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Towards a General Method to Construct Regional Climatic Scenarios for Model-Based Impacts Assessments¹

with 1 figure

Zusammenfassung:

Auf dem Weg zu einer allgemeinen Methode zur Erstellung regionaler Klimaszenarien für modellbasierte Klimawirkungsstudien

Studien, welche die möglichen regionalen Auswirkungen von Klimaveränderungen mit Hilfe von Simulationsmodellen abzuschätzen versuchen, weisen sehr unterschiedliche und anspruchsvolle Bedürfnisse nach klimatisch-meteorologischen Eingangsdaten auf. In der vorliegenden Arbeit wird eine allgemeine Methode vorgestellt, um Szenarien möglicher zukünftiger Klimata für solche Studien zu konstruieren. Die Methode wurde im Kontext von drei Fallstudien entwickelt, die sich mit den möglichen Auswirkungen von Klimaveränderungen auf die Waldsukzession, das Grünland, die Schneedecke und den Abfluß in den europäischen Alpen befassen. Aufgrund der Bedürfnisse dieser und einer Reihe weiterer, unabhängiger Studien wurde der folgende Anforderungskatalog ermittelt: Die benötigte Methode sollte physikalisch konsistente, räumlich und zeitlich ausgedehnte Szenarien mit einer hohen räumlichen und zeitlichen Auflösung liefern, sie sollte auf einer statistisch präzisen Beschreibung des heutigen Wetters und Klimas basieren, und sie sollte robust, formal definiert und effizient sein. Ausgehend von unseren Fallstudien und der Evaluation bereits existierender Methoden zur Konstruktion von Klimaszenarien wurde die folgende Prozedur hergeleitet: (1) Beschreibung des Wetters an den interessierenden Standorten als einen stochastischen Prozeß; (2) Schätzung der Prozeß-/Klimaparameter für das heutige Klima anhand von Messungen; falls keine Messungen vorliegen, Interpolation der Parameter aus umgebenden Meßstationen; (3) statistische Regionalisierung der Ausgangsdaten eines Klimamodells zwecks Abschätzung zeitabhängiger Veränderungen in ausgewählten Klimaparametern; (4) Verwendung der so erhaltenen Resultate, um die Parameter des stochastischen Prozesses abzuändern, und Generierung von Wetterdaten mittels stochastischer Simulation. Die vorliegende Arbeit beschreibt die Implementierung der einzelnen Komponenten (Regionalisierung, stochastische Simulation des Wetters, Interpolation) sowie deren Zusammenführung innerhalb einer Gesamtmethodik zur Konstruktion von Klimaszenarien. Die vorgeschlagene Methode wird mit alternativen Verfahren verglichen und im Lichte der in den Fallstudien gesammelten Erfahrungen diskutiert. Es wurde gefolgert, daß die Methode die meisten der oben erwähnten Bedürfnisse zu erfüllen vermag und somit für modellbasierte Klimawirkungsstudien allgemein tauglich ist. Ihr Hauptnachteil besteht in der Verwendung statistisch-deskriptiver Modelle, die unter einem zukünftigen Klima ihre Gültig-

keit verlieren könnten. Die vorgeschlagene Methode kann jedoch gut für ausgedehnte Sensitivitätsstudien verwendet werden, und dank ihrer modularen Struktur lassen sich Verbesserungen der einzelnen Komponenten problemlos einbauen, sobald sie verfügbar werden.

Резюме:

На пути к общему методу разработки региональных климатических сценариев для исследования последствий климата на основе моделей

Исследования, которые пытаются оценить возможные региональные последствия изменений климата с помощью симуляционных моделей, предъявляют весьма различные и большие духовные запросы относительно климатически-метеорологических входных данных. В предлагаемой статье представляется общий метод построения сценариев возможных будущих климатических условий для таких исследований. Данный метод был развит в контексте трёх примерных этюдов, занимающихся возможными последствиями изменений климата на лесные сукцессии, луга и пастбища, снежный покров и сток в европейских Альпах. На основе потребностей этих и других, независимых исследований был разработан следующий каталог требований: Нужный метод должен был предоставить физически постоянные, обширные по пространству и по времени сценарии с высоким пространственным и временным разрешением; он должен был основываться на статистически точном описании нынешней погоды и климата, и он должен был быть надёжным, формально определённым и эффективным. Исходя из примерных этюдов авторов и оценки уже существующих методов построения климатических сценариев, была выведена следующая процедура: (1) описание погоды на вызывающих интерес местах в качестве стохастического процесса; (2) оценка процессуальных и климатических параметров нынешнего климата при помощи измерений, в случае отсутствия измерений – интерполяция параметров из близлежащих измерительных станций; (3) статистическая регионализация исходных данных модели климата для предварительного определения временных изменений избранных климатических параметров; (4) применение полученных таким образом результатов для изменения

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параметров стохастического процесса и производство метеорологических данных посредством стохастической симуляции. Предлагаемая статья описывает имплементацию отдельных компонентов (регионализация, стохастическая симуляция погоды, интерполяция) и их сведение внутри общей методики построения сценариев климата. Предлагаемый метод сравнивается с альтернативными приёмами и обсуждается в свете накопленного с примерными этюдами опыта. Был сделан вывод, что этот метод может выполнить большинство выше названных потребностей и тем самым в общем годится для исследования последствий климата на основе моделей. Главный недостаток метода состоит в применении статистически-дескриптивных моделей, которые могут перестать быть действительными в условиях будущего климата. Предлагаемый метод можно, однако, успешно применить для обширных исследований чувствительности, и благодаря их модульной структуре без проблем можно включить улучшения отдельных компонентов, как только они имеются в распоряжении.

Summary:

Studies that use simulation models to assess possible regional impacts of climatic change have very diverse and demanding requirements for climatic input data. This paper presents a general method to construct climatic scenarios for such studies. It was developed in the context of several case studies dealing with possible climatic impacts on forest succession, grasslands, and snowpack/run-off in the European Alps. The following set of requirements was identified from the case studies

1. Introduction

Studies dealing with the possible regional impacts of a changing climate have very diverse needs for climatic input data (ROBINSON & FINKELSTEIN 1991, GYALISTRAS et al. 1998). Many of these studies rely on simulation models (CARTER et al. 1994), and these tend to have very demanding input requirements. For instance, the assessment of climatic impacts on ecosystems often requires a local spatial resolution and a high flexibility in terms of bioclimatic input variables, such as temperature sums above a given species-specific threshold, or wind speeds considered only during particular periods of the diurnal and seasonal cycles (for a complete list of variables of likely interest see GYALISTRAS et al. 1994, 1998). Generally, model-based studies cover wide ranges of scale, resolution and precision, e.g. temporal scales ranging from a few years up to millennia, and temporal resolutions ranging from an hour to a year (see IPCC 1996).

Moreover, such studies critically depend on the availability of *quantitative* information on present and possible future climatic conditions. This is for three main reasons: Firstly, many of the modelled impacts

and other, independently formulated scenario needs: The method should provide physically consistent, spatially and temporally extended scenarios at a high spatial and temporal resolution, be based upon a statistically accurate description of local weather and climate, and be robust, flexible, formally defined, and efficient. Based on our case studies and an evaluation of existing methods we derived the following general procedure: (1) Describe weather at the locations of interest as a stochastic process; (2) Estimate the process/climatic parameters for present climate from measurements; if no measurements are available, use a spatial interpolation procedure to estimate the parameters from nearby climatological stations; (3) Apply statistical downscaling to the output of a climate model to estimate time-dependent changes in selected climatic parameters; (4) Use the results from downscaling to adjust the parameters of the stochastic process, and generate weather sequences by means of stochastic simulation. The paper describes the current implementation of the individual components of the method (downscaling, stochastic weather generation, interpolation) and their combination within an overall framework for scenario construction. The proposed method is then compared to alternative approaches and discussed in light of our case studies. It is concluded that the method satisfies most of the above formulated requirements and thus provides a generally useful technique for model-based impact assessments. A main limitation presents the extensive use of statistical-descriptive models, which may not necessarily hold under a future climate. However, the proposed method supports extensive sensitivity studies, and thanks to its modular structure enhancements of the individual components can be easily incorporated as soon as they become available.

are expected to depend strongly on the magnitude, rate and form of anticipated climatic change. For instance, a sustained temperature increase of 1 °C can have a major effect on the probability of occurrence of many tree species (KIRSCHBAUM & FISCHLIN 1996), but a decadal "warming" of twice that magnitude may be negligible. Another example is the carbon budget of temperate forests, which has been shown to sensitively depend on the rate and pattern of possible changes in temperature and precipitation (PERRUCHOU 1996). Secondly, many of the modelled systems, such as ecosystems, are inherently complex and our scientific understanding is limited. The more complex the response, the more it becomes necessary to accurately define the scenario driving the impacted system in order to be able to relate a particular response phenomenon to a particular forcing. And finally, climate is typically just one of several system drivers that need to be considered in impact projections. Again, the precise definition of all starting assumptions is a prerequisite if one wishes to assess the relative importance of the various forcings and study their interactive effects.

From the above follows that quantitative scenarios of possible future climatic conditions present essential

tools to explore system behaviours and interpret the modelled impacts. Hence the questions arise: What is an optimal method to derive quantitative climatic scenarios? Moreover, is there a general method which could be applied to derive scenarios for several types of impact studies simultaneously? If such a method existed, it would not only minimize the efforts for scenario construction, but it would also allow for more consistent impact assessments across different sectors within a given region.

