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Inconsistencies at the interface of climate impact studies and global climate research

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Summary. Most climate impact studies, whether they deal with, for instance terrestric or aquatic ecosystems, coastal morphodynamics, storm surges and damages, or socio-economic aspects, utilize "scenarios" of possible future climate. Such scenarios are mostly based on the output of complex climate models, whenever they are in any sense detailed. Unfortunately, the user community of such scenarios usually is not well informed about the limitations and potentials of such models. On the other hand, the climate modeller community is not sufficiently aware of the demands on the side of the "users".

The state of the art of climate models is reviewed and the principal limitations concerning the spatial/time resolution and the accuracy of simulated data are discussed. The need for a "downscaling strategy" on the climate modeller side and for an "upscaling" strategy on the user side is demonstrated. Examples for successful exercises in downscaling seasonal mean precipitation and daily rainfall sequences are shown.

Probleme beim Informationstransfer von der Klimaforschung in die Klimawirkungsforschung

Zusammenfassung. Die meisten Untersuchungen über die möglichen Folgen von Klimaänderungen, etwa in bezug auf terrestrische oder aquatische Ökosysteme, Küstenmorphodynamik, Sturmfluten und Sturmschäden oder auch sozioökonomische Vorgänge, verwenden „Szenarien" möglicher zukünftiger Klimate. In den meisten Fällen sind diese Szenarien abgeleitet aus den Resultaten von Simulationen mit detaillierten Klimamodellen. Dabei ist des öfteren festzustellen, daß Benutzer solcher Szenarien im Unklaren sind über den Realitätsgrad und die implizit gemachten Annahmen bei der mathematischen Konstruktion solcher Klimamodelle. Auf der anderen Seite wissen die Konstrukteure von Klimamodellen nicht ausreichend Bescheid über die Bedürfnisse auf seiten der Klimaforschung.

In diesem Beitrag wird versucht, den Stand der Klimamodellierung zu umreißen und die grundsätzlichen Grenzen in bezug auf die raum/zeitliche Auflösung und auf die Genauigkeit von simulierten Daten darzustellen. Die Notwendigkeit einer „Downscaling"-Strategie auf seiten der Klimaforschung und einer „Upscaling"-Strategie auf Seiten der Klimafolgenforschung wird erklärt. Beispiele erfolgreicher „Downscaling"-Ansätze zur Spezifikation von saisonal gemittelten Niederschlägen und von täglichen Niederschlagssequenzen werden gezeigt.

1 Introduction

The notion that the ongoing increase of greenhouse gas concentrations in the atmosphere will ultimately change the climate on Earth has become widely accepted in the republic after having circulated in physics and meteorology for seven decades since the first hypothesis by ARRHENIUS (1896). In consistence with the enhanced public awareness many scientific programs have been launched on the details of the expected climate change. Because of the separation of science in many almost independent "science states" the interaction between different disciplines, such as climtology and coastal dynamics, hydrology and ecology, is often insufficient. This insufficient communication causes methodical errors in the evaluation of possible impacts of climate change. One error refers to the spatial scales. On the side of climate modelling *large* scales are of the order of sevearal thousand kilometres; on the "user" side often spatial scales of hundred or less kilometres are regarded as being "large scale". Climate people deliver (potentially reliable) information on *their* large scale and "users" request large-scale information on *their* large scale. Unfortunately, the meaning of "large scale" deviates significantly on the two sides, with the effect that the output/input scales do not match. This contribution deals with the clarification of this mismatch and with a possible cure, named "downscaling", to deal with it.

2 Data requirements for climate impact studies

Climate impact studies usually require detailed information on present or future climate with high resolution and accuracy (ROBINSON and FINKELSTEIN 1991). For instance, hydrologists ask for daily data with a spatial resolution corresponding to a catchment. Coastal engineers want information on the sea-level rise and the frequency and intensity of storms, and the resulting extreme value statistics for high and low waters, for such "small" areas like the Netherlands or the Southern Baltic coast. Insurance companies need to assess the frequency distributions of the strength of maximum gusts. The oil industry asks for changes in the extreme wave heights in order to guarantuee the safety standards of their offshore structures. Ecologists who are studying the dynamics and responses of forests in mountainous terrain need information of monthly mean rainfall and temperature with a spatial resolution of a few kilometres (GYALISTRAS and FISCHLIN 1993). The modelling of the population of red deer requires information on monthly snow height; agroecosystem models or insect

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population models need daily data as input (after GYALISTRAS et al. 1994, see also PARRY 1990).

