Report from the PAGES/CLIVAR Workshop on “Climate of the last Millennium”

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1. INTRODUCTION

The workshop on "Climate of the last Millennium" was a continuation of the joint effort of IGBP PAGES and WCRP CLIVAR, following the first joint PAGES/CLIVAR workshop that took place in Venice 1994 and the first meeting of the official PAGES/CLIVAR working group in Villefranche-sur-Mer in 1996. Prof. Dr. L. Alberotanza, director of the 'Instituto per lo studio della dinamica delle grandi masse' welcomed about 40 participants in the very impressive historic palazzo overlooking the 'Canale Grande'. After his overview about the institute's history and the current research, the co-chairs of the PAGES/CLIVAR working group J.-C. Duplessy and J. Overpeck expressed a warm welcome to the participants and thanked Prof. Dr. L. Alberotanza and the staff of the IDGM for the opportunity to hold this meeting in this extraordinary location. J. Overpeck presented the current plans for a number of joint activities in the coming years. Although for some of the meetings the proposals for financial support are still pending or have to be submitted, more frequent meetings are planned.

Current plans encompass:

1. A workshop "Reconstructing Late Holocene Climate" Planned for April 17-20 2001 in Charlottesville Virginia, organized by M. Mann and H. von Storch.
2. A session on ENSO past and future at the IGBP/WCRP/IHDP Global Change Open Science Meeting, July 2001 Amsterdam, co-organized by K. Alverson and G. Burgers. Alongside this conference a meeting of the C/P working group is also planned.
3. An ESF meeting on abrupt climate change in Italy, November 10-15, 2001 organized by J.-C. Duplessy, T. Stocker and K. Alverson.
4. A workshop on Regional Hydrologic variability in 2003 organized by J. Overpeck
5. An ESF meeting on North Atlantic Variability in Spain Oct. 2003 organized by J.-C. Duplessy, T. Stocker and K. Alverson.
6. a PAGES/CLIVAR Synthesis meeting in 2004.

The major outcome of this meeting, in addition to this report, was a joint PAGES/CLIVAR newsletter, highlighting the most interesting joint research questions.
A. Villwock, staff scientist in the International CLIVAR Project Office recalled in his introduction from the CLIVAR perspective the three foci selected by the PAGES/CLIVAR Working group:

- *A detailed study of the climatic variability of the last 400 years (globally) and the last 1000 years (where possible)*
- *A comprehensive study of climate variability given climatic states and forcing that are significantly different from today*.
- *A detailed investigation of major abrupt transient climatic events of the Holocene and Pleistocene*

This meeting focused on the first topic whereas the others may be captured by the workshops planned for the future.

Dr. Villwock pointed out that future issues for the joint effort of PAGES/CLIVAR could be:

Data including forcing (PAGES side):
- High resolution (time)
- Exact dating
- Coherent methods
- Data + metadata (with error bars, etc.) available online

Model (CLIVAR side):
- Coupled runs (eventually. including natural forcing)
- Vegetation
- Data + metadata (model constraints, etc.) available online
- Downscaling and extreme events

Besides the scientific issues discussed at this workshop, Villwock mentioned that the PAGES/CLIVAR working group should be reconstituted to work more efficiently. This re-structuring has subsequently taken place.

In his introduction, K. Alverson from the PAGES Project Office emphasised the need to involve more young scientists in this collaborative effort to educate the communities as early as possible to work together. In addition, he stressed the need for freely accessible high quality data from both communities to facilitate future scientific research.

2. PRESENTATIONS

For more comprehensive information, see abstracts in Appendix 3

Session 1: Climate Change Detection and Attribution
The scope of the first session was directed towards climate change detection and attribution. R. Bradley focused in his presentation on climate examples of the last 1000 years in the context of the Holocene. Although the Holocene is mainly regarded as a period with stable climatic conditions for 6-8k years, significant changes in temperature occurred on regional scales. For example a temperature decline of about 3K was found in Greenland over the last 6000y, in conjunction with an increase in precipitation. In low latitudes much higher lake levels compared to the late Holocene were found in the early period, whereas lakes in South America show an opposite sign.