To date a series of approaches to construct climatic scenarios have been proposed, which have been reviewed e.g. in LAMB (1987), GIORGI & MEARNs (1991), CARTER et al. (1994) and VON STORCH (1995). The various approaches vary widely in terms of complexity and sophistication. Purely empirical approaches, such as the construction of temporal (e.g., FLOHN 1979) or spatial (e.g., BROWN & KATZ 1995) analogues for the future climate, or arbitrary adjustments of the weather record (e.g., ROBOCK et al. 1993), can provide at small expenses a first indication of future climates, and thus appear particularly suitable for initial sensitivity studies. More sophisticated methods, which rely upon information on global and/or regional climate models (see reviews in VON STORCH 1995, CUBASCH et al. 1996, GYALISTRAS et al. 1998) can be expected to yield physically more consistent scenarios and therefore appear more suitable for advanced, quantitative impact studies.

Attempts to incorporate different methods for scenario construction within a general framework have been reported for instance by ROBINSON & FINKELSTEIN (1991), ROBOCK et al. (1993) and VINER & HULME (1994). However, we are not aware of any study which has rigorously demonstrated the feasibility of a given, general approach in the context of several case studies. Moreover, most authors have focused mainly on the physical consistency of the derived scenarios, in particular on the problem of how to specify regional climatic changes consistent with global climatic change. As is shown below, these are but two of several requirements that have to be considered when aiming at developing a general method.

A general method should also pass a practical test of application and may gain improvements from its use in specific, challenging situations. Today various studies attempting to assess possible impacts of climatic change in a complex terrain such as the European Alps render themselves to such uses: Models have been developed which simulate, e.g., grassland productivity (RIEDO et al. 1998), snow-cover (ROHRER & BRAUN 1994), run-off (STADLER et al. 1997), forest succession (BUGMANN 1994, FISCHLIN et al. 1995), or potential natural forest vegetation (BRZEZIECKI et al. 1993). The case studies also cover a large range of variables with varying temporal resolutions: The grassland and the snow-cover models require local hourly data on temperature, pre-

cipitation, global radiation, wind speed, and relative humidity, the run-off model requires information for the same variables at a daily time step, the forest succession model is driven by monthly means of local temperature and precipitation, and finally the statistical model by BRZEZIECKI et al. (1993) requires high resolution (100 x 100 m) maps of climatic parameters related to mean temperature and precipitation.

Here we report on the development and evaluation of a new general method to construct regional climatic scenarios for model-based impact assessments. First we present the profile of requirements, summarize the method's design, describe its major technical features, and report the current status of implementation. Then we discuss the feasibility and generality of the method in light of a series of case study applications dealing with possible climatic impacts on grasslands (RIEDO et al. in press), run-off (STADLER et al. 1997) and forests (FISCHLIN & GYALISTRAS 1997) in the Alps. Finally we compare the method to alternative approaches and draw some general conclusions for future developments.

2. Material and Methods

The profile of requirements was derived based on an analysis of the following sources: The reviews by ROBINSON & FINKELSTEIN (1991) and GYALISTRAS et al. (1998), the IPCC (1996) Working Group II report (in particular Part II – Assessment of impacts and adaptation options), a series of selected, recent publications (see next section), and the experience gathered in the above-mentioned case studies from the Alpine region.

3. Results

3.1. Profile of Requirements

(1) *Internal consistency*: The method should start from sound assumptions, be based upon a logical procedure, and yield scenarios which are consistent with empirical data and the physics of climate. In particular, the scenarios should be as far as possible consistent across space and time scales, between weather variables, and with the assumed causes of future global climatic change (see also HULME et al. 1990, GIORGI & MEARNs 1991, GYALISTRAS et al. 1998).

(2) *Resolution*: Most impact studies require climatic/meteorological inputs at a spatial resolution of 100 m up to 10² km, and at a hourly to monthly time step (see Introduction). Hence, the needed method should allow to generate scenarios with a high resolution in time and space.

(3) *Spatial and temporal extension*: Several applications, such as the mapping of potential natural vegeta-

tion (e.g., KIENAST et al. 1996), or hydrological studies (e.g., WIGMOSTA et al. 1994) require spatially extended scenarios. Other studies typically need scenarios at specific, representative locations within a given region, e.g. along an altitudinal (FISCHLIN & GYALISTRAS 1997) or latitudinal (PRICE & APPS 1995) transect. If dynamic models are used, the scenarios should provide data for a sufficiently large number of years (e.g., 100 years, RIHA et al. 1996) to ensure statistically stable estimates of possible impacts. Moreover, to enable the study of processes which operate at long time scales, such as forest succession or the carbon balance of soils (e.g., PERRUCHOU & FISCHLIN 1995), the method should allow to construct time-dependent scenarios that extend over several centuries to millennia.

(4) *Precision*: Many systems impacted by climate are sensitive to already small shifts in the means or the higher-order statistics of weather variables. For example, NONHEBEL (1994) reported partially strong sensitivity of simulated crop yields to relatively small deviations in the expected values of daily weather variables, and GYALISTRAS (1997) found strong sensitivity of tree species compositions as simulated by a forest patch model to the presence of autocorrelation and skewness in monthly inputs for temperature and precipitation, respectively. Hence, the method should ensure that the construction of scenarios starts from a statistically accurate description of present-day weather and climate.

(5) *Robustness*: The procedures used for scenario construction should be robust with regard to outliers in the data used to estimate model parameters, errors in driving inputs (e.g., input data provided from global climate models), and variations in starting assumptions (such as the details of a forcing scenario, or the choice of climate model).

(6) *Flexibility*: The method should be flexible in several respects. First, in order to enable the exploration of the many uncertainties related to the projection of future climate, it should be easily applicable to different scenarios of global climatic change. Second, to meet the very diverse requirements of impact studies, it should be applicable to any desired combinations of weather variables or climatic parameters, be spatially flexible, and support a wide range of temporal resolutions (cf. point 3). Finally, it should allow to perform extensive tests and sensitivity studies. In particular, it should support the construction of arbitrary scenarios (e.g. ± 3 °C for temperature and ± 20 % for precipitation), as well as scenarios that incorporate changes in climatic variability (cf. WILKS & RIHA 1996).

(7) *Formal definition*: The method should be formally defined to enable a transparent construction of scenarios, facilitate their documentation, and support the interpretation of the estimated impacts. Formal definition is also a prerequisite for the implementation and automated execution of the method on a computer.

(8) *Efficiency*: Finally, the method should be computationally efficient, such that the above requirements can be satisfied at tolerable computational costs.

3.2. Design of Method

The design of the method involved several key decisions:

Firstly, we decided to use information from climate models (e.g., HENDERSON-SELLERS & MCGUFFIE 1987), since these models present the only means to project possible global climatic changes in a physically based and precise, quantitative manner. A major alternative would have been the use of temporal analogues (e.g., ROSENBERG et al. 1993). However, this approach was not further pursued because (1) of its weak physical basis (see e.g. GIORGI & MEARNES 1991), (2) analogues from the instrumental record cover only a relatively small range of changes, and (3) palaeoclimatic analogues generally provide only a restricted set of variables, or an insufficient resolution of the annual cycle (see also GYALISTRAS et al. 1994).

Secondly, a suitable type of climate model had to be chosen. At present two main approaches to model the global climate system can be distinguished: the "full-scale" and the "end-to-end" approach. The "full-scale" approach attempts to represent the full range of issues raised by climatic change and is based upon so-called Integrated Assessment Models (IAMs; e.g., WEYANT et al. 1996). IAMs simulate a large number of interactions between human activities, atmospheric composition, climate, sea level, and ecosystems. On the other hand, the "end-to-end" approach focuses mainly on bio-physical interactions and is organized along the causal chain "emissions into the atmosphere – atmospheric composition – global and regional climatic change". The most sophisticated tools available to simulate global climate in "end-to-end" assessments are coupled General Circulation Models of the atmosphere and the oceans (AO-GCMs; e.g., GATES et al. 1996).

IAMs have the advantage that they are relatively efficient and thus can be used to generate a wide range of scenarios under different assumptions on, say, anthropogenic emissions of greenhouse-gases (e.g., ALCAMO et al. 1994). However, in IAMs the atmosphere and oceans are only crudely represented (e.g., DE HAAN et al. 1994), such that these models appear to be sub-optimal for the construction of regional climatic scenarios.

We therefore chose to use GCMs. GCMs have typical horizontal gridpoint-distances in the order of a few 100 km, so that these models also fail to supply the required spatial resolution. However, they give a comprehensive, three-dimensional picture of (possible changes in) the atmospheric circulation with a temporal resolution of 1 hr or less, and thus provide generally a much more convenient starting point for scenario

construction. Furthermore, as is shown later, the GCM-based method proposed here still allows for the construction of scenarios under in principle arbitrary assumptions on possible future anthropogenic forcings of the climate system.

Thirdly, the question arose how to infer possible associated changes in regional weather and climate from the coarse-resolution GCM output, a task commonly termed "downscaling". Several downscaling approaches have been proposed so far. A first possibility would have been to directly interpolate climatic information from individual GCM-gridpoints in the vicinity of the region of interest (e.g., BACH et al. 1985). However, GCMs simulate regional climates only poorly (GROTCH & MACCRACKEN 1991, CUBASCH et al. 1996), so that this approach would have been likely to give inconsistent results. A second possibility would have been to rely on simulations with high-resolution global (e.g., BENISTON et al. 1995) or regional (e.g., GIORGI 1996) climate models. However, these models still have a relatively coarse horizontal resolution (typically 20 up to 100 km). This would have restricted the applicability of our procedure to topographically simple regions, where climate can be expected to show only little variation within the area represented by single model grid-cells. Moreover, the accurate simulation of climate at the grid-cell scale would have required knowledge and correct modelling of all relevant processes within each grid-cell (cf. MACHENHAUER et al. 1996). Finally, high-resolution models have enormous computing requirements, and this would have prevented the construction of many different scenarios, especially over longer time spans.

