice-Sheet Model)

1. The CLIMBER-GREMLINS model, in which the atmosphere, the ocean, the vegetation and the northern hemisphere ice sheets and the interactions between those components are represented, simulates a glacial inception over northern North America under the transient insolation and $CO_2$ forcings of the period 126–106 kyr.
2. Glacial inception does not occur when vegetation is fixed to its interglacial state and is twice as slow, in terms of volume, when the icesheet albedo feedback is not taken into account.
3. The role of the ocean and sea ice are more ambiguous. A first experiment in which the seasonal cycle of the ocean surface characteristics is fixed to its interglacial state shows that this yields a faster inception than with an interactive ocean. On the other hand, when the Atlantic meridional overturning circulation is forced to stop, this yields an even faster inception.

**Claudia Kubatzki**, *Alfred Wegener Institute for Polar- and Marine Research, Bremerhaven, Germany*

(39. Modelling the End of an Interglacial (MIS 1, 5, 7, 9, 11))

1. The CLIMBER-SICOPOLIS model, which describes the dynamics of atmosphere, ocean, vegetation and northern hemispheric inland ice, simulates a glacial inception over northern North America at about 117.5 kyr as a result of mainly changes in precession (perihelion), obliquity as well as $CO_2$ changes act as amplifiers.
2. Glacial inception in North America at the end of the Eemian might not have happened with vegetation and ocean surface remaining at their interglacial (Eemian)

state, i.e. the feedback of the changing Earth's surface on climate is needed (compare with 38).

3. Cold events at the end of the interglacial can be reproduced, by the introduction of freshwater disturbances into the model North Atlantic.

**Synthesis on the chronology and forcing of climate change during the last interglacials**

1. There is clear evidence that insolation changes are the primary driver of past climate variations. The 100-kyr rhythm of eccentricity dominates the occurrence of past interglacials, but it is still not fully understood why interglacials have occurred even at times when insolation on the northern hemisphere was quite low in absolute terms (for example, during MIS 11). Presumably, it is not the amplitude of insolation, but the change of the amplitude, which drives the climate system to cross some thresholds.
2. Some model studies indicate that precession is the main driver of glacial inception.
3. North Atlantic SST patterns, mainly a function of deep-water formation in the far north Atlantic, are an important mechanism for the temperature and availability of moisture in central Europe.
4. Also changes in vegetation cover, mainly a shift in Artic tree line, and changes in ocean dynamics appear to amplify glacial–interglacial climate changes. In some models, a glacial inception does not occur if vegetation is set to interglacial values.
5. Ice melting (Termination) and ice accumulation (glacial inception), primarily controlled by 100 000-year insolation changes, occurred in the high latitudes of the northern hemisphere and were synchronous by definition. What did not occur simultaneously was the response of the different regions in the world to these insolation changes. The southern hemisphere and low-latitude regions appear to respond to orbital forcing earlier than the north.

**MIS 5**

1. The last interglacial MIS 5 began earlier than 135 kyr in the low latitudes with a humid phase in Equatorial Africa, i.e. at a time when the seasonal contrast between spring and fall insolation was at a maximum, which is a condition favourable for strong El Niño, which apparently increased suddenly in strength at the end of the MIS 6 ice age.
2. Sea level began rising also around 135 kyr, leading to Termination II with the main transgression during the time of strong increase of northern summer insolation. The first well-dated evidence of interglacial conditions in central Europe come from speleothems in the Spannagel cave at 130 kyr, which implicates that the mean annual temperature in the Alps were on a modern level well before the northern insolation maximum at 127 kyr. This is consistent with speleothem data from Italy, where the onset of the last interglacial has recently been determined at $129 \pm 1$ kyr. This date should be the beginning of the Eemian *sensu stricto* on the continent, but this date is in conflict with a marine age model which places the beginning of the Eemian *sensu stricto* at 126 kyr $\pm 2$, established on botanical grounds in a marine core off Portugal.
3. The Eemian, *sensu strictu* (Zagwijn, 1961), is characterized by a typical succession of pollen zones (E1/E2: *Betula*–*Pinus* forest, E3: *Quercetum mixtum*, E4: *Quercus*–*Corylus* forest, E5: *Carpinus* forest, E6: *Picea*–*Abies* forest), which can be correlated across Europe and has a duration of about 10 000 years according to varve counts in northern Germany and in the Eifel.
4. A direct correlation between pollen and marine proxies conducted on Iberian margin deep-sea cores indicates that a

