CLIMATE VARIABILITY, PREDICTABILITY AND CLIMATE RISKS

A European Perspective

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Climate variability, predictability and climate risks: a European perspective

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The aim of climate research is to increase our knowledge about the nature of climate and the causes of climate variability and change. Increasing our understanding of the physical processes on various spatial and temporal scales will ultimately reduce uncertainty and improve our capabilities to predict climate on monthly to seasonal timescales and allow us to separate the anthropogenic and natural causes of long term climate change.

Current estimates of past and future climate change, projections of future greenhouse gas (GHG) emissions and their effects are subject to various uncertainties. Climate policy-making faces a wide range of significant scientific and socio-economic uncertainties pointing to the question of whether scientific understanding is sufficient to justify particular types of technical and political actions (Lempert et al. 2004; Manning et al. 2004).

The public and policy-makers need current and accurate estimates of climate change projections, uncertainty in future costs, benefits and impacts of potential choices, design of greenhouse gas mitigation, preparation for adaptation, and the funding level of research across many related disciplines. (Webster 2003; Webster et al. 2003). Without this information, policy discussion is unavoidably divided in two opposing parties, those who support calls for immediate action, i.e., reduction of human-caused greenhouse gases emissions, and those who wish not to take action because they are waiting for more information (e.g., Reilly et al. 2001). In addition, due to the potential social disruptions and high economic costs of emissions reductions, a vigorous debate has developed concerning the magnitude and the nature of the projected climate changes and whether they will actually lead to serious impacts (e.g., Mahlman 1997). Thus, climate-change policy formulation constitutes a great challenge since it introduces the problem of decision-making under uncertainty (Webster et al. 2003 and references therein).

The uncertainty analysis seems at first rather "uncomplicated", in reality however many empirical, methodological, institutional and philosophical challenges arise. Additionally, the optimal decisions of today do not only depend on the current uncertainties but also on the change in the uncertainties and our past and future responses. Policy decisions are therefore

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better modeled as sequential decisions under uncertainty (Hammitt et al. 1992; Manne and Richels 1995; Webster 2002). The sequential decision process adapts to new knowledge and responds to new information and events. This flexible decision process requires a careful adhesion to the uncertainties' change whilst continuously integrating new knowledge on climate system processes and socio-economic consequences and reactions (Webster 2003; Webster et al. 2003).

The quantification of uncertainty requires a model describing the fundamental and well known multi-sectoral (scientific as well as socio-economic) processes that contribute to the results. Furthermore, the use of consistent and well-documented methods to develop uncertainty estimates will allow the changes in our understanding to be tracked through time. In this case, a useful proportion of the uncertainties could be captured, although the parameters and assumptions of the model will still include some uncertainty (Webster 2003). Hence, a significant part of our uncertainty about past and future climate change will be unavoidable (Webster et al. 2003).

The importance of adequately quantifying and communicating uncertainty has been recently accepted in the climate research community. The authors for the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) were encouraged to quantify uncertainty as much as possible (Moss and Schneider 2000).

However, various limitations characterise these attempts to quantify uncertainty: (a) Climate observations were not used to constrain the uncertainty in climate model parameters (Wigley and Raper 2001). (b) By using only one Atmosphere-Ocean General Circulation Model (AOGCM), uncertainties in climate model response are reduced to uncertainty in a single scaling factor for optimizing the model's agreement with observations (Stott and Kettleborough 2002). (c) The IPCC emissions scenarios have been used as of equal likelihood (Wigley and Raper 2001). (d) Some studies analysed the uncertainty only in the climate system response without characterizing the economic uncertainty except through individual IPCC emissions scenarios, by estimating uncertainty in future climate change only applied to specific IPCC emissions scenarios (Allen et al. 2000; Knutti et al. 2002; Stott and Kettleborough 2002). (e) The uncertainty analysis was in no case done under a policy scenario leading to stabilisation of GHG concentrations. (f) Uncertainty estimates for reconstructions of past climate (e.g., Mann et al. 1999; Luterbacher et al. 2004; Xoplaki et al. 2005) usually do not take into account dating uncertainty of the climate proxies (natural and documentary), loss of signal confidence within the twentieth century calibration period, uncertainties in the instrumental data (e.g. Brohan et al. 2006 and references therein), assumptions about signal stationarity, proxies exhibiting an unquantified degradation in reliability, reduction of sample replication, etc. (Esper et al. 2005).