Therefore we chose to base our procedure upon a third approach, statistical downscaling (KIM et al. 1984, VON STORCH et al. 1993). The basic idea of statistical downscaling is to exploit empirical relationships between variations of the large-scale and the regional weather. Regional climatic scenarios can then be constructed by applying these relationships to the large-scale weather simulated by a GCM. Several statistical downscaling approaches have been proposed which operate at the daily to seasonal resolution, use different kinds of statistical models, and focus on different large-scale predictors and regional variables. Reviews can be found in ZORITA & VON STORCH (1997) and GYALISTRAS et al. (1998). Statistical downscaling has the advantage that it provides a very high (up to local) resolution and is computationally efficient. Its limitations will be discussed later (Section 4).

Finally, a strategy had to be found how to attain the high temporal resolution required by several applications. One possibility would have been to directly use weather variables as statistically downscaled at the needed (e.g., daily) resolution (e.g., BARDOSSY & PLATE 1992, ZORITA et al. 1995). This approach would have had the advantage that it would have allowed to base

the simulation of the variability of the regional weather upon the physically consistent output of a climate model. However, such an approach has several problems: (1) The temporal statistics of the large-scale weather are not yet very reliably simulated by climate models (e.g., HULME et al. 1993), and this can lead to large errors also in the statistics of downscaled weather sequences (BÜRGER 1996). (2) The approach depends on large-scale weather data as an input, which are available from simulations with climate models typically only for a relatively small (say, 10 to 200) number of years, and this contrasts with the requirements of many impacts studies. (3) The approach does not support the construction of arbitrary scenarios, which are typically needed for systematic sensitivity studies.

To circumvent these problems we chose to base our method upon stochastic models which are fitted to local measurements only (e.g., RICHARDSON 1981). These models are commonly termed "weather generators". To simulate weather under a hypothetically changed climate, one or several parameters of a weather generator can be adjusted according to ad-hoc assumptions or estimates of local climatic change as e.g. statistically downscaled from a GCM (cf. WILKS 1992, KATZ 1996). However, a problem occurs because stochastic models generally simulate the variability of weather and climate correctly only within a restricted frequency range. For example, though weather generators which have been fitted to daily data produce generally realistic daily weather sequences, they tend to underestimate the year-to-year variability of monthly to annually averaged weather variables (e.g., GREGORY et al. 1993, MEARNS et al. 1996). One possible solution is to use a separate stochastic model for each time scale of interest (GYALISTRAS et al. 1997). To ensure consistency among temporal aggregation levels, the data produced at a coarser (e.g., monthly) temporal resolution can then be used as inputs for the simulation at the next higher (e.g., daily) resolution (GYALISTRAS et al. 1997, cf. WILKS 1989, KATZ & PARLANGE 1996).

These considerations lead us to the formulation of the following procedure for scenario construction:

- (1) Describe weather at the location(s) of interest as a stochastic process.
- (2) Estimate the process/climatic parameters for present climate from measurements. If no measurements are available, use a spatial interpolation procedure to estimate the parameters from nearby climatological stations.
- (3) Apply statistical downscaling to the output of a climate model to estimate time-dependent changes in selected climatic parameters.
- (4) Use the results from downscaling to adjust the parameters of the stochastic process and generate weather sequences by means of stochastic simulation.

The construction of scenarios by means of this procedure is illustrated in Fig. 1. In a first step, the large-scale weather patterns (Fig. 1a) as simulated by a global (or regional) climate model under a given global forcing scenario, $GHG_{(t)}$, are fed into a statistical downscaling procedure. The weather data downscaled at a particular location (jagged curve in Fig. 1c) are then used to estimate for all climatic parameters κ of interest (such as the expected value of a given weather variable, or the cross-correlation coefficient of two weather variables) a response function $\kappa_{(t)} = f(GHG_{(t)})$ (see also Eqs. 4.1 – 4.5 later). For example, the smooth rising curve in Fig. 1c shows the response of the expected value of July mean temperature at the inner-Alpine location of Bever, as estimated from a “Business-as-Usual” simulation (CUBASCH et al. 1995) with the ECHAM1/LSG-GCM. The response function f can further be used to estimate possible behaviours $\kappa_{(t)}$ conditional on arbitrary transient scenarios $GHG_{(t)}$ (e.g., “Stabilization” case in Fig. 1c). The obtained $\kappa_{(t)}$ can be post-processed in two ways:

Firstly, the values obtained for a given future time window (e.g., around the timepoint of CO_2 -doubling) at several locations (Fig. 1b) can be interpolated in space to produce spatially extended scenarios (Fig. 1d). Secondly, the $\kappa_{(t)}$ can be used as inputs to a stochastic weather generator (respectively a chain of weather generators, see next section) to simulate possible local weather sequences under the respectively hypothesized climate for a given future timepoint t (Fig. 1e). If no measurements are available at the location of interest, the $\kappa_{(t)}$ and all other parameters needed for the stochastic simulation of weather must be interpolated from nearby climatological stations (dashed arrow in Fig. 1).

3.3. Implementation

To describe local weather we use three stochastic models which operate at a monthly, daily, and hourly temporal resolution, respectively.

The simulation of monthly weather is based upon a first-order, cyclostationary (HASSELMANN & BARNETT 1981, GARDNER 1994) autoregressive process with a period length of 12 months:

$$\underline{X}_{(k)} = \mathbf{A}_{(m)} \underline{X}_{(k-1)} + \mathbf{B}_{(m)} \underline{\varepsilon}_{1(k)} \tag{1.1}$$

$$\underline{M}_{(k)} = \underline{\sigma}'_{(m)} f(\underline{\phi}_{(m)}, \underline{X}_{(k)}) + \underline{\mu}_{(m)} \tag{1.2}$$

Here $\underline{X}_{(k)}$ is a N_x -dimensional state vector of standardized (zero mean, unit variance) monthly weather variables (e.g., monthly mean temperature and precipitation); k denotes the current time (time step = 1 month); $\mathbf{A}_{(m)}$ and $\mathbf{B}_{(m)}$ are $N_x \times N_x$ system and input matrices, respectively; m is the phase within the year, i.e., $m = \{(k-1) \text{ MOD } 12\}$,

where $m=0$ corresponds to January and $p=11$ to December; $\underline{\varepsilon}_1$ is an input vector of independent random components from a N_x -dimensional normal distribution $N(0,1)$; $\underline{M}_{(k)}$ is a N_x -dimensional output vector of monthly weather variables M_i ; $\underline{\mu}_{(m)}$ and $\underline{\sigma}_{(m)}$ are the monthly variables’ expected values and *interannual* standard deviations, respectively; and f is a functions vector with parameters $\underline{\phi}_{(m)}$. The functions $f_{i(m)}$ are given for positively ($\phi_{i1(m)} = 1$) or negatively ($\phi_{i1(m)} = -1$) skewed variables as $\phi_{i1(m)} \cdot \text{Exp}((\phi_{i2(m)} X_{i(k)} + \phi_{i3(m)}) + \phi_{i4(m)})$, otherwise as $f_{i(m)} \sim X_{i(k)}$. Details, and the procedures used to estimate all parameters can be found in GYALISTRAS (1997).

The simulation of daily weather is based upon an extended version of the model proposed by RICHARDSON (1981). The extended model simulates daily weather variables D_i (such as daily precipitation, daily minimum and maximum temperature, or the daily global radiation total) conditional on a monthly input vector $\underline{M}_{(k)} = (\pi_{(k)}, \text{prcp}_{(k)}, \mu_{1(k)}, \text{sig}_{1(k)}, \mu_{2(k)}, \text{sig}_{2(k)}, \dots, \mu_{N_y(k)}, \text{sig}_{N_y(k)})'$, where $\pi_{(k)}$ is the monthly probability for a wet day, $\text{prcp}_{(k)}$ is the monthly precipitation total, and $\mu_{i(k)}$ and $\text{sig}_{i(k)}$ ($i=1 \dots N_y$) are the means and *within-month* standard deviations of the D_i . The model is given by the following equations:

$$Q_{(d)} = \text{Markov}\{Q_{(d-1)}, P_{01(\underline{\alpha}_{(m)}, \pi_{(k)}), P_{11(\underline{\beta}_{(m)}, \pi_{(k)})}\} \tag{2.1}$$

$$P_{(d)} = \begin{cases} 0, & \text{if } Q_{(d)}=0 \\ \text{Exp}(\theta_{(\pi_{(k)}, \text{prcp}_{(k)}, m)}), & \text{if } Q_{(d)}=1 \end{cases} \tag{2.2}$$

$$\underline{Y}_{(d)} = \mathbf{F}_{(m)} \underline{Y}_{(d-1)} + \mathbf{G}_{(m)} \underline{\varepsilon}_{2(d)} \tag{2.3}$$

$$\underline{D}_{(d)} = \begin{cases} \underline{\sigma}'_{0(d)} f_0(\underline{\psi}_{0(m)}, \underline{Y}_{(d)}) + \underline{\mu}_{0(d)}, & \text{if } Q_{(d)}=0 \\ \underline{\sigma}'_{1(d)} f_1(\underline{\psi}_{1(m)}, \underline{Y}_{(d)}) + \underline{\mu}_{1(d)}, & \text{if } Q_{(d)}=1 \end{cases} \tag{2.4}$$

$$\underline{\mu}_{q(d,.)} = f_{\mu q}(d, \underline{\xi}_{q(m)}, \underline{\mu}_{(k-1)}, \underline{\mu}_{(k)}, \underline{\mu}_{(k+1)}, \pi_{(k)}) \tag{2.5}$$

$$\underline{\sigma}_{q(d,.)} = f_{\sigma q}(\underline{\zeta}_{q(m)}, \underline{\text{sig}}_{(k)}, \underline{\mu}_{(k)}, \pi_{(k)}) \tag{2.6}$$