To sum up, in most cases detailed information is asked for, with spatial resolutions of the order of 100 km or less, and with high accuracy concerning the tails of statistical distributions (in particular the frequency and intensity of rare events) (ROBINSON and FINKELSTEIN 1991). Sometimes these requests are made since impact researchers are used to have such detailed information available from the observational record; one may speculate that in many cases considerably less detailed information may be sufficient. But in some cases the requested accuracy is really needed: An example is an agroecosystem model simulating the potential yield of a wheat field as a response to climate forcing functions, which looses most of its skill when forced with observed meteorological data from the same time interval but from a weather station about 100 km away (NONHEBEL 1994).

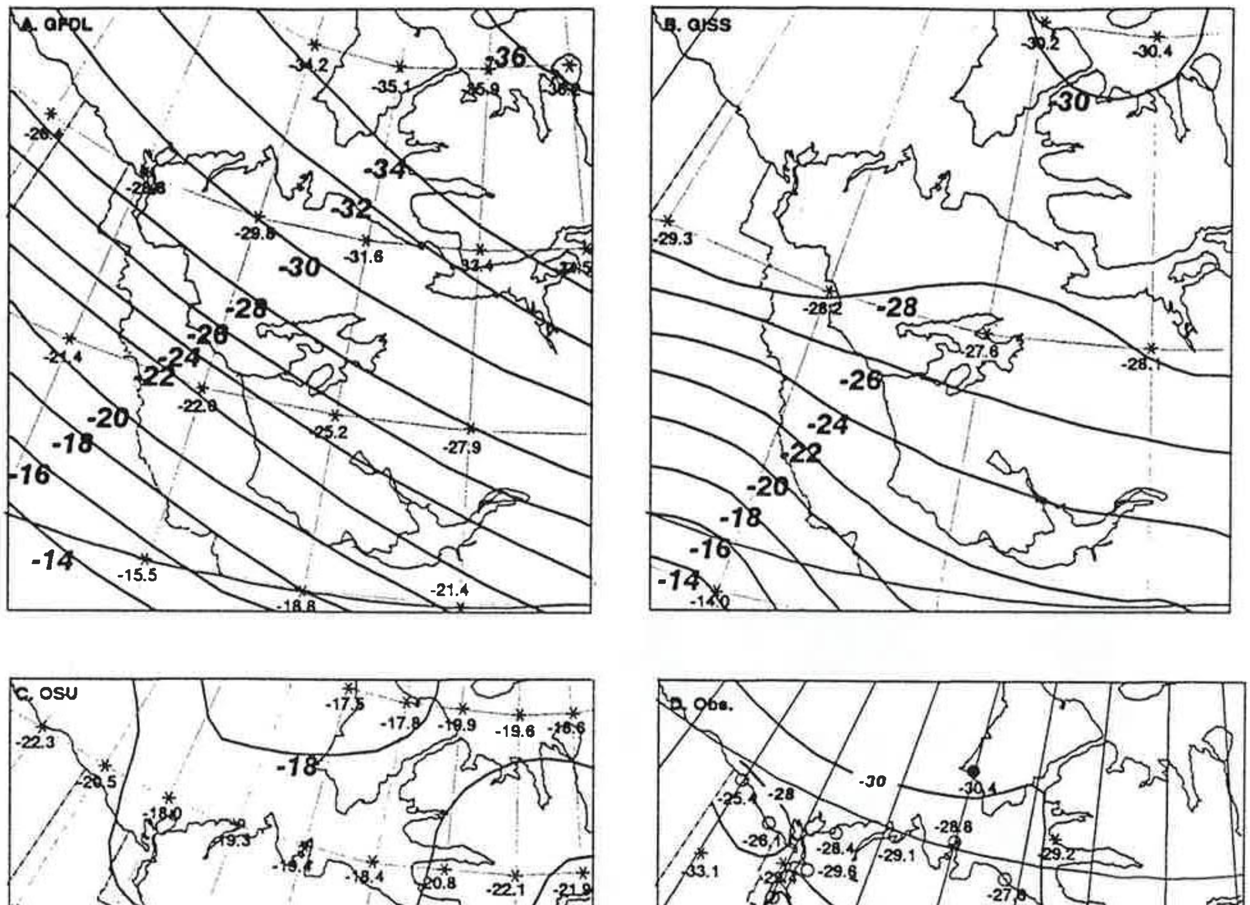


Fig. 1. January mean precipitation in the Mackenzie Valley, Canada, as given by the often used output of three climate models (A: GFDL (Geophysical Fluid Dynamics Laboratory), B: GISS (Goddard Institute for Space Studies) and C: OSU (Oregon State University)) and as given from point observations (D). Units: equivalent millimetres of water. From STUART and JUDGE (1991).

Abb. 1. Mittlere Niederschlagssumme im Januar im MacKenzie Gebiet (Kanada), simuliert von drei häufig benutzten Klimamodellen (A: GFDL, B: GISS und C: OSU) und gemessen an einzelnen Stationen (D). Einheiten: mm. Von STUART und JUDGE (1991).

3 The standard approach in impact studies

Many studies of systems, which are suspected to be sensitive to climate change, such as the physics or the biology of the North Sea, the hydrology of a river or a lake, or ecosystems in an Alpine valley, make use of statistical or dynamical models. These models run with internal parameters which have been tuned to describe the influence of the present-day climatic environment. Sometimes the value of these parameters is inferred from field experiments under controlled external conditions and from observed climate data of high accuracy and high spatial and temporal resolution. For present-day climate this approach is adequate since the atmospheric (oceanic) forcing functions are indeed often known with high accuracy and resolution.