time lag exists between ice volume decay/growth and forest development in Europe during the last interglacial *sensu strict,*: (1) the minimum in ice volume is reached at 128 kyr, 2000 years before the onset of the Eemian forest. (2) The substantial accumulation of ice in high northern latitudes (MIS5e/MIS5d transition) occurs at 115 kyr, i.e. 5000 years before the demise of the temperate and conifer forests in Iberia, France and the Eifel. The 11 000-year duration of the Eemian in northern European latitudes above 50°N suggests that tundra vegetation expanded during the first 5000 years of MIS 5d when forest still occupied southern latitudes.

5. Earth models of intermediate complexity (EMIC) indicate that the shift in Arctic tree line played a major role in the last glacial inception, mainly via the albedo changes around 122–120 kyr. Pollen data are in agreement with this prediction as they identify a replacement of the temperate forest by conifers at 52°N as early as 120 kyr. This suggests a southward displacement of the boreal vegetation belt of around 10° by comparison to its location (60°N–70°N) at the beginning of the Eemian.
6. There are no indications of abrupt cooling during the Eemian *sensu stricto*. Air temperature reconstructions for central Europe based on botanical fossils reveal a slight summer cooling (2°C/10 kyr) and a little stronger winter cooling (3°C/10 kyr) for the Eemian *sensu stricto*. However, climatic reconstructions from a new pollen dataset of La Gande Pile using an inverse modelling procedure with $\delta^{13}C$ to constrain pollen data-derived estimations would identify substantial climatic changes within the Eemian.
7. Stalagmite growth at Spannagel terminates at 118–119 kyr, which leaves us with a time of about 10 000–12 000 years at which annual temperature in the Alps were quite similar to modern conditions.
8. About 118 kyr is identified by several model experiments with ice-sheet dynamics as the time when snow cover in North America became perennial and the ice sheet over North America began to expand significantly. The cause for the perennial snow and expansion of ice sheets is most likely a threshold in the insolation regime, with summer insolation being no more sufficient to melt the snow in the northern Arctic of North America. The further increase in ice-sheet extent is caused by a positive feedback, i.e. further cooling over the snow and ice with a high albedo and growing ice sheets with higher and cooler surfaces.
9. During the entire length of MIS5 (132–74 kyr), seven episodes of ice rafting, C19 to C25, occurred in the mid-latitude North Atlantic related not only to periods of maximum ice volume but also to episodes of ice-sheet growth and decay. The beginning of the substantial ice-sheet growth, MIS5e/MIS5d transition (115 kyr), is associated with a 2–3°C reduction in surface water temperature and labelled C26 event, but no ice-rafted detritus have been recorded.
10. The Laurentian ice sheet became first unstable at around 112 kyr (C25 event), and the surface water of the mid-North Atlantic experienced a widespread substantial cooling by at ~6-7°C.
11. Major icebergs surged for the first time not before 110 kyr (C24), i.e. after a growth period of 8000 years, which would be enough time to reach a height of more than 1 km. This pronounced cold event coincides, based on the direct correlation between marine proxies and pollen, with the Mélisey I steppic period on land.
12. Sea-level drop was about 50 m between the last glacial inception around 118 kyr and C24, corroborating the build-up of a massive ice sheet.
13. $CO_2$ was still at an interglacial level during these first seven millennia of

the new ice age (118–111 kyr), indicating that the global carbon cycle responded to changing insolation later than the atmosphere or even later than the ice-sheets in their initial growth phase.