Here $Q_{(d)}$ is the daily precipitation state ($Q=0$ if no precipitation, otherwise $Q=1$); d denotes the current time (time step = 1 day); k and m are defined as in Eqs. 1.1 and 1.2; *Markov* denotes a first-order, two-state Markov process with state variable $Q_{(d)}$ and transition probabilities $p_{01(\cdot)}$ and $p_{11(\cdot)}$; $\underline{\alpha}_{(m)}$ and $\underline{\beta}_{(m)}$ are parameter vectors; $P_{(d)}$ is the daily total precipitation; $\text{Exp}(\theta_{(\cdot)})$ denotes a variate from an exponential distribution with mean $\theta_{(.)} = \text{prcp}_{(k)} / (\pi_{(k)} \text{NDays}_{(m)})$, where $\text{NDays}_{(m)}$ is the number of days in month m ; $\underline{Y}_{(d)}$ is a N_y -dimensional state vector of standardized (zero mean, unit variance) daily weather variables; $\mathbf{F}_{(m)}$, $\mathbf{G}_{(m)}$ and $\underline{\varepsilon}_2$ are defined similarly as their counterparts in Eq. 1.1; $\underline{D}_{(d)}$ is a N_y -dimensional output vector of daily weather variables D_i ; $\underline{\mu}_{q(d,.)}$ and $\underline{\sigma}_{q(d,.)}$ are the daily variables’ expected values and within-month standard deviations for dry ($q=0$), respectively wet ($q=1$) days; $f_{\mu q}$ and $f_{\sigma q}$ are functions vectors with para-

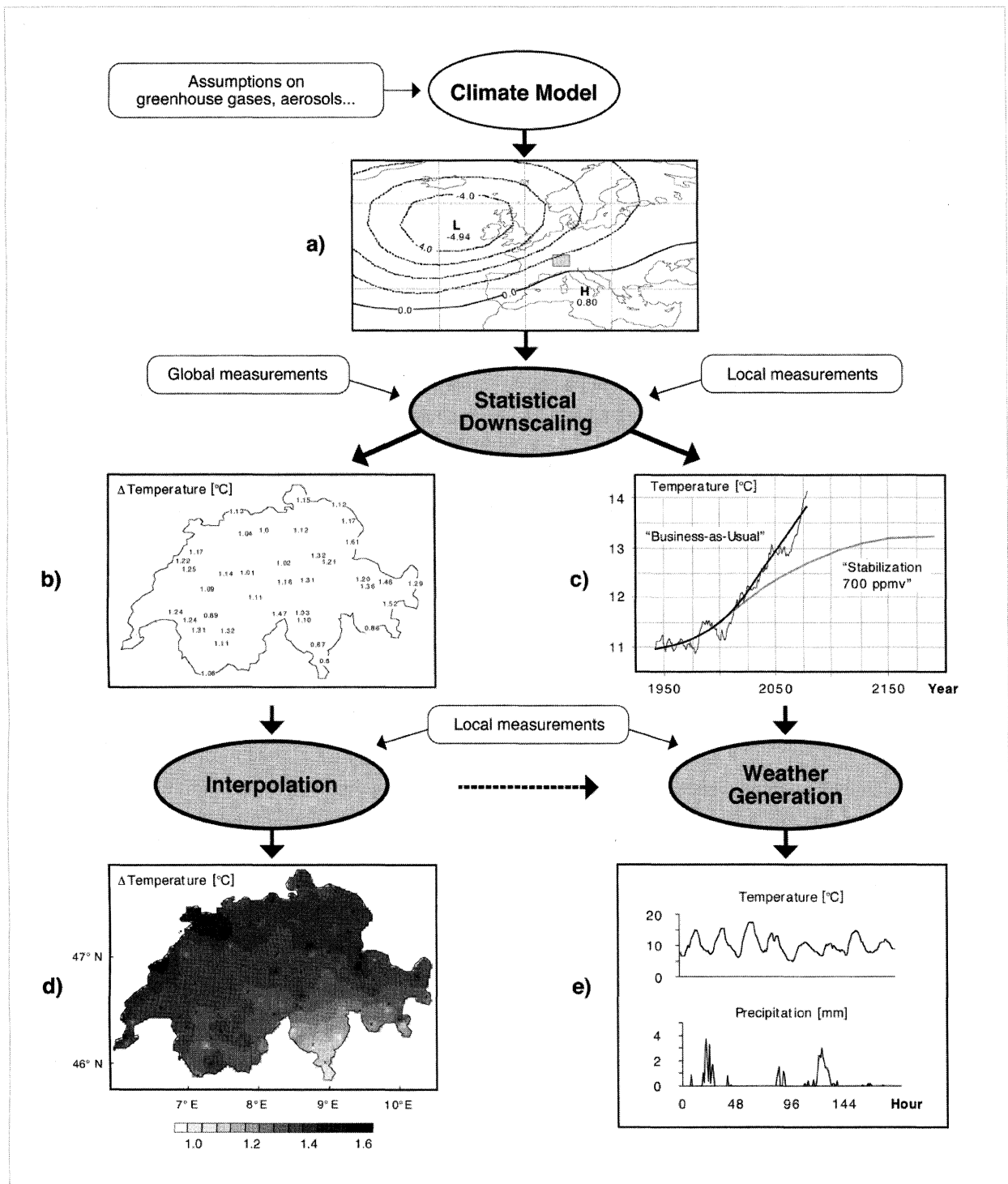


Fig. 1 Overview of the proposed procedure to construct regional climatic scenarios. Ovals: models; round-edged rectangles: input data and assumptions; arrows: flow of information

meter vectors $\xi_{q(m)}$ and $\zeta_{q(m)}$ ($q=0$ or 1); and $\underline{mu}_{(k)}$ and $\underline{sig}_{(k)}$ denote sub-vectors of the monthly input vector $\underline{M}_{(k)}$. A more detailed description of the functions $p_{01(i)}$, $p_{11(i)}$, $f_{\mu q}$ and $f_{\sigma q}$ which are used to adjust the weather

generator's parameters conditional on $\underline{M}_{(k)}$ can be found in GYALISTRAS et al. (1997; see also KATZ 1996). The \underline{f}_0 and \underline{f}_1 are functions vectors with parameter vectors $\underline{\psi}_{0(m)}$ and $\underline{\psi}_{1(m)}$, respectively. These functions serve

the simulation of skewed distributions and are determined similarly as the f in Eq. 1.2.

To describe weather at a hourly resolution we use again a first-order, two-state Markov process for precipitation, however in combination with a first-order, cyclostationary process (period length = 24 hr) for all other meteorological variables. The following hourly weather variables are simulated: hourly total precipitation, and hourly mean temperature, global radiation, vapour pressure, and wind speed. The hourly data are generated conditional on the daily precipitation amount, the daily global radiation total, and the daily mean, minimum and maximum temperature, vapour pressure, and wind speed. A complete description of the daily and hourly weather generators, and the procedures used for parameter estimation can be found in GYALISTRAS et al. (1997) and GYALISTRAS & FISCHLIN (manuscript in preparation).

Spatial interpolation is realized as follows:

$$\kappa_{(t)} = f_{(\omega_{(t)}, H_{(t)})} + \sum_{j=1}^{n_s} w_j \eta_j \tag{3.1}$$

$$\eta_j = \kappa_j - f_{(\omega_{(t=r_j)}, H_{(t=r_j)})} \tag{3.2}$$

Here $\kappa_{(t)}$ is the climatic parameter of interest (such as an $\mu_{i(m)}$ or $\sigma_{i(m)}$, Eq. 1.2) at location r ; f is a function with parameter vector $\omega_{(t)}$ describing the dependence of $\kappa_{(t)}$ on a vector of orographic parameters $H_{(t)}$ (such as elevation, slope, aspect etc.; e.g., BENICHOUE & LE BRETON 1987, DALY et al. 1994); n_s is the number of climatological stations used for interpolation; w_j is the weight attributed to the j -th station; κ_j is the value of κ at this station; and η_j is its residual from f . In the current implementation (GYALISTRAS & FISCHLIN 1995, FISCHLIN & GYALISTRAS 1997) we use for f a linear, or piecewise linear (e.g. for temperature, breakpoint at 1500 m), function of elevation, $H_{(t)}$, and the weights w_j are inversely proportional to the distances of the used stations from the interpolation location r .

Downscaling is performed at a monthly time step based on the procedure proposed by VON STORCH et al. (1993) as follows:

$$M_{i(m, t)} = \mu_{i(m)} + \sum_{j=1}^{n_p} P'_{ij(m)} (L_{(m, t)} - L_{0(m)}) \tag{4.1}$$

where $M_{i(m, t)}$ is the downscaled value for the i -th local monthly weather variable at phase m and year t ; $\mu_{i(m)}$ is its present-day expected value (Eq. 1.2); the $P'_{ij(m)}$ are parameter vectors estimated from simultaneous local and large-scale monthly measurements by means of Canonical Correlation Analysis (BARNETT & PREISENDOFFER 1987); $L_{(m, t)}$ is a vector of gridded, large-scale at-

mospheric fields (e.g., monthly mean sea-level pressure and near-surface temperature; GYALISTRAS et al. 1994) as simulated in a scenario run with a climate model for year t ; and $L_{0(m)}$ denotes the long-term mean state simulated by the same model under present ("1 x CO₂") boundary conditions. Note that the vector $M_{(k)}$ used for downscaling can be flexibly defined (e.g., VON STORCH 1995, BÜRGER 1996, ENKE & SPEKAT 1997, ZORITA & VON STORCH 1997), and may in particular include (GYALISTRAS et al. 1994, 1997) variables describing the day-to-day variability of weather, such as the monthly probability for precipitation, $\pi_{(k)}$, or the within-month standard deviations $\text{sig}_{i(k)}$ of the daily variables D_i (cf. Eqs. 2).