Within this approach the response of the system to climate change is derived by running the model with the new forcing functions that are expected in the new climate. Frequently these forcing functions are taken directly from the output of *G*eneral *C*irculation *M*odel (GCM) experiments. To infer the response of the considered system to future climate change, then, the maps of climate model output are taken as forcing functions. Usually these maps represent the difference Δ between the simulated future climate and the simulated present climate. Then the present-day climate *C* plus the "signal" Δ together are used as forcing function. The motivation for this approach is the belief that climate models would correctly simulate the deviations from the normal in climate change experiments.

Δ is given on a grid because the numerical models integrate the discretized differential equations of the thermo- and hydrodynamics of the atmosphere and of the ocean on a grid (examples of horizontal grids are given in Fig. 1A–C). In climate impact studies, however, the output of climate models is often implicitly considered as a continuous field. Then, the gridding is just a convenient way to store the output economically; the information resolved by the grid is reliable and the sub-grid scale information may be recovered from the gridded data simply by spatial interpolation.

With such a concept in mind it is fully consistent to use the output ofthe GISS (Goddard Institute for Space Studies) model, which operates on a 7,5° × 10° latitude × longitude grid (see Fig. 1B), and to try to infer the details of possible climate change on the northern and southern slopes of the Alps (OZENDA and BOREL 1990). Obviously, however, such an approach is simply wrong.

Some models of suitability to grow certain crops or to host tourists, require as their input the annual cycles of monthly mean temperature and precipitation (for instance CLIMAPS, CRU and ERL (1992) or LEEMANS and SOLOMON (1993). Nicely coloured diagrams are produced which