14. Vegetation around the Mediterranean, France and into the Eifel region showed a continuation of almost interglacial conditions from 118 to 111 kyr. Vegetation in northern Europe at this time was already cold adapted.
15. The major vegetation change in the Mediterranean and also in the Eifel region occurred during C24, when the late interglacial forest changed abruptly to tundra in central Europe, to steppe in western Europe between 50°N and 40°N and to a semidesert in the Mediterranean region.
16. Severe cold and aridity is most likely the effect of severe SST lowering during C24 over the North Atlantic, caused by a spread of icebergs and a cold melt-water lid that inhibited deep-water formation and advection of warm waters from the Carribean via the North Atlantic drift (Gulf Stream).
17. The final successive minor cold episode of MIS 5 was the C21 event (86 kyr), Mélisey II on land, which was also characterized by massive ice discharges. C24 and C21 were coincident with the most extreme glacial events MIS 5d and MIS 5b, respectively. Icebergs did not reach the southern latitudes below 40°N during any of these seven events.

## MIS 7

1. Similar to MIS 5, a direct link between terrestrial pollen and marine benthic/planktic foraminifera as well as oxygen isotopes has been obtained only in W Iberian margin deep-sea cores for MIS 7 and for older interglacial stages. In this region, the first warm period during MIS 7 was only half the length of the Eemian and does not appear substantially warmer than the successive ones occurring during MIS 7.3 and MIS 7.1. Generally, the magnitude of the different climatic changes of MIS 7 is large and mirrored by the volume of ice in concert with the large amplitude of insolation variations which characterizes this stage. MIS 7.4 shows similar climatic conditions as the previous glacial: icecaps were particularly developed and related with the coldest and driest climate on the continent and the lowest sea surface temperatures of MIS 7.
2. The equivalent of MIS 7 in continental European is well developed in southern European long sequences from the Velay region (Massif Central, France), Valle di Castiglione (Italy) and Tenagi Phillipon (Greece). This stage is characterized by three warm phases interrupted by stadials. It is interesting to note that none of these warm intervals in the Massif Central (named as Bouchet interstadials 1–3) reach the climatic state of a fully developed interglacial (such as in MIS 5e or 9e and 11c), while they did in sequences from Greece and Italy.
3. There is no direct link between the north-central European terrestrial records and the marine isotope stages. In addition, the correlation with long continental sequences in southern Europe is under debate caused by uncertainties of absolute dating older than the last interglacial.
4. There is some evidence in north-central Europe of at least one warm event that could be correlative with the warm intervals of MIS 7: the Dömnitz warm stage in northeastern Germany, the possibly synonymous Wacken warm stage in northwestern Germany and the Reinsdorf and Schöningen warm stages. These warm phases are not separated by glacial sediments and are situated stratigraphically above the Holsteinian, and before the first Saalian ice advance.

## MIS 9

1. New $^{230}$Th/U datings based on peat deposits from the type section of the

Holsteinian stage at Bossel (near Hamburg, Germany) indicate an age of about 310–330 kyr BP which would correspond to MIS 9 (and therefore to the Landos interglacial in the Massif Central).

2. The INQUA Subcommission on European Quaternary Stratigraphy defined the lower boundary of the Holsteinian as the transition from subarctic (still late Elsterian) to boreal conditions and the upper boundary as the transition from boreal to subarctic (Saalian) conditions.
3. The interglacial vegetation development reconstructed by palynological data is very similar throughout north-central Europe and begins with a pine-birch forest. The immigration of thermophilous trees including alder, oak, elm, lime, esh, yew and hazel occurred more or less simultaneously. The early expansion of spruce is remarkable. Hornbeam and fir immigrated during the course of the interglacial. Particulary characteristic of the Holsteinian Stage in north-central Europe is the appearance of *Pterocarya* and *Azolla filiculuides*.
4. The first half of the Holsteinian is characterized by temperatures somewhat lower than today. In the second half, the reconstructed mean temperatures are higher than today, in particular the July temperature. In addition, the Holsteinian seems to be less stable than the present interglacial (Holocene) or the last interglacial (Eemian) with some intra-interglacial coolings. The magnitude of the main cooling in the mid-Holsteinian is reconstructed as approximately 5°C for January temperature. No great change is reconstructed for July temperature during this episode.
5. The duration of the Holsteinian in central Europe is estimated as about 15 000–16 000 years, based on varve counts at Munster-Breloh.
6. This duration disagrees with the new evidence from the multiproxy study of Iberian margin records, allowing the establishment of the timing of botanical events through the benthic isotopic chronology. The first forested phase of MIS 9 lasted 12 000 years in NW Iberia, France and Greece but only at around 3600 years in southwestern Iberia due to the occurrence of a dry cold event particularly affecting the forest in this region.