Across all areas of climate change, it is found that uncertainty tends to increase when moving from global to regional scales. Regional information is clearly highly relevant to policy, but generally is much less precise and can be ambiguous and confusing. Thus, a careful balance is needed when considering the scale at which policy relevant information can be provided (Manning et al. 2004). The assessment of potential regional impacts of climate change has, up to now, relied on data from coarse resolution AOGCMs, which do not resolve spatial scales of less than ∼300 km (Mearns et al. 2001).

According to Dessai and Hulme (2004) there are two different sources of uncertainty, the "epistemic" and the "stochastic". Epistemic uncertainty originates from incomplete knowledge of processes that influence events. These sources of uncertainty can be reduced by further studying the climate system, improving the state of knowledge, etc. Stochastic sources of uncertainty are those that are considered "unknowable" knowledge – items such as variability in the system, the chaotic nature of the climate system, and the indeterminacy of human systems

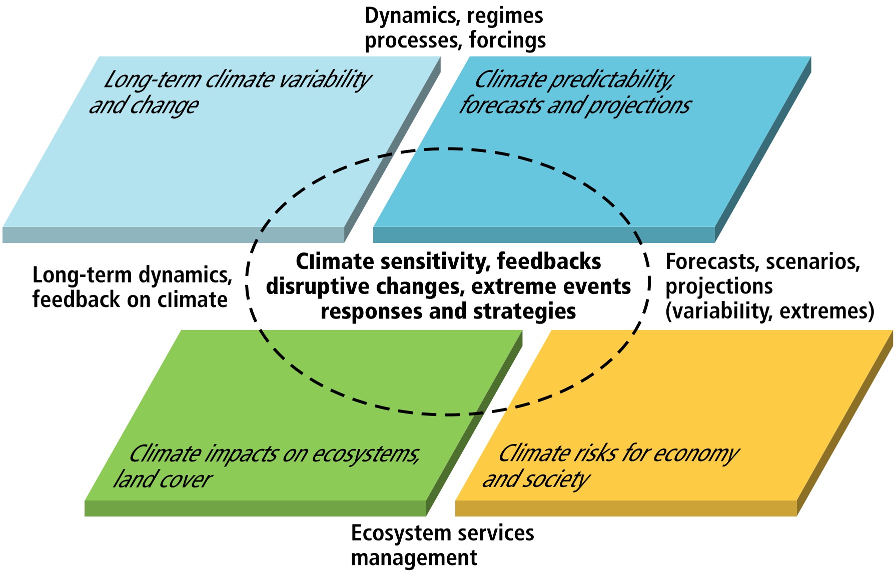

Fig. 1 Structure of NCCR Climate and major fields of inter-Work-Package (in different colours) collaboration and interaction

(Dessai and Hulme 2004). Further, the likelihood of various scenarios will likely change as soon as a prediction is made, because society begins to react (and adapt) and therefore change the outcome in ways that were not incorporated into the prediction (Sarewitz et al. 2003).

The sources of uncertainty in climate forecasting that have to be taken into consideration, as suggested at the IPCC Workshop on Communicating Uncertainty and Risk (Manning et al. 2004), are: (a) Uncertainty in anthropogenic forcing due to different emission paths (“scenario uncertainty”). (b) Uncertainty due to natural variability, encompassing internal chaotic climate variability and externally driven (e.g., solar, volcanic) natural climate change (“natural variability”). (c) Uncertainty in the climate system’s response to external forcing due to incomplete knowledge of feedbacks and timescales in the system (“response uncertainty”) (Allen et al. 2004).

The National Centre of Excellence in Research on Climate (NCCR Climate), which is based in Bern, Switzerland, aims at increasing our knowledge of the climate system by carrying out interdisciplinary research on its variability and future change, climate impacts and their financial evaluation, and climate policies (Figure 1). It is a scientific network bringing together 130 researchers from 13 Swiss partner institutions (http://www.nccr-climate.unibe.ch/). The NCCR Climate is a long-term research programme that started in 2001.[1]

The core theme of NCCR Climate is: “Climate variability, predictability, and climate risks”. It builds on three interlinked research fields that frame the research activities:

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[1] The NCCR Climate in its second phase (2005–2009) is building on the scientific and institutional achievements of the first phase and focuses on: (1) European past climate variability covering the last 1000 years; (2) Climate predictability, global to regional climate processes, and projections on seasonal to interannual scales and more accurate predictions and extreme events; (3) Ecosystem impacts and adaptation, assessing implications for ecosystems and evaluating strategies for the management of forests and agriculture; (4) Climate risks addressing questions on the potential perspectives for regional and global post-Kyoto climate policies and the vulnerability and adaptation costs of regional and global economies to global climate change.