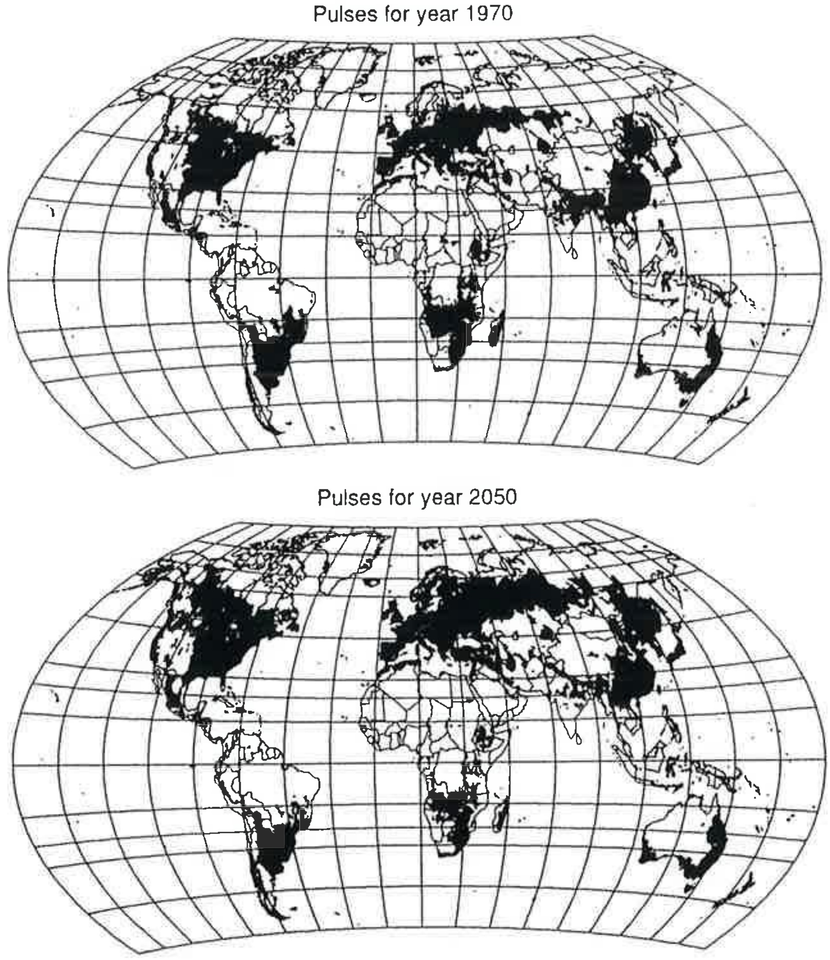


Fig. 2. Present-day potential distribution of pulses and scenario for the year 2050 calculated from a climate model. From LEEMANS and SOLOMON (1993).

Abb. 2. Heutige potentielle Verteilung von Hülsenfrüchten und ein aus Klimamodelldaten abgeleitetes Szenario für das Jahr 2050. Von LEEMANS und SOLOMON (1993).

show the response of these models to a changed climate $C + \Delta$ on a resolution of 50×50 km^2. All information on this scale comes of course from C since the grid scale of Δ is typically of the order of 500×500 km^2. As an example we show in Fig. 2 the potential distribution of (non-irrigated) pulses (leguminous plants) as derived by LEEMANS and SOLOMON (1993) from present-day conditions and from the climate change associated with a doubling of CO_2 as calculated by the GFDL model (the same from which Fig. 1A is derived).

4 The skill of climate models

4.1 The failure of climate models on the regional scale

Present-day climate models are GCMs. As such these models are designed to simulate the large-scale state of the climate. A larger scale allows for a more reliable simulation of a feature. At the lowest end of the spatial resolution, with scales of one or a few grid distances, the climate models have little or no skill (GROTCH and MACCRACKEN 1991). Mean annual cycles of precipitations or near-surface temperature at grid points deviate in part strongly from respective observed annual cycles (VON STORCH et al. 1993, CUBASCH et al. 1995). The ECHAM T21 model simulation was found to yield an annual cycle of Central Europan rainfall which is 180° out-of-phase with respect to observations (URBANOWICZ et al. 1992). Fig. 1 shows the failure of three frequently used climate models to simulate the intensity and pattern of the January mean precipitation in the Mackenzie Valley (STUART and JUDGE 1991).

There are several reasons for the failure of the models on the regional scale which we define here as several mesh sizes of the model's grid (with the implication that the 500 km scale must be attributed to regional scales in a "T21" model but to the large scales in a "T106" model):

— The spatial resolution provides an inadequate description of the structure of the earth's surface. The land-sea distribution is heavily smeared out. Most climate models in the past have operated with a "T21" resolution, many models still do so in these days and the upcoming generation of models is integrated with a "T42" resolution. The "T63" and "T106" resolutions are also shown — models with such a resolution will not be available for long-term experiments in the near future; shorter experiments may be done occasionally (BENGTSON et al. 1995a, b). Fig. 3 visualizes the spatial resolution of Europe for these resolutions. The mountains appear as broad flat hills. A clear example for the limitations of climate models is provided by the complex variations of the annual cycle of precipitation in the Alps: in the northern side a summer rainfall maximum is observed, somewhat further south a semi-annual component becomes dominant, and even further south, in the mediterranean climate, a winter maximum prevails (FLIRI 1974). Present-day climate models are not able to reproduce this fact, let alone to predict its changes in a new climate.