In a further step the downscaled variables are used to infer time-dependent scenarios for all climatic parameters of interest. The identification of an appropriate set of such parameters for a given application can be based on sensitivity studies with impact models (e.g., NONHEBEL 1994, GYALISTRAS 1997, GYALISTRAS et al. 1997). Note that the proposed chain of weather generators (Eqs. 1, 2) is particularly suitable to this purpose, since it can be used to test in as far an impact model can be driven with monthly rather than daily (or hourly) weather data as an input. Experiments with the grassland model by RIEDO et al. (1998) and a simplified version of the snow-cover model by ROHRER & BRAUN (1994), which both depend on hourly weather inputs, showed that monthly input data were actually sufficient to estimate at good accuracy system responses of interest such as the annual grass yield (GYALISTRAS et al. 1997) or the annual number of days with snowheights exceeding a given threshold (results unpublished). Therefore, here we discuss the estimation of changes in parameters related to the simulation of monthly weather only (Eqs. 1). Though in principle a different estimation procedure is needed for each type of parameter, a general approach can be outlined:

First, an initial estimate for each climatic parameter κ and timepoint t of interest is computed based on data from a time window $[t-b \dots t+b]$, where $b \approx 10$ years. For example, to obtain an initial estimate $m_{i(m, t)}$ for the expected value $\mu_{i(m, t)}$ of the monthly weather variable M_i at phase m (cf. Eqs. 1) we use:

$$m_{i(m, t)} = \frac{1}{(2b+1)} + \sum_{\tau=t-b}^{t+b} M_{i(m, \tau)} \tag{4.2}$$

To obtain an initial estimate $s_{i(m, t)}$ for the transient behaviour of an interannual standard deviation $\sigma_{i(m, t)}$ we start from the equation:

$$\sigma^2_{i(m, t)} = \sigma^2_{L_{i(m, t)}} + \sigma^2_{\sigma_{i(m)}} \tag{4.3}$$

where $\sigma^2_{L_{i(m, t)}}$ is the variance of the local weather variable M_i at phase m caused by the year-to-year variability

of the large-scale weather ($L_{(m,t)}$), and $\sigma_{\alpha_{i(m)}}$ is the variance due to all remaining processes not explicitly considered in Eq. 4.1 (cf. ZORITA & VON STORCH 1997). Note that Eq. 4.3 assumes as a first approximation that the large-scale process is statistically independent from all other processes contributing to the variability of the local variable $M_{i(m,t)}$. The estimate $s_{i(m,t)}$ is then obtained using linearly detrended data in $[t-b \dots t+b]$ according to:

$$s_{i(m,t)} = \text{Sqrt} \left\{ \left(\frac{1}{2b} \sum_{\tau=t-b}^{t+b} [M_{i(m,\tau)} - (a_{i(m,t)}\tau + b_{i(m,t)})]^2 + s_{\alpha_{i(m)}}^2 \right) \right\} \quad (4.4)$$

Here, $a_{i(m,t)}$ and $b_{i(m,t)}$ are the parameters of the linear regression line through the data points $M_{i(m,\tau)}$, and $s_{\alpha_{i(m)}}^2$ is the estimated value for $\sigma_{\alpha_{i(m)}}^2$, which is given by the variance of the residuals of the regression equation Eq. 4.1. This variance is assumed to remain constant under a changing climate.

Finally, the actual climate change signal is extracted by fitting to the $m_{i(m,t)}$ or $s_{i(m,t)}$ the response function

$$\kappa_{i(m,t)} = \lambda_{i(m)} \text{Ln}(\text{GHG}_{(t-\tau)}/\text{GHG}_0) + \alpha_{i(m)} \kappa_{i(m,t-\tau)} \quad (4.5)$$

where $\kappa_{i(m,t)}$ denotes the estimated value for $\kappa_{i(m)}$ ($= \mu_{i(m)}$, $\sigma_{i(m)}$, or possibly some other parameter) at timepoint t ; $\tau \approx 20$ years (e.g., TOL & DE VOS 1993); $\lambda_{i(m)}$ and $\alpha_{i(m)}$ are fitted parameters; GHG_0 is the greenhouse-gas concentration assumed in the "1xCO₂" run of the climate model used for downscaling; and $\text{GHG}_{(t)}$ is the transient forcing scenario assumed in the climate change experiment with this model. Eq. 4.3 can be utilized to estimate time-dependent scenarios $\kappa_{i(m,t)}$ under in principle arbitrary scenarios for $\text{GHG}_{(t)}$.

4. Discussion

Similar methods to construct climatic scenarios to the one proposed here have been suggested by WILKS (1992), OELSCHLAGEL (1995), and BARROW et al. (1996). Our method presents however an extension of this work in several respects: Firstly, the above-mentioned studies have focused on the construction of scenarios only with a daily temporal resolution, whereas we considered the simultaneous simulation of weather at a monthly, daily and hourly time step. Secondly, in these earlier studies climatic scenarios were derived based only upon general indications from climate models (WILKS 1992), or information from single model grid-points (OELSCHLAGEL 1995, BARROW et al. 1996), whereas our downscaling procedure relied upon large-scale atmospheric fields (Eq. 4.1); thirdly, unlike the procedures proposed by WILKS (1992) and BARROW et al. (1996), our

method supported the construction of spatially extended scenarios (Eqs. 3); and finally, our method included a strategy for scenario construction under in principle arbitrary scenarios for future greenhouse-gas concentrations (Eq. 4.5).

The feasibility of the proposed method has been demonstrated in three case studies which required scenarios of local weather respectively at a monthly (FISCHLIN & GYALISTRAS 1997), daily (STADLER et al. 1997), and hourly (RIEDO et al. 1999) temporal resolution. These studies pursued their own research goals, so that they were considered to represent realistic research situations. Moreover, their input needs were typical also for other studies. For instance, the forest succession model FORCLIM (BUGMANN 1994, FISCHLIN et al. 1995) used in the study by FISCHLIN & GYALISTRAS (1997) required 200 realizations of monthly mean temperature and precipitation over several centuries, and at a spatial resolution of ~ 100 m. These needs were representative for a whole family of models, including JABOWA (BOTKIN & NISBET 1992), FORSKA (PRENTICE et al. 1993), or PnET-II (ABER et al. 1995). Our method has also been used to derive first, spatially extended scenarios (Fig. 1d; see also GYALISTRAS & FISCHLIN 1995). The application of these scenarios to impact models that require maps of climatic parameters as inputs (e.g., KIENAST et al. 1996) should be straight-forward.

The physical consistency of the scenarios obtained with our method cannot strictly be proven. On the one hand, the outcome of statistical downscaling strongly depends on the quality of the inputs provided by the driving GCM (MATYASOVSKY & BOGARDI 1994, GYALISTRAS et al. 1994, BÜRGER 1996). On the other hand, one or several of the statistical models (Eqs. 1.1 – 4.3) used by our method might no more hold under a changed climate. Nevertheless, there are several reasons why we believe that our approach can generally provide valid first-order approximations of possible future climates and associated weather sequences:

Firstly, statistical downscaling according to Eq. 4.1 has been demonstrated in several studies to yield physically generally plausible (VON STORCH et al. 1993, GYALISTRAS et al. 1994, BUSUIOC et al. 1999), and spatially (e.g., FISCHLIN & GYALISTRAS 1997), as well as between different weather variables consistent (GYALISTRAS et al. 1994, 1997) estimates of possible regional to local climatic changes. Secondly, the proposed weather generators (Eqs. 1.1 – 2.6) were found to reproduce measured distributions of monthly to hourly weather variables as derived from independent data for different subperiods of this century with reasonable accuracy (GYALISTRAS 1997, GYALISTRAS et al. 1997). Thirdly, extensive testing of the spatial interpolation procedure (Eqs. 3) showed that if a few years of measurements are available at the location of interest, the climatic parameters needed to simulate monthly weather for a demanding application

(forest modelling) can be estimated at sufficient accuracy (GYALISTRAS & FISCHLIN 1996). Moreover, it was found that long-term changes in climatic parameters can be generally interpolated at very good accuracy at any location of interest, even in a topographically complex region such as the European Alps (GYALISTRAS & FISCHLIN 1996; see also correlation analyses by BENISTON et al. 1994). Finally, the postulated relationships (Eq. 4.5) between global forcings and regional climate responses remain to be tested, but at least there are some indications (JONAS et al. 1996; see also the stability of large-scale patterns of climatic change reported by CUBASCH et al. 1994) that they present defensible approximations.

An advantage of our procedure is that it matches the limited precision of GCMs. This was accomplished by using the GCM-simulated weather data to estimate changes but in long-term climatic parameters (Eqs. 4.2 – 4.5), by removing model biases *prior* to downscaling (Eq. 4.1), and by using only the first few principal components (PREISENDORFER 1988) for downscaling of monthly averaged fields. This enabled us to construct plausible scenarios (GYALISTRAS et al. 1994) in cases where errors of the driving GCM were directly propagated into, and possibly even amplified, by a high-resolution climate model (ROTACH et al. 1997). This, however, does not defy the use of regional climate models in principle; it only demonstrates that it is easier to obtain plausible scenarios with the proposed method. Accordingly, our scenarios may have to be revised as improved high-resolution simulations become available.

