COMBINING PALEOCLIMATIC EVIDENCE AND GCMS BY MEANS OF DATA ASSIMILATION THROUGH UPSCALING AND NUDGING (DATUN)

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1. INTRODUCTION

In the past decade considerable progress has been made in understanding and modeling climate on time scales of years to decades. General Circulation Models (GCMs) can simulate variability on time scales up to decades adequately. GCMs have also been used to run time slice experiments simulating past equilibrium states forced by the chemical composition of the atmosphere, astronomical parameters and boundary conditions. Proxy data have been used to set up the boundary conditions, as well as to validate the output of these models. With the increasing speed of computers, climate modelers can now move on to simulating the transient behavior of the climate system over millennia. At the same time increasingly more proxies of climatic variables, namely tree rings, ice cores, laminated sediments and coral reefs, have been detected, and there has been a growing Research effort in reconstructing the temporal evolution of the climate from these proxies (Villalba et al. 1997,Appenzeller et al. 1998, Cook et al. 1998,, Mann et al. 1998).

Our project aims at an improvement in understanding the global climate of the last millennium by reaching a synergy between the proxy data collection and the numerical modeling of the ocean-atmosphere system. Apart from conducting free and externally forced GCM experiments, a newly developed method for proxy Data Assimilation Through Upscaling and Nudging (DATUN) will be a central element of our work. This paper outlines our general concepts, and presents examples and first results.

We attempt to obtain a physically-based, spatial and temporal interpolation of paleoclimatic data, and to identify mechanisms that contributed to the past climatic variability. These tasks can be formulated conveniently by means of a state space model. It consist of equations for the temporal evolution of the unobservable climate state, which are given by a coupled atmosphere-ocean GCM, and of observation equations that link these climate states to observables recorded in proxy records. For many applications the observation equations need to be inverted, leading to so-called transfer functions. In some cases a given proxy value may be associated with multiple climate states.

In contrast to the common use of local transfer functions, which link individual proxy records to the local climate, we use relations between multiple proxy records and continental-scale climate patterns. Determining the observation equations therefore is a downscaling problem, while the transfer functions are upscaling models. Such problems were extensively investigated during the last decade in other branches of climate research and several statistical methods are now well-tested and readily available to determine the observation equations and transfer functions needed in paleoclimatology.

A prerequisite for upscaling multi-proxy networks is the alignment of the individual records in time. Until now the absolute datings of individual proxy records are partly inconsistent and therefore it is not yet possible to use the full network for upscaling purposes. Developing a consistent, absolute time scale for a large number of proxy records is one of the main tasks of our collaborating groups within the project `natural climate variations from 10 000 years to the present day' (KIHZ, Klima in historischen Zeiten, http://www.gfz-potsdam.de/pb3/pb33/kihzhome/).

The GCM we use is ECHO-G. It consists of ECHAM4 with a T30 resolution for the atmosphere and HOPE-G with a T42 resolution (finer in the tropics) for the ocean. HOPE-G includes a dynamic-thermodynamic representation of sea ice with snow cover.We are working on three types of integrations:

1 A control run with present external forcing.

2.A run with estimated historic external forcings.

3.A run driven by climate variability as inferred from proxy records using the DATUN technique.

The control simulation is running and covers currently about 700 years. It will help to identify the contribution of internal variability of the coupled system to the observed climate variability and to assess the low-frequency model performance. Externally forced contributions to the observed variability, due to changes in the orbital parameters of the earth, intrinsic solar variability, variations in the chemical

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composition of the atmosphere and volcanic activity, will be estimated by means of the second type of simulation.

When comparing the free and externally forced simulations with the proxy records (using the observation equations) one has to keep in mind that the actual temporal evolution of the climate system is just one random realization out of many that are consistent with the internal dynamics and the external forcings. The external forces acting upon climate do not determine its state but merely condition it. At best an externally forced run will generate a random realization from the same ensemble and therefore a comparison with the observed climate should focus on statistical properties.