— The hydrodynamics of the atmosphere are non-linear and the energy, which is fed into the system on the cyclonic scale, is cascaded to smallest scales through nonlinear interactions. Because of the numerical truncation this cascade is interrupted and the flow to smallest scales is parameterized. This parameterization affects the smallest resolved scales most strongly (see ROECKNER and VON STORCH 1980).

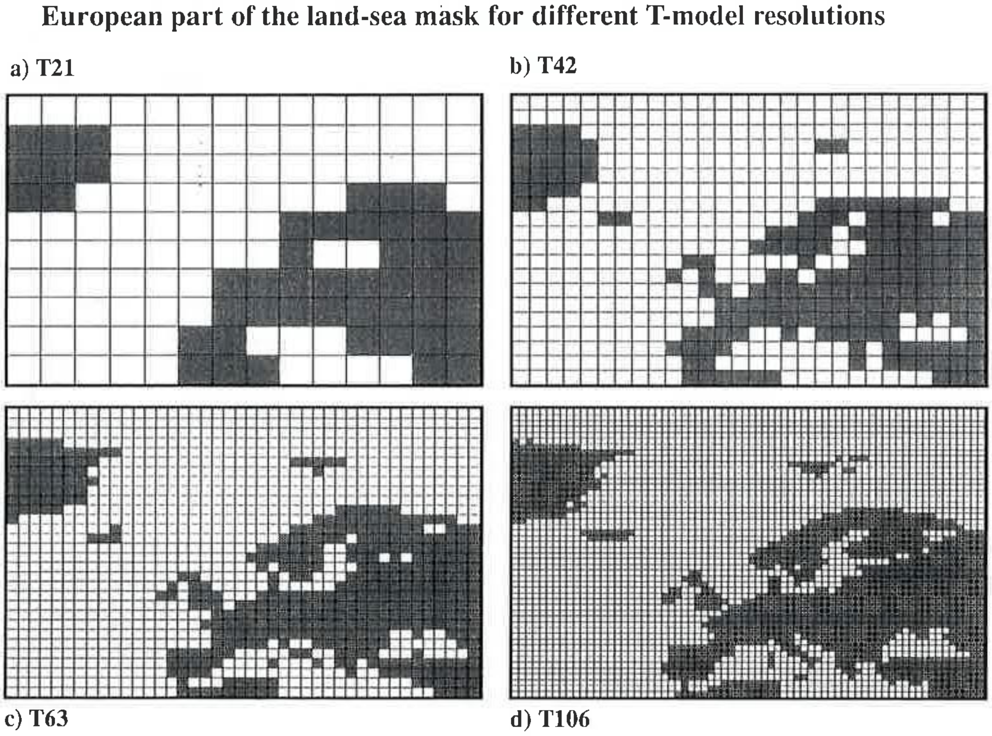


Fig. 3. Spatial discretization of Europe in a climate model with "T21", "T42", "T63" and "T106" resolution.

Abb. 3. Räumliche Auflösung von Europa in Klimamodellen mit „T21", „T42", „T63" und „T106" Diskretisierung.

— Sub-grid scale processes in the models are parameterized. These parameterizations have been fitted globally and might not be equally adequate for different parts of the world.

4. 2 The success of climate models on the large scale

The comparison of simulated global mean maps with observed ones yields that the models are quite powerful in the reproduction of large-scale features (e.g. Hadley cell, extratropical storm tracks) but that there are considerable differences on the regional scale (Houghton et al. 1990). As an example we show in Fig. 4 the latitude-height cross-section of the zonally averaged zonal wind as derived from observations and as simulated by a GCM. Also, the models are capable to reproduce the planetary scale EOFs (*E*mpirical *O*rthogonal *F*unctions) as dominant modes of large-scales variability (Zorita et al. 1992, von Storch et al. 1993, Zorita et al. 1995). We already mentioned above that a scale might be "large" in a high-resolution model but "regional" in a low-resolution model.

The fact that the models do a credible job on the global scale and fail on the regional scale seems to be a contradiction. But this is not the case. The global climate is the response to the large-scale structure of the earth's surface (land-sea distribution, topography) and to the differential heating. The regional climates, on the other hand, represent the result of an interaction of the global climate and regional details. Therefore, it is possible to simulate the global climate adequately even though none of the regional climates is simulated realistically in its details.