1. What is the nature of past, current and future climate? What is the sensitivity of the climate system (including the internal variations and extremes) to anthropogenic and natural perturbations? What are the feedbacks between the atmosphere, the ocean, the cryosphere, land surfaces and the anthroposphere?
2. What are the forced climate impacts on ecosystems, economy and society? What is the likelihood of rapid transitions and changes with disruptive impacts? What is the role of extreme climate events on ecosystems, the economy and society?
3. What are the options and strategies for the management of ecosystems, economic systems and societal systems to respond to such climate changes and to reduce vulnerability?

Within the structure of the NCCR climate research, there are three geographical scales (Switzerland including the greater Alpine area, Europe and global) and three temporal scales (the last 500 years, the present and the 21st century).

The issues targeted in NCCR Climate require work at a wide range of spatial and temporal scales as well as the combination and integration of results from observational, experimental and modelling studies. Developing methodologies and providing an environment to work across the boundaries of different scales and methods is a priority area in climate research. It is intellectually and technically challenging, but a prerequisite to address the complex nature of the research issues in an adequate manner.

This book (special issue) compiles seven consecutive and integrative chapters, which (i) address some of the aforementioned common scientific challenges in current climate and climate impact research and (ii) synthesize the interdisciplinary research across the large thematic umbrella of the NCCR Climate. The scientific voyage starts with two selected problems of atmospheric and climate research, that address (i) different scales in time from the past to the future with different types of data availability (Raible et al. 2006), and (ii) reducing uncertainty of climate predictions and projections (Schwierz et al. 2006). We then move on to the topic of future climate change impacts on natural and managed ecosystems. The main challenge of climate impacts research is to consolidate the large scale projections to regional or local scales of climate variability and change, which can then be integrated into more specialised climate impact models (Calanca et al. 2006). Impacts are not limited to ecosystems but encompass the entire social, technological and economic systems (Fuhrer et al. 2006). Thus, building a modelling framework where the climate system and the energy-economy-environment systems communicate interactively with each other (Bahn et al. 2006) is fundamental in order to assess future development paths, strategies and options for climate change mitigation policies (Viguier et al. 2006). Finally, it is the society, at different hierarchical levels with different organizational forms and institutions, which makes the decisions and assesses the future failure or success of any climate change policy (Bürgenmeier et al. 2006).

Raible et al. (2006) assessed the natural climate variability on interannual to decadal timescales by using AOGCMs, state-of-the-art regional circulation models in combination with multiproxy climate reconstructions from regional to continental scales. The reconstructions reveal pronounced interdecadal variations, which seem to “lock” the atmospheric circulation in quasi-steady long-term patterns over multi-decadal periods, which partly control the continental alpine temperature and precipitation variability. In contrast, the climate model simulations indicate some substantial differences to the observations, indicating that the teleconnectivity between modeled climate variables is weaker than in observations however, in the future these teleconnections seem to be more stable. This partial disagreement between the reconstructions and the model simulations implies the need for better instrumental and more numerous natural/documentary proxy data sets, further improvement in reconstruction methods and multi-model ensemble approaches (combination of regional and global models) (e.g., Yoshimori et al. 2005; Goosse et al. 2005, 2006; Raible et al. 2006).

Today's climate models capture the essence of the large-scale aspects of the current climate and its considerable natural variability reasonably well on time scales ranging from one day to decades. Despite this significant achievement, the models show weaknesses that add uncertainty to the very best model projections of human-induced climate changes.

Schwierz et al. (2006) present an overview of the uncertainties in climate model projections that arise from various sources. They identified uncertainties stemming from the complexity and non-linearity of the climate system, its irregular evolution and the changing climate sensitivity, the emission scenarios selection and their implications for the radiative forcing, and the inevitably incomplete and inadequate representation of the climate system in a weather or climate model. The latter uncertainty can be separated into that which is connected with the model equations representing the climate system interactions, the limited representation of physical processes due to the low resolution of the models and the limited knowledge of some physical processes including the non-linear interactions between the climate components. Schwierz et al. (2006) report that a hierarchy of models is a powerful approach to estimate and assess uncertainty, while the combination of different kinds of models of different complexity with an overlap between the model evaluations can contribute to the quantification and reduction of uncertainties from future climate model projections.