D. Rayaud reviewed in his presentation the record of atmospheric CO_2 and methane during the Holocene. Over the last 10K the ice core data showed only relatively little variability, e.g. the CO_2 changes were of the order of 10-20ppm, whereas the changes in Methane were much more important. The estimated forcing due to CO_2 and methane changes through the Holocene were both about 0.1W/m^2
P. Jones discussed climate change over the instrumental period in context of the last millennium. Since the middle of the 19th century average global surface temperatures have risen by about 0.6K. There are important gaps in our knowledge of warming/cooling patterns in some parts of the globe before 1950. In addition, in his analysis he showed that the percentage of low temperature increase is higher than the high temperature increase which can be related to a night-time temperature increase.

M. Mann presented results of reconstructions of the last 1000 years from annual-resolution natural archives, documentary evidence and long instrumental records. Although the proxy data still have gaps (e.g. over Africa) long-term reconstructions using multi-proxy data are feasible. The major hemispheric pattern of the 1000y reconstruction has the following characteristics:
1) a gradual decline from AD 1000 to the mid-19th century. This appears to have occurred at a rate that would be consistent with astronomic factors, although solar irradiance changes may also be involved;
2) variation around this decline, much of which can be correlated with the climate effects of major volcanic eruptions and reconstructed variations in solar output;
3) a sudden and dramatic reversal of this decline in the nineteenth century, leading to late 20th century temperatures clearly in excess of those at any time since AD 1000. Subsequent to the meeting, Crowley used a model to reproduce the entire Mann et al 1000 year record. Only by including recent anthropogenic inputs of CO_2 to the atmosphere was the model able to capture the recent warming trend.

One of the most prominent proxy data sources used in Mann's reconstruction are tree-ring data. K. Briffa reported on large-scale temperature signals in tree-ring density data found in a network of sites circling the Northern Hemisphere, mostly in areas representative of northern boreal forest or high elevations in western American and European mountain regions. Despite the recent divergence between tree-ring density and increasing temperature, it is possible to calibrate regional-average growth records with equivalent regional mean temperatures and provide estimates of variability extending over 500 years. At several special northern Eurasian locations tree-ring width data provide year by year estimates that extend over millennia.

A typical PAGES/CLIVAR collaboration was presented by M. Collins. He compared the variability of the third version of the Hadley Centre coupled ocean-atmosphere model with a network of tree-ring densities from the Northern Hemisphere. Two different methods of combining individual tree-ring records were used. His study suggested that further quantification of the uncertainties in the proxy data, and inclusion of natural climate forcings in the model simulations, are important steps in making future comparisons of climate models with the proxy record over the last 1000 years.

Another important source of proxy data are ice cores. L. Thompson showed results from three cores drilled in 1997 at an altitude of 7200 meters on the summit of the Dasusopu glacier on the China-Nepal border. These ice core records provide a high resolution record of the last 1000 years while providing a perspective of the monsoon variability for the last 20,000 years. He also addressed the general problem that in response to the global warming the glaciers throughout the tropics have started to melt, removing not only valuable climate archives in these areas, but also critical water resources.

Session 2: Pacific Variability

The second session focused on variability in the Pacific region. Although in this region coral data serves as the most prominent proxy data source the first two presentations highlighted other methods to obtain information about climate variability of the last 1000 years.

H. Diaz presented a study using historical information on sailing ship transit times to infer cir-culation changes in the North Pacific Ocean since the late 16th Century. With this archive of historical information, he showed that it is possible to extract useful climatic signals regarding the strength of the northeast trade winds in the Pacific from the 16th to 18th centuries. Interpretation of decadal-scale changes in the North Pacific trades, and in the onset of the summer monsoon near the Phillipines, is possible by comparing estimated ship transit time using the modern surface wind record of the past five decades, and by comparison with other high resolution proxy climate records.

The other ‘non-coral’ paper presented by J. White focused on the potential for ENSO/SOI reconstruction's from stable isotopes in ice cores from western Antarctica. The key problems related to this topic are a) the uncertainties in dating of about 5 to 10% because of the low accumulation rate of snow at that site and b) the relationship between the local Amundsen Sea Low and ENSO may flip sign if the ASL shifts its position too far. Methods are under way to overcome this problem and a potential to extract useful information on ENSO out of the ice core data could be shown.