### MIS 11 and earlier interglacials

1. MIS 11 is an exceptional interglacial complex. Weak changes in insolation during this stage are surprisingly associated with substantial climatic and greenhouse gas variations. The duration of its first warm period, ~30 000 years, is much longer than the succeeding interglacial periods. For instance, direct correlation between marine and terrestrial signals indicates that this warm period is twice as long as the Eemian in the Iberian Peninsula.
2. The continental equivalent of the MIS 11 in central Europe could be the Rhume interglacial documented at Bilshausen where 27 000 varve years have been counted. The pollen record shows that this interglacial stage was climatically unstable. Several fast climatic deteriorations are documented.
3. If this dating is correct, the consequence would be that the Cromerian Complex terminated with MIS 11. This would be in agreement with the $^{230}Th/U$ datings of the Holsteinian-type section above the Elsterian stage, but contradicts the often-used correlation of MIS 11 to be the Holsteinian.
4. The ‘Cromerian Complex’ stage of the Netherlands is defined by the recognition of at least four warm temperate (Waardenburg, Westerhoven, Rosmalen and Noordbergum interglacials) and three (unnamed) cold substages indicating the climatic complexity of this time interval.
5. The Early–Middle Pleistocene boundary, the begin of the Cromerian Complex, is linked to the Brunhes–Matuyama palaeomagnetic boundary which has been recognized within the first Cromerian interglacial (Waardenburg) at 780 kyr (MIS 19).

6. The above discussion shows that the correlation of interglacial pollen for all older interglacials than MIS 5 between north-central Europe and southwestern Europe is still uncertiain because there are no established chronozones and few absolute dates, but also because of biogeographical reasons. Based on the long continental sequence from the Massif Central, a correlation of the Praclaux interglacial (MIS 11) and the Holsteinian appeared to establish, now several authors argue, on the basis of U/Th dates that the Holsteinian represents MIS 9, and for a synchronization between the last Cromerian interglacial (Bilshausen) with MIS 11 including the Praclaux interglacial.

## Open questions and recommendations for future research

The majority of the open questions concern problems of dating. In the following, we will summarize the background for these problems and try to recommend steps towards solving these gaps in our knowledge on past interglacials.

- U/Th dates from stalagmites match in general the chronology derived from orbitally tuned marine records; in detail, however, dates from terrestrial sites in central Europe show differences up to 4000 years for the beginning and end of the last interglacial in comparison with the marine records off Portugal tuned to the SPECMAP timescale and coral $^{230}$Th/U age. Whether this reflects uncertainties in the $^{230}$Th/U dating or the SPECMAP chronology, or whether these offsets are related to time-transgressive behaviour of vegetation zones across Europe, cannot be finally decided yet. Thus, there is an urgent need for a precise correlation of speleothem dates to the marine chronology and terrestrial pollen sites.
- There are many sites across Europe with pollen sequences of the Eemian type. Very few of these sites have been absolutely dated with dates published. If there are other interglacials/interstadials with a pollen succession similar to the Eemian, correlation of records on biostratigraphical grounds can lead to misinterpretations. Thus, as many as possible interglacial pollen records should be dated by U/Th or advanced luminescence techniques to assure that the classical Eemian pollen sequence in central Europe is a pattern indeed typical only of MIS 5e.
- Radiometric ages for past interglacial sediments have large analytical errors and cannot be precise enough to correlate any sediment section by absolute dating. Thus, we will always depend on biostratigraphy or event correlation. Event correlation is done at the moment mostly relative to North Atlantic cold events, but this works reliably only if the records are long enough and reach from MIS 5e at least into MIS5c and show the structure of the C21–C26 events clearly. We need independent marker layers, probably from tephra and dust, which allow to correlate terrestrial records independently from the marine and ice core chronology.
- The time-transgressive development of vegetation succession and local/regional/overregional patterns across Europe complicate a detailed correlation of records by biostratigraphy and palynology only. The successful analysis of the terrestrial vegetation in marine records off Iberia was a big step forward for the land–ocean correlation in southern Europe. Comparable records to link the vegetation development of Central and Northern Europe to the North Atlantic SST are still missing.
- There are at the moment only two varve counted records for the Eemian; these are from Northern Germany and the Eifel region. None of these records is completely varved and undisturbed. In Northern Germany, only about 4000 individual varve laminae have been counted, in the Eifel, 12 000 varves were counted. There is an urgent demand for cores totally