Calanca et al. (2006) combined simulations with a state-of-the-art Global Circulation Model (GCM) complemented by an experiment with a high-resolution spatially distributed hydrological model in order to quantify the impact of climate change and to reveal regional differences in the response, both across the alpine region as well as within individual river basins in Switzerland. They found that GCMs alone cannot capture the detailed regional scale results, demonstrating the danger of a simple extrapolation of GCM results and underlining the importance of a highly resolved hydrological model for the quantitative assessment of the regional impacts of climate change. Current spatial resolution of GCMs is too coarse to adequately represent areas of complex topography and land use change (Calanca et al. 2006).

Fuhrer et al. (2006) assessed climate risks on ecosystems using simulations for present climate with a 50-km Regional Climate Model (RCM) with boundary conditions from a GCM control experiment and compared the model output with observations. Climate risks arise from complex interactions between climate, environment, social and economic systems. They represent combinations of the likelihood of climate events and their consequences for society and the environment. The assessment of climate risks depends on both the ability to simulate extreme events in various scales and the understanding of the responses of the target system. The projections of climate risks are dependant on the quality of the link between larger-scale climate simulations and small-scale effects. Extreme climate events are often related to large-scale synoptic conditions, but the scales at which impacts occur can vary from local to regional (Fuhrer et al. 2006).

In order to obtain an integrated assessment of climate policies, Bahn et al. (2006) established a two-way coupling between the economic module of a well-established integrated assessment model and an intermediate complexity "3-D" climate model. The coupling is achieved through the implementation of an advanced "oracle based optimisation technique" which permits the integration of information coming from the climate model during the search for the optimal economic growth path. They showed that further applications of this method could include the coupling of an economic model and an advanced climate model that could describe the carbon cycle. Additionally, the spatial resolution of the climate model allows the construction of regional damage functions or in other words, the ability to link climate feedbacks with economic activity (e.g. agriculture). A further step is the coupling of a macro-economic growth module with a detailed techno-economic model, in addition to the coupling with a moderate complexity climate model (Bahn et al. 2006).

Viguier et al. (2006) used an optimal economic growth model, a multi-region bottom-up process model and a multi-region computable general economic equilibrium (CGE) model for the assessment of climate change policies. Their assessment reveals the important effect of endogenising technological learning by early investments in research and development (R&D) activities and demonstration and deployment (D&D) programs. These programs could support the development and diffusion of cleaner technologies in the long term, and influence the strategic behaviour of climate policy makers and ultimately the success of international climate-policy. The strategic behaviour of the different countries towards the Kyoto protocol is related with the connected costs and the ability of the governments to afford these costs.

Bürgenmeier et al. (2006) explore the reasons behind the reluctant application of economic instruments of climate change. They stress the need for interdisciplinary research linking economic theory and empirical testing to deliberative political procedures. They found that the promotion of economic policies of climate change has to be completed by social policies to capture the ethical aspects. Additionally, the problem of the social acceptance of economic instruments of climate change can be overcome by using a) Conventional models that consider the environment, either through public goods theory or through property rights theory and b) More global models featuring relationships between economics, the biosphere and social aspects in order to come closer to the concept of sustainable development.

The understanding of the likelihood of future climate requires further and repeated analysis of the up-to-date combined knowledge on the climate and socio-economic systems (Webster et al. 2003).

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Climate variability – observations, reconstructions, and model simulations for the Atlantic-European and Alpine region from 1500–2100 AD

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Abstract A detailed analysis is undertaken of the Atlantic-European climate using data from 500-year-long proxy-based climate reconstructions, a long climate simulation with perpetual 1990 forcing, as well as two global and one regional climate change scenarios. The observed and simulated interannual variability and teleconnectivity are compared and interpreted in order to improve the understanding of natural climate variability on interannual to decadal time scales for the late Holocene. The focus is set on the Atlantic-European and Alpine regions during the winter and summer seasons, using temperature, precipitation, and 500 hPa geopotential height fields. The climate reconstruction shows pronounced interdecadal variations that appear to "lock" the atmospheric circulation in quasi-steady long-term patterns over multi-decadal periods controlling at least part of the temperature and precipitation variability. Different circulation patterns are persistent over several decades for the period 1500 to 1900. The 500-year-long simulation with perpetual 1990 forcing shows some substantial differences, with a more unsteady teleconnectivity behaviour. Two global scenario simulations indicate a transition towards more stable teleconnectivity for the next 100 years. Time series of reconstructed and simulated temperature and precipitation over the Alpine region show comparatively small changes in interannual variability within the time frame considered, with the exception of the summer season, where a substantial increase in interannual variability is simulated by regional climate models.