An actual reconstruction of the historic climate trajectory will be attempted with the third type of simulation. In the DATUN run we will use patterns of climate variables with a temporal resolution of one year or more, obtained from multi-proxy networks with upscaling methods, and nudge the GCM states towards these patterns. In order to avoid damping of synoptic variability these patterns must have continental or larger scales. The goal is to obtain estimates for global historic climatic states that

- are physically more consistent than those obtained from a mere statistical merging of the large-scale patterns;

- include information about regions that is not apparent in individual patterns;

- include synoptic-scale variability consistent with the continental-scale forcing.

DATUN advances to unknown terrain and a careful validation has to determine to what extent these goals can be met.

GCMs provide detailed and dynamically consistent data, but fail to provide immediate knowledge about the dynamics of the system. Such knowledge is acquired by the construction of reduced models. Simpler models are not meant to be superior to GCMs in terms of the resolved dynamics, but to be significantly reduced in comlexity while retaining the most important properties of the full models. This issue is addressed within KIHZ by collaborating groups who use dynamical models of intermediate complexity similar to CLIMBER (Ganopolski et al. 1997) and ECBILT (Selten et al. 1999).

In section 2 first results from upscaling proxy records are presented. Section 3 describes our GCM setup, shows some preliminary model diagnostics, and outlines experiments that are planned.

2. UPSCALING MODELS

Proxy records reflect the local climate, which in turn can be strongly correlated with the climate at locations several thousand kilometers away. Such spatial correlations and teleconnections are the basis for upscaling models.

Currently our research is focussed on ring width chronologies obtained from the International Tree Ring Data Bank. Tropical and polar ice core records

and coral data will be included later. The first step in developing our upscaling methods is the selection of a suitable subset of tree ring records by using only those that are significantly correlated with the leading EOFs of seasonal means of sea level pressure in the domain of interest. These subsets are then used to build the upscaling models by means of Canonical Correlation Analysis (CCA, e.g. Von Storch and Zwiers 1999) applied to the leading EOFs of proxy and circulation data.

Ten tree ring records in Scandinavia and Eastern North America showed significant correlations with wintertime SLP in the North Atlantic sector. The leading canonical correlation pattern from a CCA performed on the two leading EOFs of both SLP and tree ring records indicates a stronger tree growth in years with a strong wintertime NAO index (Fig.1). This is plausible since in those years the trees in Northeast America and in Scandinavia are affected by anomalous warm and moist air masses. The statistical link was obtained with respect to the period 1873-1930 and then used to reconstruct the NAO index for the period 1650 - 1950 (Fig.2). The NAO reconstruction from tree rings agrees remarkably well with that of Appenzeller et al. (1998), which is based on Greenland ice cores.
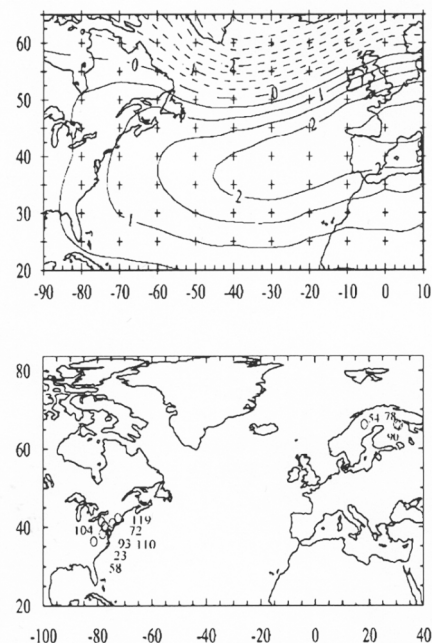

Figure 1: First canonical correlation pattern of a CCA between the leading two EOFs of average DJF SLP and tree ring width. The canonical correlation coefficient for the independent validation period is 0.6. The SLP pattern explains 28% of total variance. The pattern loadings for the tree records are indicated as numbers.