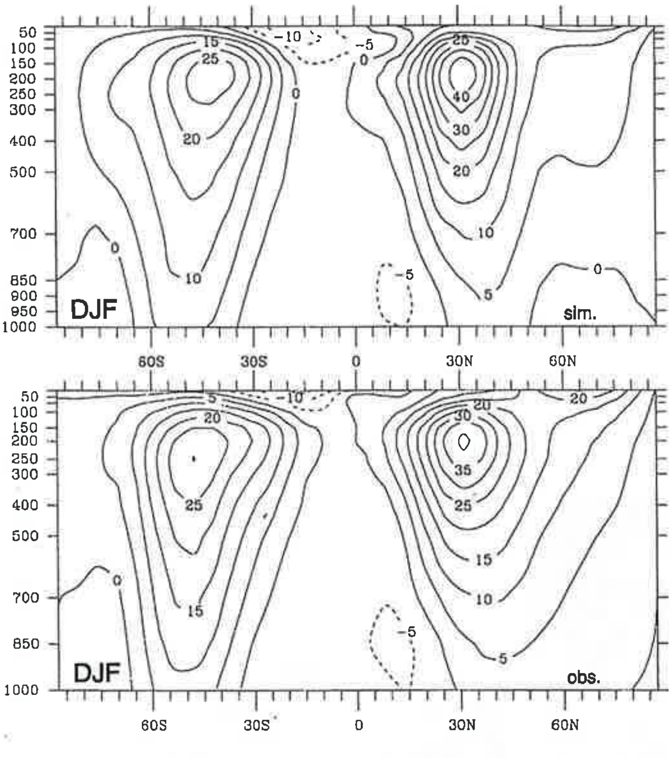


Fig. 4. Latitude-height (in deg and hPa) cross-section of the zonally averaged zonal component of the wind in winter (December–January–February) calculated from analyses (of operational observations; lower panel) and from the output of a GCM (upper panel). Units: m/sec. From Roeckner et al. (1992).

Abb. 4. Längen/Höhen Schnitt (in Grad und hPa) der zonalgemittelten Zonalkomponente des Windes im Winter (Dezember bis Februar) abgeleitet aus operationellen Analysen (links) und von einem Klimamodell (rechts). Einheiten: m/sec. Von Roeckner et al. (1992).

5 Synthesis: Downscaling procedures

The spatial-scale gap between climate research and climate impact studies has to be bridged by "downscaling" on the side of the climate research and "upscaling" on the side of the climate impact research. Downscaling means to use information from the climate model output which is considered to be modelled reliably and to relate this information by means of dynamical or statistical models to regional or local parameters which are not adequately modelled by the climate models. In general, the larger the scale, the larger are the chances to simulate the parameter reliably. Upscaling means to modify the impact models in such a manner that they can be run with forcing functions with the considerable uncertainty that is to be expected from general circulation models.

Four strategies for downscaling have been proposed:

— *Statistical models* relate large-scale information to regional climates (von Storch et al. 1993). The models are fitted to observed data. A meaningful downscaling strategy is obtained by the procedure outlined in Fig. 5. In the following sections we will deal exclusively with this approach. The merits of the statistical downscaling concept are demonstrated by two hydrological examples.

— In the *Combined Analogue — Dynamical Modelling Approach* all possible large-scale situations are categorized into a finite set of characteristic situations, for instance Großwetterlagen. For each of these characteristic situations a detailed integration with a mesoscale climate model is run. The climate change scenario is then determined through the changed frequency of the characteristic situations. An example of this approach has been put forward by Frey-Buness et al. (1993).

— A powerful alternative approach is the use of dynamical *Limited Area Models* (LAMs) which are forced with large-scale information from a climate model. The feasibility of this approach has convincingly been demonstrated by Giorgi et al. (1991). However, one has to keep in mind that the principal limitations of dynamical models, which arise from the limited spatial resolution, also hold for LAMs – on a smaller scale.