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1 Introduction

Observations and reconstructions for the late Holocene show that the warming since the 1960s is likely unprecedented over the last millennium (Jones and Mann 2004). Modelling studies give some evidence that the temperature change of at least the second half of the 20th century can only be explained by including anthropogenic forcing (Rind et al. 1999; Crowley 2000; IPCC 2001; Meehl et al. 2003; Bauer et al. 2003). Nevertheless, to assess future climate change for key regions, like the Atlantic-European area, with confidence, a thorough understanding of the underlying mechanisms of natural climate variability on different spatio-temporal scales for the late Holocene is necessary (Jones and Mann 2004).

One possibility to address the understanding of natural climate variability of the Atlantic-European region is to investigate general circulation models (GCMs). Modelling results show that for the mid-latitudes the coupling between atmosphere and ocean plays a major role on decadal variability (Grötzner et al. 1998; Raible et al. 2001; Marshall et al. 2001, and references therein). This coupling has implications for the low-frequency (decadal) behaviour of the North Atlantic Oscillation (NAO), with its well-known linkage to temperature and precipitation on the interannual time scale (Hurrell 1995; Hurrell and Loon 1997; Wanner et al. 2001; Hurrell et al. 2003). Even baroclinic high-frequency variations characterised by stationary and transient wave activity should be incorporated to understand enhanced low-frequency variability of the NAO (Raible et al. 2004). Additionally, future projections integrated with coupled atmosphere-ocean (AO-) GCMs show a systematic northeastward shift of the northern center of action of the NAO (Ulbrich and Christoph 1999), indicating that at least the modelled position of the pressure centers is not stable in time. Recently, a strong connection between sea surface temperature (SST) and the North Atlantic Thermohaline Circulation has been presented in unforced control AO-GCM simulations (Latif et al. 2004; Cheng et al. 2004). These SST anomalies, containing strong multi-decadal variability, may mask anthropogenic signals in the North Atlantic region. Another potential mechanism of generating low-frequency NAO variability is the stratosphere, where stratospheric processes can be influenced by changes in the external solar and volcanic forcing (Shindell et al. 2001, 2003). Another problem present in this region is illustrated by an ensemble modelling study for the Maunder Minimum from 1640 to 1715 (Yoshimori et al. 2005), showing that forcing signals, e.g., solar forcing, are difficult to detect due to the strong internal variability induced by the NAO.

Another approach to improve our understanding of natural climate variability is to extend the existing climate records for temperature, precipitation, and atmospheric circulation patterns back in time. One first step was to reconstruct temperature on hemispheric to global scales over the past centuries to millennia based on empirical proxy data (Bradley and Jones 1993; Overpeck et al. 1997; Jones et al. 1998; Mann et al. 1998; Briffa et al. 2001; Esper et al. 2002a; Cook et al. 2004; Jones and Mann 2004; Esper et al. 2004; Moberg et al. 2005). However, hemispheric-scale reconstructions provide little information about regional scale climate variability. Therefore, studies focusing on reconstruction of specific regions, e.g., Atlantic-Europe or high Asia, utilising documentary (Luterbacher et al. 2004; Xoplaki et al. 2005; Guiot et al. 2005) and tree-ring data (Esper 2000; Esper et al. 2002b, 2003; Büntgen et al. 2005) are also valuable.

Jones et al. (2003) found amongst others changes in the annual cycle of Northern Hemisphere temperatures indicating that, compared with earlier times, winters have warmed more relative to summers over the past 200 years.

A third research focus is on atmospheric circulation variability. Besides traditional reconstructions of the NAO index (Appenzeller et al. 1998; Luterbacher et al. 2002a; Cook et al. 2002; Vinther et al. 2003), atmospheric circulation modes (Jacobeit et al. 2003) for each month in the year were derived from sea-level pressure field reconstructions (Luterbacher et al. 1999, 2002b). Utilising reconstructions of the 500 hPa geopotential height fields for the Atlantic-European region, Casty et al. (2005a) found that climate regimes, defined by the joint probability density function of the first two leading Empirical Orthogonal Functions, are not stable in time.