Additional factors which contributed to increasing the robustness of the derived scenarios were the applicability of statistical downscaling to long-term GCM-simulations (GYALISTRAS et al. 1994), which allowed to enhance the signal-to-noise ratio of the downscaled climatic change signal (Eq. 4.5); the use of principal component analysis (PREISENDORFER 1988) which allowed to reduce the degrees of freedom in the data used to fit the downscaling models; and the application of a robust procedure (HASSELMANN & BARNETT 1981) to estimate the system matrices of the monthly (Eq. 1.1) and hourly weather generators. The robustness of our method could nevertheless be further increased by using improved parameter estimation procedures, for instance by estimating the parameters of the monthly downscaling models (Eq. 4.1) not separately for each month, but in a sub-space spanned by the first few Fourier-harmonics of the annual cycle.

The proposed method was found to be economic and efficient in several respects. Firstly, the adopted "top-down" design (Fig. 1) made it possible to restrict the construction of scenarios to the variables, locations, and time scales precisely needed in each case study. Secondly, our approach was found to have only medium data requirements: the construction of reasonably accurate stochastic models to simulate monthly weather

(Eq. 1) required only 30 yr of local measurements (GYALISTRAS 1997), whereas for the simulation of daily (Eqs. 2) or hourly weather conditional on monthly inputs already 5 yr of data proved sufficient (GYALISTRAS et al. 1997). More stringent data requirements apply for statistical downscaling, which should preferably be based on several decades of data (VON STORCH et al. 1993, WILBY 1994). However, these data needs are still modest compared to the needs of regional climate simulations, which require large-scale forcing fields at a time step of ~10 min or less. Finally, our approach was also found to be computationally efficient. For example, downscaling of 100 years of global climate model output to a particular location (Fig. 1c) took only ~1 min on a modern workstation; the stochastic simulation of monthly weather sequences required only an additional ~1/2 min per 10,000 years per location; and the simulation of daily and hourly weather took only ~5 min per 100 years each. In contrast, simulations with, e.g., the NCAR second generation regional climate model at a resolution of 60 km per simulated year would have required 60 hr of CPU time on a Cray Y-MP (GIORGI 1996).

The obtained scenarios were, however, subject to several limitations: they were partially based on weak statistical relationships between the large-scale and local weather (e.g., in the case of summertime precipitation; see also BÜRGER 1996, ENKE & SPEKAT 1997), depended strongly on the choice of large-scale predictors and partially presented extrapolations beyond present conditions (GYALISTRAS et al. 1994), or were in some instances possibly contaminated by inhomogeneities in the local measurements (e.g., for wind speeds) used to fit the downscaling models (GYALISTRAS et al. 1997). A further problem was that downscaling was applied to infer possible changes but in a subset of the several climatic parameters (Eqs. 1 – 2) actually used to describe the local weather. Though these adjustments were done in a manner that ensured statistical consistency across climatic parameters (KATZ 1996, GYALISTRAS et al. 1997), the physical consistency of the simulated weather sequences remains debatable.

However, all components of our method can be relatively easily tested. This contrasts with the use of regional climate models, which not only depend on the availability of sufficiently accurate forcing fields and boundary conditions (e.g., for land-surface characteristics), but also of regional climatologies (e.g., FREI & SCHÄR 1998) against which model behaviours can be compared. In particular, with our method it was possible if not to reduce, so at least to quantify the uncertainties related for instance to spatial interpolation (GYALISTRAS & FISCHLIN 1996; see also PHILLIPS et al. 1992, DALY et al. 1994) or downscaling (GYALISTRAS & FISCHLIN 1995; see also CARBONE & BRAMANTE 1996). The proposed approach also proved generally suitable for extensive sensitivity studies to explore the range of likely scenar-

ios with impact models (FISCHLIN & GYALISTRAS 1997, STADLER et al. 1997, RIEDO et al. 1999).

Finally, some more general restrictions of our method should be mentioned: Firstly, the decadal-scale variability of climate is not simulated at present (cf. Eq. 4.5). A possible improvement could consist in using an additional stochastic model to prescribe slow variations in selected parameters (Eq. 1.2) of the monthly weather generator. The parameters of this model could be fitted to long-term time series of regional weather variables as reconstructed from proxy data (e.g. PFISTER 1992), or statistically downscaled from a long-term simulation (STOUFFER et al. 1994, VON STORCH et al. 1997) with a coupled oceanic-atmospheric climate model. Secondly, our method does not account for possible systematic changes in smaller-scale climate forcings (e.g., land use) or feedbacks to the regional climate system (e.g., due to changes in vegetation cover). However, indications from simulation studies addressing these issues (e.g., GIORGI 1996) could easily be included by adjusting the corresponding parameters used for weather generation. Thirdly, our method does not yet support applications which require both, spatially extended scenarios *and* a high temporal resolution, such as hydrological studies. A possible solution would be to extend the state vectors of the weather generators (Eqs. 1, 2) to consider weather variables from several locations simultaneously (cf. BARDOSSY & PLATE 1992, HUGHES & GUTTORP 1994). Finally, the estimation of the regional climate response according to Eq. 4.5 could be extended to account for more than one global forcing, for instance by considering in addition to greenhouse gases also possible emission paths for aerosols. At present, however, little is known on how the effects of different forcings combine at the regional scale. Quantitative estimates could be obtained by applying statistical downscaling to a set of global simulations that consider the different forcings individually and combination (e.g., MITCHELL & JOHNS 1997).

5. Conclusions

Our analysis of scenario requirements (Section 3.1) and methods to construct climatic scenarios (Section 3.2) suggests that present-day climate models alone can not satisfy the scenario needs of model-based impacts assessments. However, by combining the output of global or regional climate models with large-scale and local measurements, as well as a series of statistical techniques (Fig. 1, Section 3.3), it was possible to derive a method which appears to be general and flexible enough to meet the requirements of a wider range of impact studies.

The proposed method provides spatially and temporally extensive scenarios at the needed, high spatial and – at individual locations only – temporal resolution.

Moreover, it allows linkage from assumptions on future emissions of greenhouse-gases through global and regional climatic scenarios to impact models, and thus enables consistent, reproducible impacts assessments.

The derived scenarios appear generally plausible. However, their physical consistency can of course not be rigorously proven, and depends among other things on the reliability of the used climate models, the climatic parameters considered, and the complexity of the terrain. Nevertheless, the obtained, quantitative information is certainly useful for impact studies in the sense of exploratory scenario investigation.

The precision of the derived scenarios is difficult to judge. Depending on the application considered, the availability of a few years of regional measurements can be crucial to enable a sufficiently accurate description of present-day climate as a basis for scenario construction. Otherwise, our method provides generally realistic weather sequences which satisfy the precision requirements of three demanding case studies. The accuracy of our procedure under hypothetical future climatic conditions could be further assessed by comparing its results with those from regional climate simulations.

The robustness of our procedure is also only partially understood. However, the used downscaling approach appears insensitive to the peculiarities of individual climate models, and the proposed strategy for the stochastic simulation of monthly to hourly weather proved to be robust with regard to the choice of the data used for parameter estimation. Improved statistical models or parameter estimation procedures for the individual components of our method can easily be incorporated as soon as they become available.

Finally, it should be noted that the method proposed here provides a concise description of regional climates. Moreover, it can contribute to reducing the input requirements of impacts models and is computationally efficient. This makes it suitable for extensive sensitivity analyses which are central to a vast range of climate change impact studies.

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7. References

- ABER, J. D., OLLINGER, S. V., FEDERER, C. A., REICH, P. B., GOULDEN, M. L., KICKLIGHTER, D. W., MELILLO, J. M., & R. G. LATHROP (1995): Predicting the effects of climate change on water yield and forest production in the northeastern United States. *Clim. Res.*, **5**: 207 – 222.