The leading EOFs of summertime (DJF) SLP for the South Pacific region are shown in Fig.3 along with their correlations with ring width records. The strongest correlation occur for EOF3 and tree records in South America, indicating a strong (weak) tree growth associated with easterly (westerly) flow anomalies. This is reasonable since the trees were located to the east of the Andes. where easterly flow brings moist air from the Atlantic, whereas westerly flow leads to a rain shadow effect.
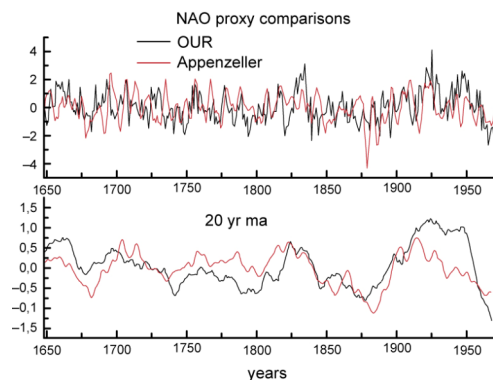
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Figure 2: Reconstruction of the NAO index based on tree ring widths (solid line) and greenland ice cores (dashed line).
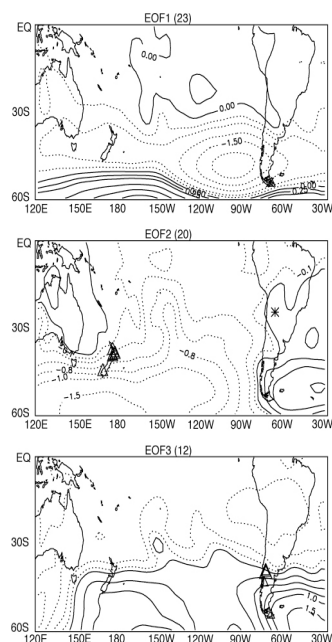

Figure 3: The first three EOFs of DJF SLP for the period 1951-1980. Triangles (stars) indicate tree ring chronologies showing a significant positive (negative) correlation with the EOF. Negative correlations occur for EOF1 (EOF2) and a record in southern (central) Argentina. Small symbol = 0.46-0.5, medium = 0.51-0.6, large = 0.61-0.7. Explained variances are given in parenthesis.

3. GCM INTEGRATIONS

3.1 Control run

The coupled atmosphere-ocean model ECHO-G (Legutke and Voss 1999) is set up from cycle 4 of the Hamburg atmosphere general circulation model ECHAM and the global version of the Hamburg Ocean Primitive Equation general circulation model HOPE-G. ECHAM has been modified for ECHO-G in order to properly account for sub-grid-scale partial ice cover (Groetzner et al. 1996). The ocean model is almost identical to the version described in Wolff et al. (1997). The component models are coupled by means of the OASIS coupling software developed at CERFACS (Terray et al. 1998), which includes a flux-correction.

A first model diagnostic comprises global or continental-scale atmospheric quantities, such as near surface air temperatures and EOFs of geopotential heights, and El Nino variability in the tropical

Pacific (Fig.4). After a short spin-up time the global temperature shows no climate drift and reveals a realistic variability. The leading EOF of northern hemispheric, seasonal 500 hPa geopotential height resembles well the observed Arctic Oscillation pattern. The Nino3 index shows a realistic stochastic behavior. It appears that ECHO-G reproduces the present climate at the level of other state-of-the-art climate models. An in-depth analysis will follow in the near future.
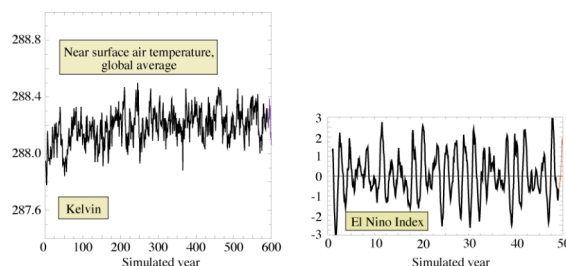