With a steadily growing data base, it is now possible to reconstruct climate variations from small regions like the European Alps (Casty et al. 2005b; Frank and Esper 2005; Büntgen et al. 2005). This could help to place extreme events, e.g., the hot European summer of 2003 (with its maximum deviation from the mean in central Europe and the Alps), in a longer-term context (Luterbacher et al. 2004). Recently, regional modelling studies (Schär et al. 2004) showed that in a scenario with increased atmospheric greenhouse-gas concentrations, future European temperature variability may increase by up to 100%, with maximum changes in central and eastern Europe. Such a change in variability would have a strong impact on not only the environment, but also on the society and the economy in these regions.

The National Center of Competence in Research on Climate (NCCR Climate) in Switzerland provides a substantial variety of different spatio-temporal highly-resolved climate information, ranging from natural and documentary proxy reconstructions, to high-quality instrumental measurements, to modeled data from state-of-the-art general circulation and regional models for both present day climate conditions (fixed to 1990 AD) as well as future scenarios. The aim of this study is to combine the two major types of information in the archive – the observations and reconstructions on the one hand, and the simulations for present day climate conditions and future scenarios on the other hand. This set of data and simulations will form the basis for the investigation of the atmospheric circulation and its links to the behaviour of temperature and precipitation in the Atlantic-European and the Alpine regions on interannual to decadal time scales. Additionally, changes in the annual cycle from 1500–2100 AD are discussed.

The outline of this paper is as follows: In Section 2 the reconstructed and modeled data, as well as some analysis techniques and definitions, are introduced. Subsequent analysis concentrates on the Atlantic-European (Section 3) and Alpine (Section 4) regions, illustrating the relationship between large-scale flow regimes and temperature and precipitation. The results are summarised and interpreted, in the context of published evidence, in Section 5.

2 Reconstructions, models, and analysis techniques

The study is based on a set of reconstructed and modeled data, which is introduced as follows. We focus on winter (December to February, DJF) and summer (June to August, JJA) of the Atlantic-European and the Alpine regions, respectively.

2.1 Reconstructions and models

Reconstructions of past pressure, temperature, and precipitation are performed through multivariate statistical climate fields reconstruction (CFR) approaches. CFR seeks to reconstruct a large-scale field by regressing a spatial network of proxy indicators (e.g., early instrumental, tree-ring data, and historical evidences) against instrumental field information (Jones and Mann 2004). During periods when both proxy and instrumental field information (reanalyses) are available, regression models are developed and fed with proxy data to reconstruct past climate variables.

For the Atlantic-European region reconstructions of seasonally resolved land surface air temperature (Luterbacher et al. 2004, 25°W–40°E and 35°N–70°N), precipitation (Pauling et al. 2006, 10°W–40°E and 35°N–70°N), and 500 hPa geopotential height fields (Luterbacher et al. 2002b, 30°W–40°E and 30°N–70°N) are available back to 1500. Independent reconstructions, i.e., sharing no common predictors, have been developed for seasonal land surface air temperatures and precipitation fields for the European Alps since 1500 (Casty et al. 2005b, 4°E–16°E and 43°N–48°N). These CFRs are multi-proxy based. The period from 1500 to the late 17th century comprises entirely documentary and natural proxies; the period from 1659 to around 1750 includes a mix of documentary, natural proxies as well as a few early instrumental data. The reconstructions for the last 250 years are entirely based on instrumental time series, the number of those increasing steadily over time. A compilation of all proxies and instrumental data used for those 500 year climate reconstructions is given in Luterbacher et al. (2004), Casty et al. (2005b), and Pauling et al. (2006). The spatial resolution for the temperature and precipitation reconstructions is 0.5° ($\sim$60 km $\times$ 60 km) similar to the instrumental field information for the 1901–2000 period: Instrumental data from New et al. (2000) were used by Luterbacher et al. (2004); data from Mitchell et al. (2004) were used by Casty et al. (2005b) and Pauling et al. (2006). The 500 hPa fields are resolved on a 2.5° grid similar to the NCEP Reanalysis data (Kalnay et al. 1996; Kistler et al. 2001). For further details about reconstruction methods, proxy information, verification, and uncertainty estimates, the reader is referred to Luterbacher et al. (2002b, 2004), Casty et al. (2005b), and Pauling et al. (2006).