- ALCAMO, J., BORN, G. J. VAN DEN, BOUWMAN, A. F., HAAN, B. J. DE, GOLDEWIJK, K. K., KLEPPER, O., KRABEC, J., LEEMANS, R., OLIVIER, J. G. J., TOET, A. M. C., VRIES, H. J. M. DE, & H. J. VAN DER WOERD (1994): Modeling the global society-biosphere-climate system. Part 2: computed scenarios. *Water Air Soil Pollut.*, **76**: 37 – 78.
- BACH, W., JUNG, H. J., & H. KNOTTENBERG (1985): Modeling the influence of carbon dioxide on the global and regional climate: methodology and results. Paderborn, 114 pp. = Münstersche geographische Arbeiten, **21**.
- BARDOSSY, A., & E. J. PLATE (1992): Space-time model for daily rainfall using atmospheric circulation patterns. *Water Resour. Res.*, **28**: 1247 – 1259.
- BARNETT, T., & R. PREISENDORFER (1987): Origins and levels of monthly and seasonal forecast skills for the United States surface air temperatures determined by canonical correlation analysis. *Mon. Wea. Rev.*, **115**: 1825 – 1850.
- BARROW, E., HULME, M., & M. SEMENOV (1996): Effect of using different methods in the construction of climate change scenarios: examples from Europe. *Climate Research*, **7**: 195 – 211.
- BENICHO, P., & O. LE BRETON (1987): Prise en compte de la topographie pour la cartographie des champs pluviométriques statistiques. *La Météorologie*, **7**: 23 – 34.
- BENISTON, M., OHMURA, A., ROTACH, M., TSCHUCK, P., WILD, M., & R. M. MARINUCCI (1995): Simulation of climate trends over the alpine region – Development of a physically-based modeling system for application to regional studies of current and future climate. Internal Report, Department of Geography, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland, 198 pp.
- BENISTON, M., REBETZ, M., GIORGI, F., & M. R. MARINUCCI (1994): An analysis of regional climate change in Switzerland. *Theor. Appl. Climatol.*, **49**: 135 – 159.
- BOTKIN, D. B., & R. A. NISBET (1992): Forest response to climatic change: effects of parameter estimation and choice of weather patterns on the reliability of projections. *Clim. Change*, **20**: 87 – 111.
- BROWN, B. G., & R. W. KATZ (1995): Regional analysis of temperature extremes: spatial analogue for climate change? *J. Clim.*, **8**: 108 – 119.
- BRZEZIECKI, B., KIENAST, F., & O. WILDI (1993): A simulated map of the potential natural forest vegetation of Switzerland. *J. Veg. Sci.*, **4**: 499 – 508.
- BUGMANN, H. (1994): On the ecology of mountainous forests in a changing climate: a simulation study. Diss. ETH No. 10638, Swiss Federal Institute of Technology, Zürich, Switzerland, 258 pp.
- BÜRGER, G. (1996): Expanded downscaling for generating local weather scenarios. *Clim. Res.*, **7**: 111 – 128.
- BUSUIOC, A., STORCH, H. VON, & R. SCHNUR (1999): Verification of GCM generated regional precipitation and of statistical downscaling estimates. *J. Clim.*, **12**: 258 – 272.
- CARBONE, G. J., & P. D. BRAMANTE (1996): Translating monthly temperature from regional to local scale in the south-eastern United States. *Clim. Res.*, **5**: 229 – 242.
- CARTER, T. R., PARRY, M. L., HARASAWA, H., & S. NISHIOKA (1994): IPCC technical guidelines for assessing climate change impacts and adaptations. Dep. of Geography, Univ. College London & National Institute for Environmental Studies, Japan, London, Tsukuba, 59 pp.
- CUBASCH, U., HEGERL, C. G., HELLBACH, A., HÖCK, H., MIKOLAJEWICZ, U., SANTER, B. D., & R. VOSS (1995): A climate change simulation starting from 1935. *Clim. Dyn.*, **11**: 71 – 84.
- CUBASCH, U., SANTER, B. D., HELLBACH, A., HEGERL, G., HÖCK, H., MAIER-REIMER, E., MIKOLAJEWICZ, U., STÖSSEL, A., & R. VOSS (1994): Monte-carlo climate forecasts with a global coupled ocean-atmosphere model. *Clim. Dyn.*, **10**: 1 – 19.
- CUBASCH, U., STORCH, H. VON, WASZKEWITZ, J., & E. ZORITA (1996): Estimates of climate change in Southern Europe derived from dynamical climate model output. *Clim. Res.*, **7**: 129 – 149.
- DALY, C., NEILSON, R. P., & D. L. PHILLIPS (1994): A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology*, **33**: 140 – 158.
- ENKE, W., & A. SPEKAT (1997): Downscaling climate model outputs into local and regional weather elements by classification and regression. *Clim. Res.*, **8**: 195 – 207.
- FISCHLIN, A., BUGMANN, H., & D. GYALISTRAS (1995): Sensitivity of a forest ecosystem model to climate parametrization schemes. *Environ. Pollut.*, **87**: 267 – 282.
- FISCHLIN, A., & D. GYALISTRAS (1997): Assessing impacts of climatic change on forests in the Alps. *Global Ecol. Biogeogr. Lett.*, **6**: 19 – 37.
- FLOHN, H. (1979): Can climate history repeat itself? Possible climatic warming and the case of paleoclimatic warm phases. In: BACH, W., PANKRATH, Y., & W. W. KELLOGG [Eds.]: *Man's Impact on Climate*. New York, 15 – 28.
- FREI, C., & C. SCHAR (1998): A precipitation climatology of the Alps from high-resolution rain-gauge observations. *J. Clim.*, **11**: 873 – 900.
- GARDNER, W. A. [Ed.] (1994): *Cyclostationarity in communications and signal processing*. IEEE, New York, 493 pp.
- GATES, W. L., HENDERSON-SELLERS, A., BOER, G. J., FOLLAND, C. K., KITOH, A., MCAVANEY, B. J., SEMAZZI, F., SMITH, N., WEAVER, A. J., & Q.-C. ZENG (1996): Climate models – evaluation. In: HOUGHTON, J. T., MEIRA FILHO, L. G., CALLANDER, B. A., HARRIS, N., KATTENBERG, A., & K. MASKELL [Eds.]: *Climate Change 1995: The Science of Climate Change – Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York, 228 – 284.
- GIORGI, F. (1996): Perspectives for Earth system modeling on the regional scale. In: GHAN, S. J., PENNELL, W. T., PETERSON, K. L., RYKIEL, E., SCOTT, M. J., & L. W. VAIL [Eds.]: *Regional impacts of global climate change: assessing change and response at the scales that matter*. Columbus, Ohio, 3 – 19.
- GIORGI, F., & L. O. MEARNES (1991): Approaches to the simulation of regional climate change: a review. *Rev. Geophys.*, **29**: 191 – 216.
- GREGORY, J. M., WIGLEY, T. M. L., & P. D. JONES (1993): Application of Markov models to area-average daily precipitation series and interannual variability in seasonal totals. *Clim. Dyn.*, **8**: 299 – 310.
- GROTCH, S. L., & M. C. MACCRACKEN (1991): The use of general circulation models to predict regional climate change. *J. Clim.*, **4**: 286 – 303.
- GYALISTRAS, D. (1997): Projecting scenarios of climatic change and future weather for ecosystem models: derivation of methods and their application to forests in the Alps. Diss. ETH No. 12065, Swiss Federal Institute of Technology, Zurich, Switzerland, 103 pp.
- GYALISTRAS, D., & A. FISCHLIN (1995): Downscaling: Applications to Ecosystems Modeling. In: MUIRCHARTAIGH, I. O. [Ed.]: *Proc. of the 6th International Meeting on Statistical Climatology*, Galway, Ireland, Jun. 19 – 23, 1995. University College, Galway, Ireland, 189 – 192.