As already mentioned corals are one of the prominent proxy data sources in the tropical Pacific. C. Charles talked about variability in long-term fossil coral records. He addressed questions such as: Can extended records be constructed from the most sensitive regions in that area? He argued that this is possible but it would require exploiting the relatively untapped fossil coral archives. In his presentation he showed that corals are useful for the investigation of long-term (decadal) variability and provide value-added information to the instrumental record.

S. Tudhope gave another example using annually-banded massive corals in the Pacific to assess the interannual-centennial time-scale variability. Again apart from the ENSO signal, useful information about long-term climate variability can be extracted from corals using new tracers, increased sample methods and other techniques to reduce the error in the determination of climate parameters.

The issue of using corals for the investigation of long-term climate variability in the Pacific region was discussed in more detail by J. Cole. She emphasised that although instrumental climate records are generally too short to permit analysis of multiple iterations of decadal variability in the tropics, new $\delta_{18}O$ results from corals in the central and western Pacific and Indian Oceans allow us to explore decadal variability over the past 2-3 centuries. Throughout the period from 1840-1990 used in this study a change in the dominant frequency of variability could be detected. The warmer/fresher 20th century experiences mostly interannual variability (e.g. ENSO), but decadal variability dominates in the cooler/drier 19th century.

Coral records in the south-west Pacific as analysed by T. Quinn showed decadal variability on time-scales of 14-15 years that have also been found in coral records from western Australia and global temperature data.

M. Gagan concluded the coral session with a presentation of results from a multi-proxy comparison of coral palaeoenvironmental records spanning 1565 to1985 AD. The majority of long coral $\delta_{18}O$ records from the Pacific and Indian Oceans show a trend towards lower values beginning in the 19th century, or earlier. If the shift in $\delta_{18}O$ is due entirely to surface ocean warming, it is equivalent to an increase of 2°C since the early 1800s. Two important issues need to be resolved to interpret this trend with confidence. First, the coral $\delta_{18}O$ shift is probably a function of both warming and freshening of the surface ocean, therefore, it is crucial to establish the temperature component of the shift using other coral paleo-thermometers. Second, the reliability of coral reconstructions over multi-century time-scales needs to be confirmed.

The discussion evolving thereafter can be summarised by three recommendations / questions:

1. A rigorous examination of what climate conditions are being recorded in each proxy indicator at each site (e.g. Antarctic ice cores, Tibet ice cores).
2. Can we get high temporal resolution maps of the large scale state of the climate system over a) the last 100-300 years, b) the last 1000 years, esp. for SST (x,t), precip. (x,t).
3. Do we want directed observational strategies for paleoclimatic indices?
   1. Global, based on analysis of the instrumental record and / or CGCM output
   2. Local, based on particular target phenomenon and/or theory.

K. Trenberth commented in his presentation on some aspects of the past and present behaviour of the ENSO cycle. Indices of ENSO for the past 100+ years, indicate that there is considerable variability in the ENSO cycle in the modern record. This variability can attributed to: (i) stochastic forcing due to weather and other high frequency “noise”, and the Madden-Julian intraseasonal oscillation in particular, (ii) determinstic chaos arising from internal nonlinearities of the tropical Pacific ENSO, (iii) forcing within the climate system but external to the tropical and (iv) changes in exogenous forcing.

The last two decades have been marked by unusual ENSO activity following the apparent climate “shift” in the tropical Pacific at around 1976. This has raised the question as to whether anticipated anthropogenic climate change might influence the statistics of ENSO. The last 20 years are characterized by relatively high ENSO variability, including the two strongest El Niño events (1982/83, 1997/ 98) in the 130+ years of instrumental records and an unusual long-lasting warm spell in the early 1990s, so that there is a distinct shift in the mean toward more El Niños.

Trenberth pointed out that although model studies have long shown that greenhouse gas forcing is likely to change the statistics of ENSO variability, the character of the change is model dependent. Thus, attribution of the mid-1970s shift to anthropogenic forcing is uncertain in view of the strong natural variability observed in the record of the past and the inability of models to fully simulate ENSO realistically.