A new millennial-long tree-ring reconstruction utilising 1527 ring width measurement series from living and relict larch and pine samples from the Swiss and Austrian Alps (46.5°N–47°N and 7.5°N–11.5°E) is applied for further comparison and validation (Büntgen et al. 2005). This record was detrended using the Regional Curve Standardisation (RCS) method (Briffa et al. 1992), and calibrated and verified against high elevation station temperature data (Böhm et al. 2001) over the 1864–2002 period. Note that this reconstruction is independent from Casty et al. (2005b).

Two different ocean-atmosphere general circulation models (OA-GCMs) are used in this study. The first model is the Max Planck Institute for Meteorology global coupled model, ECHAM5/MPI-OM. The resolution of the atmospheric component, ECHAM5 (Roeckner et al. 2003, version 5.0), is 19 levels in the vertical dimension and T42 in spectral space, which corresponds to a horizontal resolution of about 2.8° $\times$ 2.8°. The oceanic component, MPI-OM (Marsland et al. 2003), is based on a Arakawa C-grid (Arakawa and Lamb 1981) version of the HOPE ocean model (Wolff et al. 1997). It is run on a curvilinear grid with equatorial refinement and includes 20 vertical levels. A dynamic/thermodynamic sea ice model (Marsland et al. 2003) and a hydrological discharge model (Hagemann and Duemenil-Gates 2001) are included. The atmospheric and oceanic components are connected with the OASIS coupler (Terray et al. 1998). The model does not employ flux adjustment or any other corrections. Initial ocean conditions are taken from a 500-yr control integration. The model is forced from stable conditions with a 1% CO_2 increase per year from 1990 (348 ppm) to 2100 (1039 ppm). Hereafter, this experiment is denoted as ECHAM5 1% CO_2. This forcing is a commonly used scenario to intercompare the sensitivity of different coupled climate models to increased greenhouse gases.

The second setup is the Climate Community System Model (CCSM), version 2.0.1,[1] developed by the National Center for Atmospheric Research (NCAR) (Kiehl et al. 1998;

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[1] http://www.ccsm.ucar.edu/models/

Blackmon et al. 2001). The atmospheric part of this coupled model has a horizontal resolution of T31 ($\sim$3.75° × 3.75°) with 26 vertical levels; the ocean component has $\sim$3.6° × 1.8° resolution with 25 levels. The CCSM also runs without any flux corrections. Two simulations were carried out: a 550-yr simulation for constant present day climate conditions fixed to 1990 AD (denoted as CCSM 1990) and a 1% CO_2 simulation (denoted as CCSM 1% CO_2) starting from the stable state of the CCSM 1990 (Raible et al. 2005). Note that for the CCSM 1990, the first 50 years are ignored until the model adjusts to its stable climate state. The CCSM is integrated on two different computer platforms, an IBM SP4 and a Linux cluster (Renold et al. 2004). Note that the different computer platforms have no influence on the mean behaviour of the simulations.

Regionally, we use the Climate High Resolution Model (CHRM) which is driven by the Hadley Center HadAM3 atmospheric GCM at the lateral boundary (Pope et al. 2000). The CHRM regional model covers Europe and a fraction of the North Atlantic on a 81 by 91 grid point domain with a resolution of approximately 56 km and a time step of 300 s (see Vidale et al., 2003 for model set-up). The CHRM has been validated regarding its ability to represent natural interannual variations (Vidale et al. 2003) and the precipitation distribution in the Alpine region (Frei et al. 2003) using a simulation that is driven by the ECMWF reanalysis ERA-15 (Gibson et al. 1999). Two time-slice simulations are performed: For the control simulation from 1961–1990 the HadAM3 and the nested CHRM uses observed SSTs and observed greenhouse gas concentrations. The second experiment for the time-slice 2071–2100 uses the forcing of an IPCC A2 scenario (IPCC 2001). To assure that changes in variability between the two simulations are not associated to SST changes, but are due to the atmospheric models and their interaction with the land surface, the so-called delta change approach is applied to the experimental setup (Jones et al. 2001). Both GCM HadAM3 simulations, delivering the boundary conditions for the CHRM regional model, use the same SST variations (taken from the 1960–1990 observations), but a mean SST warming is added to the A2 scenario simulations by using the warming signal from the coupled HadCM simulation. Both simulations have a one year spin-up phase: 1960 and 2070, respectively.