- GYALISTRAS, D., & A. FISCHLIN (1996): Derivation of climate change scenarios for mountainous ecosystems: a GCM-based method and the case study of Valais, Switzerland. Swiss Federal Institute of Technology ETHZ, Zurich, Switzerland, 21 pp. = Systems Ecology Report, **22**.
- GYALISTRAS, D., & A. FISCHLIN (in preparation): Temporal downscaling – a method to reduce the climatic input requirements of impact models. To be submitted to Climate Research
- GYALISTRAS, D., FISCHLIN, A., & M. RIEDO (1997): Herleitung stündlicher Wetterszenarien unter zukünftigen Klimabedingungen. In: FUHRER, J. [Ed.]: Klimaänderung und Grünland – eine Modellstudie über die Auswirkungen zukünftiger Klimaveränderungen auf das Dauergrünland in der Schweiz. Zürich, 207 – 263.
- GYALISTRAS, D., SCHÄR, C., DAVIES, H. C., & H. WANNER (1998): Future Alpine climate. In: CEBON, P., DAHINDEN, U., DAVIES, H. C., IMBODEN, D., & C. G. JÄGER [Eds.]: Views from the Alps: regional perspectives on climate change. Cambridge, Massachusetts [a. o.], 171 – 223.
- GYALISTRAS, D., STORCH, H. VON, FISCHLIN, A., & M. BENISTON (1994): Linking GCM-simulated climatic changes to ecosystem models: case studies of statistical downscaling in the Alps. *Clim. Res.*, **4**: 167 – 189.
- HAAN, B. J. DE, JONAS, M., KLEPPER, O., KRABEC, J., KROL, M. S., & K. OLENDZYNSKI (1994): An atmosphere-ocean model for integrated assessment of global change. *Water Air Soil Pollut.*, **76**: 283 – 318.
- HASSELMANN, K., & T. P. BARNETT (1981): Techniques of linear prediction for systems with periodic statistics. *J. Atmos. Sci.*, **38**: 2275 – 2283.
- HENDERSON-SELLERS, A., & K. MCGUFFIE (1987): A climate modelling primer. Chichester, 217 pp.
- HUGHES, J. P., & P. GUTTORP (1994): A class of stochastic models for relating synoptic atmospheric patterns to regional phenomena. *Water Resour. Res.*, **30**: 1535 – 1546.
- HULME, M., BRIFFA, K. R., JONES, P. D., & C. A. SENIOR (1993): Validation of GCM control simulations using indices of daily airflow types over the British Isles. *Clim. Dynamics*, **9**: 95 – 105.
- HULME, M., WIGLEY, T. M. L., & P. D. JONES (1990): Limitations of regional climate scenarios for impact analysis. In: BOER, M. M., & R. S. DE GROOT [Eds.]: Landscape-ecological impact of climatic change. Amsterdam, 111 – 129.
- IPCC (1996): Climate Change 1995: Impacts, adaptations and mitigation of climate change: scientific-technical analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Ed. by R. T. WATSON, M. C. ZINYOWERA & R. H. MOSS. Cambridge and New York, 880 pp.
- JONAS, M., FLEISCHMANN, K., GANOPOLSKI, A. V., KRABEC, J., SAUER, U., OLENDZYNSKI, K., PETOUKHOV, V. K., & R. W. SHAW (1996): Grid point surface air temperature calculations with a fast turnaround: combining the results of IMAGE and a GCM. *Clim. Change*, **34**: 479 – 512.
- KATZ, R. W. (1996): Use of stochastic models to generate climate change scenarios. *Clim. Change*, **32**: 237 – 255.
- KATZ, R. W., & M. B. PARLANGE (1996): Mixtures of stochastic processes: application to statistical downscaling. *Clim. Res.*, **7**: 185 – 193.
- KIENAST, F., BRZEZIECKI, B., & O. WILDI (1996): Long-term adaptation potential of Central European mountain forests to climate change: a GIS-assisted sensitivity assessment. *For. Ecol. Manage.*, **80**: 133 – 153.
- KIM, J. W., CHANG, J. T., BAKER, N. L., WILKS, D. S., & W. L. GATES (1984): The statistical problem of climate inversion: determination of the relationship between local and large-scale climate. *Mon. Wea. Rev.*, **112**: 2069 – 2077.
- KIRSCHBAUM, M., & A. FISCHLIN (1996): Climate change impacts on forests. In: WATSON, R., ZINYOWERA, M. C., & R. H. MOSS [Eds.]: Climate Change 1995: Impacts, adaptations and mitigation of climate change: scientific-technical analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge [a. o.], 95 – 129.
- LAMB, P. J. (1987): On the development of regional climatic scenarios for policy-orientated climatic-impact assessment. *Bull. Amer. Met. Soc.*, **68**: 1116 – 1123.
- MACHENHAUER, B., WINDELBRAND, M., BOZET, M., & M. DEQUE (1996): Validation of present-day regional climate simulations over Europe: nested LAM and variable resolution global model simulations with observed or mixed boundary conditions. Hamburg, 60 pp. = Max-Planck-Institut für Meteorologie, Report No. **191**.
- MATYASOVSKY, I., & I. BOGARDI (1994): Comparison of two general circulation models to downscale temperature and precipitation under climate change. *Water Resour. Res.*, **30**: 3437 – 3448.
- MEARNS, L. O., ROSENZWEIG, C., & R. GOLDBERG (1996): The effect of changes in daily and interannual variability on CERES-wheat: a sensitivity study. *Clim. Change*, **32**: 257 – 292.
- MITCHELL, J. F. B., & T. C. JOHNS (1997): On modification of global warming by sulfate aerosols. *J. Clim.*, **10**: 245 – 267.
- NONHEBEL, S. (1994): Inaccuracies in weather data and their effects on crop growth simulation results – II. Water-limited production. *Clim. Res.*, **4**: 61 – 74.
- OELSCHLAGEL, B. (1995): A method for downscaling global climate model calculations by a statistical weather generator. *Ecol. Model.*, **82**: 199 – 204.
- PERRUCHOUD, D. O. (1996): Modeling the dynamics of nonliving organic carbon in a changing climate: a case study for temperate forests. Diss. ETH No. 11900, Swiss Federal Institute of Technology, Zurich, Switzerland, 196 pp.
- PERRUCHOUD, D. O., & A. FISCHLIN (1995): The response of the carbon cycle in undisturbed forest ecosystems to climate change: a review of plant-soil models. *J. Biogeogr.*, **22**: 759 – 774.
- PFISTER, C. (1992): Monthly temperature and precipitation in central Europe 1525 – 1979: quantifying documentary evidence on weather and its effects. In: BRADLEY, R. S., & P. D. JONES [Eds.]: Climate since A.D. 1500. London & New York, 118 – 142.
- PHILLIPS, D. L., DOLPH, J., & D. MARKS (1992): A comparison of geostatistical procedures for spatial analysis of precipitation in mountainous terrain. *Agric. For. Meteorol.*, **58**: 119 – 141.
- PREISENDORFER, R. W. (1988): Principal component analysis in meteorology and oceanography. Amsterdam [a. o.], 425 pp.
- PRENTICE, I. C., SYKES, M. T., & W. CRAMER (1993): A simulation model for the transient effects of climate change on forest landscapes. *Ecol. Model.*, **65**: 51 – 70.
- PRICE, D. T., & M. J. APPS (1995): The boreal forest transect case study: global change effects on ecosystem processes and carbon dynamics in boreal Canada. *Water Air Soil Pollut.*, **82**: 203 – 214.
- RICHARDSON, C. W. (1981): Stochastic simulation of daily precipitation, temperature, and solar radiation. *Water Resour. Res.*, **17**: 182 – 190.

- RIEDO, M., GRUB, A., ROSSET, M., & J. FUHRER (1998): A pasture simulation model for dry matter production, and fluxes of carbon, nitrogen, water and energy. *Ecol. Model.*, **105**: 141 – 183.
- RIEDO, M., GYALISTRAS, D., FISCHLIN, A., & J. FUHRER (1999): Using an ecosystem model linked to GCM-derived local weather scenarios to analyse effects of climate change and elevated CO₂ on dry matter production and partitioning, and water use in temperate managed grasslands. *Global Change Biol.*, **5**: 213 – 223.
- RIHA, S. J., WILKS, D. S., & P. SIMOENS (1996): Impact of temperature and precipitation variability on crop model predictions. *Clim. Change*, **32**: 293 – 311.
- ROBINSON & FINKELSTEIN (1991): The development of impact-oriented climate scenarios. *Bull. Amer. Meteorol. Soc.*, **72**: 481 – 490.
- ROBOCK, A., TURCO, R. P., HARWELL, M. A., ACKERMAN, T. P., ANDRESSEN, R., CHANG, H. S., & M. V. K. SIVAKUMAR (1993): Use of general circulation model output in the creation of climate change scenarios for impact analysis. *Clim. Change*, **23**: 293 – 335.
- ROHRER, M., & L. N. BRAUN (1994): Long-term records of snow cover water equivalent in the Swiss Alps: 2. Simulation. *Nordic Hydrol.*, **25**: 65 – 78.
- ROSENBERG, N. J., CROSSON, P. R., FREDERICK, K. D., EASTERLING, W. E., MCKENNEY, M. S., BOWES, M. D., SEDJO, R. A., DARMSTADTER, J., KATZ, L. A., & K. M. LEMON (1993): The MINK methodology: background and baseline. *Clim. Change*, **24**: 7 – 22.
- ROTACH, M. W., MARINUCCI, M. R., WILD, M., TSCHUCK, P., OHMURA, A., & M. BENISTON (1997): Nested regional simulation of climate change over the Alps for the scenario of a doubled greenhouse forcing. *Theor. Appl. Climatol.*, **57**: 209 – 227.
- STADLER, D., BRUENDL, M., SCHNEEBELI, M., MEYER-GRASS, M., & H. FLUEHLER (1997): Wasserregime in der Schneedecke und im Boden an bewaldeten Gebirgsstandorten: Schneeinterzeption, Schmelzwasser- und Oberflaechenabfluss. Zürich, 145 pp.
- STOUFFER, R. J., MANABE, S., & K. YA. VINNIKOV (1994): Model assessment of the role of natural variability in recent global warming. *Nature*, **367**: 634 – 636.
- TOL, R. S. J. & A. F. DE VOS (1993): Greenhouse statistics – time series analysis. *Theor. Appl. Climatol.*, **48**: 63 – 74.
- VINER, E., & P. HULME (1994): The climate impacts LINK project: Providing climate change scenarios for impacts assessment in the UK. Report prepared for the UK Department of the Environment. Climatic Research Unit, Norwich, 24 pp.
- VON STORCH, H. (1995): Inconsistencies at the interface of climate impact studies and global climate research. *Meteorol. Z.*, **4**: 72 – 80.
- VON STORCH, H., ZORITA, E., & U. CUBASCH (1993): Downscaling of global climate change estimates to regional scales: an application to Iberian rainfall in wintertime. *Journal of Climate*, **6**: 1161 – 1171.
- VON STORCH, J.-S., KHARIN, V. V., CUBASCH, U., HEGERL, G. C., SCHRIEVER, D., STORCH, H. VON, & E. ZORITA (1997): A description of a 1260-year control integration with the coupled ECHAM1/LSG general circulation model. *J. Clim.*, **10**: 1525 – 1544.
- WEYANT, J., DAVIDSON, O., DOWLATABADI, H., EDMONDS, J., GRUBB, M., PARSON, E. A., RICHEL, R., ROTMANS, J., SHUKLA, P. R., TOL, R. J. S., CLINE, W., & S. FANKHAUSER (1996): Integrated assessment of climate change: an overview and comparison of approaches and results. In: BRUCE, J. P., LEE, H., & E. F. HAITES [Eds.]: *Climate Change 1995: Economic and social dimensions of climate change*. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge [a. o.], 367 – 396.
- WIGMOSTA, M. S., VAIL, L. W., & D. P. LETTENMAIER (1994): A distributed hydrology-vegetation model for complex terrain. *Water Resour. Res.*, **30**: 1665 – 1679.
- WILBY, R. L. (1994): Stochastic weather type simulation for regional climate change impact assessment. *Water Resour. Res.*, **30**: 3395 – 3403.
- WILKS, D. S. (1989): Conditioning stochastic daily precipitation models on total monthly precipitation. *Water Resour. Res.*, **25**: 1429 – 1439.
- WILKS, D. S. (1992): Adapting stochastic weather generation algorithms for climate change studies. *Clim. Change*, **22**: 67 – 84.
- WILKS, D. S., & S. J. RIHA (1996): High-frequency climatic variability and crop yields. A guest editorial. *Clim. Change*, **32**: 231 – 235.
- ZORITA, E., HUGHES, J. P., LETTEMAIER, D. P. & H. VON STORCH (1995): Stochastic characterization of regional circulation patterns for climate model diagnosis and estimation of local precipitation. *J. Clim.*, **8**: 1023 – 1042.
- ZORITA, E., & H. VON STORCH (1997): A survey of statistical downscaling techniques. GKSS Report No. 97/E/20. GKSS Research Centre, Geesthacht, Germany.

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