undisturbed and also varve counted from the late MIS 6 and well into MIS 5d.

- There is only one varve counted core for the Holsteinian (MIS 9 or MIS 11) and one varve counted core for the Rhume interglacial (MIS 11 or Cromerian). No varve counted record is available for MIS 7 or any older interglacial.
- U/Th dates from peat is a rather newly developed dating method, but distinguishing MIS9 (320 kyr) from MIS 11 (420 kyr) is at the limit of the applicability of this method, and it can be problematic to proove that a respective site is a closed system for uranium.
- There is general agreement that insolation is the prime forcing mechanism of past interglacials. The character and exact value of the threshold at which a glacial terminates and develops into an interglacial is, however, not determined yet. This is particularly difficult because the interaction between changes in insolation, ice-sheet stability, sea-level change, continental vegetation and albedo, atmospheric dust and greenhouse gas concentration is a complex process which lasts over several millennia with abrupt events intercalated. Final interpretation from data has not yet been possible, mainly because the records from different geoarchives (ice, land and ocean) cannot be plotted on a commonly agreed timescale for past interglacials. Accordingly, we have avoided to plot all results from this final synthesis into one big figure. At least the 4000-year offset between the marine and speleothem chronologies has to be explained before this can be tried with some faith for the last interglacial. The most reliable approach would probably be a detailed parallel study of cave speleothems and ocean terrace corals, both dated by the same U/Th technique, in comparison with Ar/Ar-dated and varve counted records from laminated lakes.
- The reconstruction of past sea level from corals is, however, hampered by the unknown isostatic changes of the continents after the melting of the large glacial icesheets. This process was quantified for Scandinavia, but it is hardly understood for ocean islands, where the isostatic adjustment is caused by the changing sea level. Thus, glacio-hydro-isostatic modelling is an important target for linking the land and ocean records worldwide.
- Interpretation of palaeorecords by using climate models is still a problem, because climate models provide information on average over a large area, whereas most palaeorecords contain mainly local information. First attempts to bridge this gap in scale are underway, but it has not been feasible to apply these so-called downscaling or data nudging methods to long-term climate simulations.
- Most climate system models which include ice-sheet dynamics are able to reproduce a glacial inception. A termination of a glacial or the beginning of an interglacial has not yet been successfully simulated.
- Most climate system models show a strong sensitivity to shifts in vegetation zones, or biomes, in the sense that if biome dynamics is missing, a glacial inception does not occur or is greatly diminished in the model.
- The role of biome dynamics as an amplifier of glacial inception seems to be a robust result in climate system models, the role of ocean dynamics, in particular the meridional overturning circulation is less clear. Climate system models yield ambiguous results.
- Most climate system models do not yet include all components of the climate system. In particular, the biogeochemical cycles are often not explicitly simulated. Instead, concentration of greenhouse gases, mineral dust and other biogeochemical substances is prescribed from data in most models. Hence, the course of atmospheric $CO_2$ concentrations during interglacials is still an unresolved riddle.

## 6.2. DATA APPENDIX (CD-ROM)