Figure 4: ECHO-G control integration. Upper left panel: Global average of annual 2m temperatures; upper right panel: monthly means of the Nino3 index. Lower panel : leading EOF of northern hemispheric, seasonal 500 hPa geopotential height;

3.2 Externally forced runs

Until today the historic external forcings for the atmosphere-ocean system are only incompletely known. Estimates for the intrinsic solar variability back to 1600 A.D., based on sun spot numbers, were provided by Lean et at. (1995) and for a slightly shorter period by Hoyt and Schatten (1993). Atmospheric CO2 (Indermühle et al.1999) and CH4 concentrations (Blunier et al. 1995) were derived from antarctic ice cores for the last 10000 years. Changes in the optical thickness of the atmosphere due to volcano eruptions were estimated for the last 2000 years by Zielinski (1995). The orbital Milankovich forcing can be obtained from Berger (1991). Changes in vegetation are a potentially important forcing (Claussen et al. 1999) that is basically unknown.

Although there is clear need for reducing the errors of some of these estimates, we will use what is currently available to force ECHO-G, in order to understand the climate sensitivity to external forcings. Similar studies were conducted by Bertrand et al. (1999) using energy balance models and by Cubasch et al. (1997), who forced the ECHAM3/LSG model with solar variability according to Hoyt and Schatten (1993). The latter study showed a large spatial variability in the response pat-

tern to increased solar irradiance (Fig.5), including non-sensitive and cooling areas.
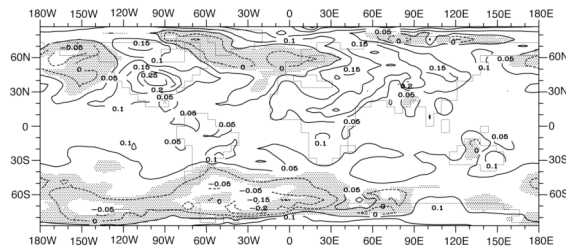

Figure 5:Horizontal response pattern of annually averaged near-surface temperature to changes in solar forcing
(K (W=m²)) according to Cubasch et al. (1997). Grey areas indicate regions with a non-significant correlation, based on the 99% threshold of a local t-test between solar variability and surface temperature response.

3.3 DATUN runs

Data assimilation techniques developed in operational meteorology and oceanography have been designed to transfer observed data as forcing terms into the evolution equations of a dynamical model. A particularly straightforward method is `nudging', where a restoring term that increases with the difference between the model state and the target state is directly added to the time evolution equations.

Other studies nudged the full 3-d state every few hours (e.g. Lyne et al. 1982; Ramamurthy and Carr 1987; Jeuken et al. 1996). In contrast Data Assimilation Through Upscaling and Nudging will only attempt to keep the GCM close to the forcing patterns on time scales of one year or longer. These continental- and basin-scale patterns will be obtained from upscaling. DATUN will allow for several (npatt) simultaneous forcing patterns and take their uncertainties into account. The temporal evolution of a variable xi nudged towards the pattern values $x\frac{pal}{ij}$ will be given by

$$\frac{dx_i}{dt} = F_i + \sum_{j=1}^{n\,patt} G_{ij}\left(x\frac{pal}{ij} - x_i,\right)$$

where the F_i describe the model physics. The nudging functions G_{ij} (Fig.6) depend on the uncertainty of the pattern j at the grid point i at time t (not included in the notation).
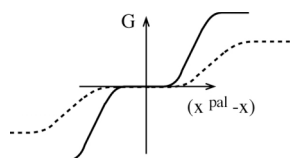

Figure 6: General shape of nudging function for DATUN. Functions of the solid (dashed) shape will be used to nudge towards pattern values that are certain (uncertain).

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