Session 3: Indian Ocean Variability

The only presentation given in this session was by P. Webster on “Observing the Indian Ocean SST dipole” or "Panen Raya"”. In his investigation he focused on the relationships between rainfall over east Africa and the dipole structure of sea surface temperature in the Indian Ocean in winter. The name "Panen Raya" (or "good harvest" referring to the high fishing yields associated with the enhanced upwelling) originates from the people of Sumatra and refers to the cold phase of the dipole (cold in the East Indian Ocean, warm in the West Indian Ocean). Furthermore, East African rainfall is very strongly related to Panen Raya. The interesting aspect of the Panen Raya is that the associated SST pattern is different from the Indian Ocean pattern associated with ENSO. Indeed, it has been argued that the Panen Raya and El Niño are independent. Further studies, using instrumental as well as proxy data could provide more insight into the variability and the mechanisms of this phenomenon and its connections to ENSO.

Session 4: Atlantic Variability

This session concentrated on the variability in the Atlantic basin. J.-C. Duplessy started this session with a study on sediments in the polar Arctic entitled: The Holocene record of the Barents Sea and the conveyor belt. The cores recovered in the Barents Sea suggest that 6000 years ago the inflow of Atlantic water into this part of the Arctic was much stronger and thus the so-called conveyer belt was enhanced. In general, the analysis of marine sediments of this region could provide a useful tool to study the variability of the large-scale ocean circulation in the North Atlantic over long time-scales.

Sediment cores have also been taken in the western North Atlantic. L. Keigwin reported on a sediment core recovered near Bermuda that goes back about 1000 y. Although the dating is difficult some relationship to the NAO has been detected. Other cores from the slopes off Newfoundland / Woods Hole in combination with repeat hydrography suggests a relationship between deep currents and the NAO. Thus, paleoceanographic data can be used in climatically sensitive areas to test the NAO as a model for climate variability in the North Atlantic region on centennial and longer time-scales.

E. Jansen presented estimates of SST that have been performed by a combination of paleo-observation techniques in sediment cores collected in the Eastern Norwegian Sea and coastal areas of southern Norway, which are influenced by the Atlantic water masses. These estimates were used to study the variability of sea surface temperatures in the Nordic Seas during the past 2500 years at decadal to centennial resolution. The core could be dated back to 14K BP and showed strong decadal to centennial signals during the last 2000y. The “Little Ice Age” as well as the “Medivial Warm period” could be detected.

The Mediterranean region is, at least during wintertime strongly affected by the phase of the North Atlantic Oscillation (NAO) as pointed out by R. Fransetto. For instance, the typical winter precipitation maximum is strongly modulated by the NAO. Important research questions in this context are: Will the frequency and strength of the NAO change in future?; Will storm surges change in frequency and amplitude?, and especially crucial for Venice: The rate of sea level rise. He proposed a concerted Mediterranean CLIVAR study linked to the Atlantic CLIVAR program. To study the interannual and interdecadal variations of the NAO index in the Mediterranean using instrumental as well as proxy data sources.

J. Jouzel presented results from an analysis of ice-core data with annual resolution in central Greenland over the last millennium. The signal in deuterium excess in this core is mainly driven by precipitation. An NAO signal is not detectable (because of the location) but characteristic climate episodes like the “Little Ice Age” and “Medivial Warm period” could be identified.

Session 5: Hydrological Variability

J. Jouzel’s presentation provided a nice introduction to Session 5 on Hydrological Variability. The first speaker of this session, E. Cook reported on reconstructed hydroclimatic variability from tree rings across the continental United States since 1200. Drought reconstructions have been performed using longer tree-ring chronologies and a recently developed optimal interpolation (OI) method. The data sets exhibit some correlation to ENSO and the Pacific decadal signal, esp. in the chronologies of the southwestern US. These data have been used to reconstruct a typical ENSO index (like Niño-3), mostly from the tree-rings in this area of the US, assuming that the teleconnection patterns have not changed over time.

E. Mosley-Thompson gave an overview and update on the PARCA program. PARCA: Program for Arctic Regional Climate Assessment is a multi-disciplinary NASA-NSF program with the overarching goal to measure and understand the mass balance of the Greenland Ice Sheet. The observational methods include laser altimetry, airborne ice thickness measurements, the Greenland climate network (16 automatic weather stations), determination of ice motion and ice stream flow via GPS and modelling of precipitation and ice coring.

The accumulation data from PARCA firn and ice cores drilled at more than 50 widely dispersed locations in Greenland are a critical requirement for mass-balance estimates. In addition, these cores provide annual proxy climate information including $\delta_{18}O$ and atmospheric chemistry.