2.2 Analysis techniques

The analysis presented in this paper is restricted to the Atlantic-European and the Alpine region. Time series are defined for both regions. The temperature time series is the mean over 25°W–40°E and 35°N–70°N for the European land area and over 4–16°E and 43–48°N for the Alpine region. For the precipitation time series the Atlantic-European region was reduced to 10°W–30°E and 35°N–70°N due to the smaller area available from the reconstructions (Pauling et al. 2006). To emphasise and extract low-frequency variability, a 31-yr triangular filter was applied. The first and the last 15 years of the time series are not analysed to avoid edge effect problems.

To merge the time series from climate simulations and reconstructions, and to account for biases of the model simulations, anomalies with respect to the overlapping 1990–2000 and 1961–1990 periods were used for the Atlantic-European and the Alpine area, respectively. Biases between the model output and the reconstructions are amongst others due to the coarse model resolution (horizontally and vertically) and the inclusion of sea areas which are not considered in the reconstructions. Moreover, due to the different horizontal resolution the size of the area slightly varies from the reconstructions. Other reasons for biases could also be the uncertainties of the proxy input data of the reconstruction method as well as systematic model errors, e.g., model drifts and underestimation of subgrid scale variability. Filtering

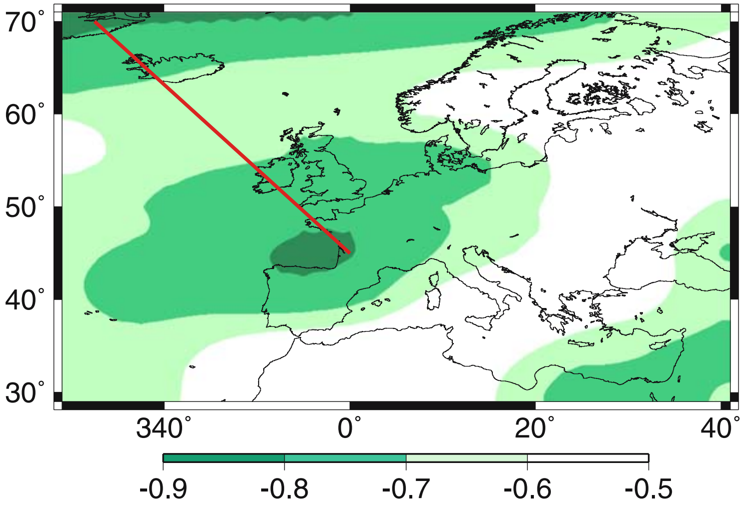

Fig. 1 An example of a 30-yr window (1973–2002), where the teleconnectivity of the 500 hPa geopotential height (DJF, shaded) and the corresponding axis of teleconnectivity (red line) is denoted

was applied to each time series separately in order to avoid mixing model and reconstruction data. However, this results in gaps in the filtered time series.

The spatio-temporal behaviour of the circulation of the free atmosphere can be characterised by the teleconnectivity of the 500 hPa geopotential height. According to Wallace and Gutzler (1981) the teleconnectivity is defined as the strongest negative correlation of one base point with all grid points assigned at the base point. As base point, all grid points are iteratively chosen. Only strong negative correlations which cluster together in a large area are considered as "centers of action". Thus, anticorrelated centers of action, e.g., the NAO with its poles near Iceland and the Azores, are easily identified. To find the center that is anticorrelated with another one, a search algorithm is applied to the teleconnectivity map. In a 20° × 10° longitude/latitude neighbourhood the strongest negative correlation coefficient is identified. Provided that the region is large enough to capture one center of action, the size of search area is not a critical factor in this procedure. Then, this grid point is again correlated with all others in the 500 hPa geopotential height providing the position of the grid point which has the strongest negative correlation. These positions are connected with lines denoting the axis of the opposing centers of action. In order to illustrate this method, Figure 1 shows the teleconnectivity of the reconstructed 500 hPa geopotential height (shadings) in winter (DJF) and the axis of the anticorrelated centers of action (red line) for the 1973 to 2002 period. The two centers of action are easily identified. Perpendicular to the axis, the atmospheric flow is strengthened or weakened, depending on the sign of the centers of action. For example, if the northern center is negative and the southern is positive, the westerly atmospheric flow is stronger than average, and vice versa.

The technique was applied to the 500 hPa geopotential height data for a 30-yr running window, where only the axes of the conversing centers of action are displayed. This results in a three-dimensional Hovmöller diagram (e.g., Figure 5) which shows the spatio-temporal behaviour of atmospheric circulation patterns. The window size was chosen to fit to the filter applied to the time series and also to correspond to the window regularly used for time-slice experiments with highly resolved climate models in the climate change community (Wild