Depending on the location, high resolution ice core data can be used to investigate relationships between precipitation / accumulation rates and the NAO as well as other climate phenomena (e.g. Little Ice Age).

The large number of shorter cores allow assessment of the spatial variability of the key proxies and contribute to the selection of optimal sites for drilling deeper cores with the temporal resolution necessary to explore annual to decadal-scale climate variability.

Session 6: Climate forcing if the last millennium

This session addressed one of the key problems in understanding the natural variability of the last millennium: the climate forcing. J. Beer presented a tool reconstruct solar forcing and thermohaline circulation using cosmogenic nuclides. These nuclides, such as C_{14}, Be_{10}, Cl_{36} are modulated by the solar wind and the magnetic field. The 11-y sunspot cycle can be shown in Be_{10} out of ice cores but there is much more variability in the record.

It was pointed out that the present reconstructions of irradiance (e.g. Lean et al., 1995) still have a large uncertainty and need a calibration with reconstructions of the solar activity.

As another application cosmogenic nuclides, in particular C_{14}, Be_{10}, can also be used to study the variability of the thermohaline circulation (THC). If the THC is reduced (e.g. during the Younger Dryas event) the rate of C_{14} increases and vice-versa.

The second talk addressing the climate forcing in the past was given by J. Overpeck. He presented a new compilation of annually-resolved time series of atmospheric trace gas concentrations, solar irradiance, tropospheric aerosol optical depth and stratospheric (volcanic) aerosol optical depth that was developed for use in climate modelling studies for the last 500 years. The volcanic reconstructions turned out to be a non-trivial problem a) the anthropogenic trends esp. in the Northern Hemisphere and due to the fact that not all volcanic eruptions are visible in all proxy data sets. As an application the GISS model was forced by this new reconstruction of the natural and anthropogenic climate forcing. Overall, the results are in good agreement with the multi-proxy reconstructions of Mann et al., 1999 although some over-sensitivity to volcanic eruptions can be seen. Further investigations will presumably include effects of ozone and land surface forcing.

Session 7: Modelling climate of the last millennium

The last session was dedicated to the modelling of the climate of the last millennium. As already pointed out in the discussions on this workshop, the quality of model simulations of the past crucially depend on the forcing.

S. Rahmstorf presented results from the CLIMBER-2 model forced with CO_2, solar and land-use reconstructions but no volcanic effects over the past 1000 years. Due to the coarse resolution (10^ox51^o) only the large scale (basin and continental scale) features can be discussed, but at this scale the agreement with complex climate models (here ECHAM/LSG) is good. The biophysical effects of deforestation (albedo, evapotranspiration) lead to a cooling trend over the past millennium comparable to the one in the Mann et al. reconstruction, but the associated CO_2 release compensates much of this cooling. Solar forcing leads to a Little Ice Age (15^{th}-18^{th} Century) cooling of up to 0.1-0.4^{o}C, depending on the solar reconstruction used. This solar-forced cooling can cause a weak (~0.5 Sv) intensification of NADW formation.

M. Cane addressed in his presentation the behaviour of ENSO within the last millennium using the standard Cane-Zebiak model. The results show that the ENSO cycle is sensitive to changes to the annual cycle that can be induced by variations in the orbital parameters. Nevertheless an intercomparison between a simulation with and without orbital forcing over the last millennium showed some influence of the external forcing but the internal ‘chaos’ of the system is stronger and capable of producing all kind of ENSO variability.

One important joint activity of PAGES and CLIVAR is the Paleoclimate Model Intercomparison Project (PMIP). S. Joussaume reported on the progress of this project that started in 1991. The first phase (1991-99) concentrated on two episodes 21k BP (last glacial max.) and 6k BP (climate optimum of the Holocene) representing two extreme phases of the climate system in the past.

In the 21k BP-experiment, designed to further understanding of the last glacial maximum, one focus has been the apparent inconsistencies between the magnitude of tropical cooling over land and oceans inferred from paleodata and simulated by models. PMIP confirmed earlier studies that model simulations with SST's prescribed according to CLIMAP, with relatively warm oceans, produce cooling over land that is generally weaker than that inferred from paleodata. Although the models reproduce the reconstructed LGM temperature and precipitation changes over Eurasia reasonably well, other regions, like western Europe in winter show discrepancies which may arise in part because of the simplifications inherent in the PMIP experiments. In the coming years, better SST estimates should become available from the EPILOG project, and coupled atmosphere-ocean models will begin to be developed for the LGM. Vegetation feedbacks may have also played an important role.

Simulations for the mid-Holocene (6K BP) with eighteen different climate models all simulate an increase in the summer monsoon over Africa and Asia as a result of increased summer insolation, but, when compared quantitatively to biome reconstructions over Africa all the models underestimate the northward displacement of the desert-steppe transition. Overall, results from PMIP and related Holocene experiments suggest that vegetation feedbacks and atmosphere-ocean interactions, which are not commonly included in state of the art simulations of future climate change, can substantially alter climate response to small perturbations. Future PMIP activities will be directed towards:

- Comparisons of coupled atmosphere-ocean models for the mid-Holocene.
- Comparisons of the early Holocene
- A discussion about an experiment focusing on inception of ice growth at the end of the last interglacial (~115k BP) has been initiated.
- Further studies on the LGM

At present, the PMIP group did not feel ready to investigate the last 1000y within a comprehensive PMIP project. This should be discussed at the next PMIP meeting.

The last presentation in the modelling session was given by L. Bengtsson on numerical simulation of climate variability over the last several hundred years. The results obtained from a 300 y control run with the coupled model ECHAM4/OPYC showed that mixed layer processes are insufficient and interactions with deep ocean processes are needed. Experiments also show that the warming during the last century cannot be explained with natural variability, solar warming or volcanic forcing. Observed trends are then consistent with forcing from greenhouse gases and sulphate aerosols.
For further investigations much more confidence in the reconstructions of the solar and volcanic forcing are needed to perform reliable and value-added model simulations.

The presentations of the workshop were concluded by S. Frisia who demonstrated the potential to reconstruct climate fluctuations in the Alps recorded using data derived from stalagmites in caves. The annual growth of stalagmites largely depends on precipitation in many European sites. Their temperature dependence is being investigated through calibration with the instrumental record. Basically, information about wet/dry periods can be derived from the Mg/Ca ratio. Overall speleothems have the capability to provide another archive of the climate in the past, although a careful and thoughtful interpretation is required to obtain reliable information.

3. DISCUSSION AND RECOMMENDATIONS

The final discussion of the workshop under the headline “Future directions for PAGES/CLIVAR” was let by the co-chairs of the working group. J.-C. Duplessy and J. Overpeck.
There was a general agreement that this meeting has shown in a very effective and comprehensive way the present scientific knowledge about “The climate of the last millennium”. Nevertheless, the presentations also have shown that further intensive collaborative efforts are needed to get a better understanding about natural climate variability and its mechanisms of the past and present climate. In particular, there is a clear need for better forcing data that could be used and motivate model experiments of the last millennium. Further analysis and subsequent improvements of the multiproxy data reconstructions will not only enhance our understanding of natural climate variability but also serve as a motivation for comprehensive model studies. Because of the limitations of the instrumental record, the use of proxy data is the only way to extent the record to a sufficient length for investigations of long-term climate variability.
In addition, the PAGES/CLIVAR collaboration will provide more insight into the problems of abrupt climate change / events, and through the extension of the climate record into the past deliver extremely valuable information for climate change detection and attribution.

Typical research questions for the PAGES/CLIVAR effort could be:
- Is the 20th century unprecedented in the last 10 centuries?
- Did the “Medivial Warm Period” exist? What are the mechanisms?
- Does the 20th century have a non natural component?
- Interannual to decadal variability in the pre-industrial period
- Assessment of the potential climate extremes and their possible changes
- Is the Holocene “stability” a myth? What are the extremes and why do they occur?

The PAGES/CLIVAR Intersection will try to answer these questions by facilitating collaborative research within the paleo and climate community. The working group, serving as the official discussion forum will be reconstituted to a smaller and more effective group that meets approximately once a year to review the progress being made in between.
In addition, the group will organise, under the leadership of the PAGES project office, a series of workshops.

4. OTHER BUSINESS

Next meeting
The next meeting of the PAGES/CLIVAR working group will be at the Global Change Open Science Conference in Amsterdam in July 2001.