— Another dynamical approach are *time slice experiments* with global atmospheric models with a high resolution such as T106 (for instance, Bengtsson et al. 1995 a, b; Cubasch et al. 1995). In such experiments the sea-surface temperature and sea-ice distribution as simulated in a regular climate model run, with a low-resolution (for instance, T21) coupled ocean-atmosphere model such as

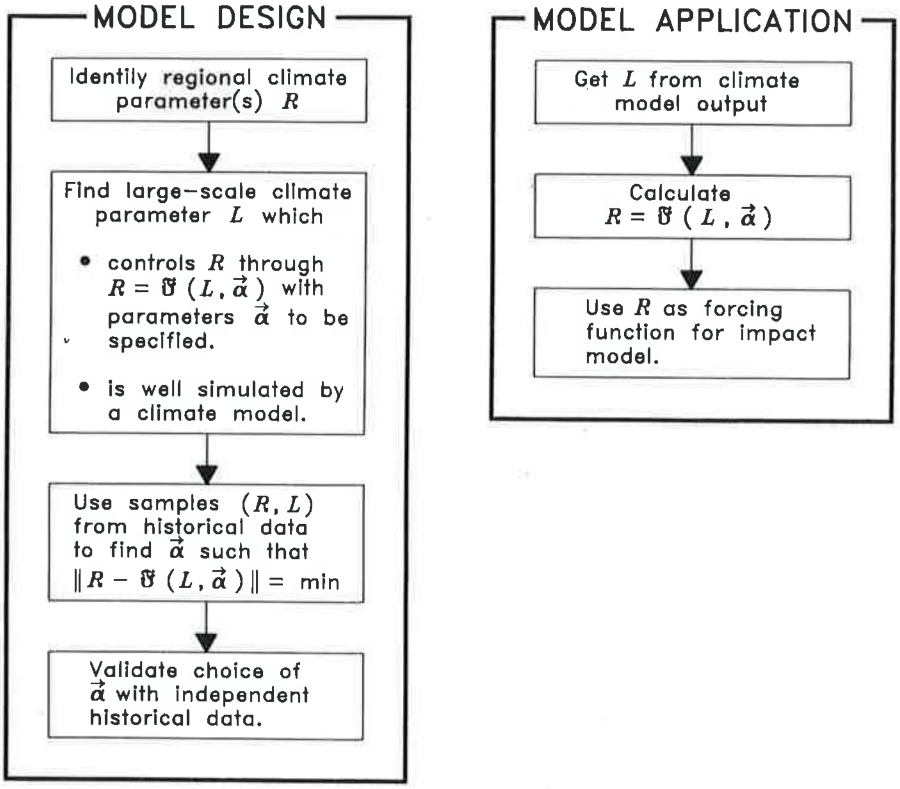


Fig. 5. Concept of statistical downscaling.

Abb. 5. Das Konzept des statistischen „downscaling".

ECHAMI/LSG (CUBASCH et al. 1992, 1994), is used as prescribed lower boundary condition for an integration with an atmospheric model. The equilibrium response to such boundary conditions, which are either taken from present-day conditions (BENGTSSON 1995a) or from the time "2035" in a climate change experiment (BENGTSSON 1995b), is then taken as an estimate of the regionally detailed climate under control or "2035"-conditions, respectively.

All downscaling procedures may be considered as a "perfect prog" approach. This expression refers to a technique for improving weather forecasts prepared by a Numerical Weather Predicition Model (NWP). The output of the NWP is considered a perfect prognosis, but it does not encompass all varibles of interest, such as the amount of rainfall in a valley. Then a statistical (dynamical) relationship between a well-simulated variable, say 700 hPa height, and the variable of interest is used to postprocess the output of the NWP. Since the predictor, 700 hPa height, is considered perfectly specified, the statistical (dynamical) model which was designed to deal with observed input, may be used unchanged to deal with NWP (climate model) output.

An alternative procedure in weather forecasting is "Model Output Statistics" (MOS), and downscaling is sometimes mistaken as a MOS-like approach. MOS relates a, possibly systematically incorrect, forecast of the predictor, say again 700 hPa, to the variable of interest at the time of the forecast. Then, a statistical model is built which relates the (possibly incorrect) forecast of 700hPa height to the actually observed rainfall in the valley. Obviously, MOS can *not* be used for downscaling purposes since climate model variables can not be matched with variables observed at a specific time.

6 Example: Seasonal mean rainfall on the Iberian Peninsula

In this example, winter (DJF) mean precipitation at a number of rain-gauge stations on the Iberian Pensinsula is related to the air-pressure field over the North Atlantic (for details, see VON STORCH et al. 1993). Through a *Canonical*

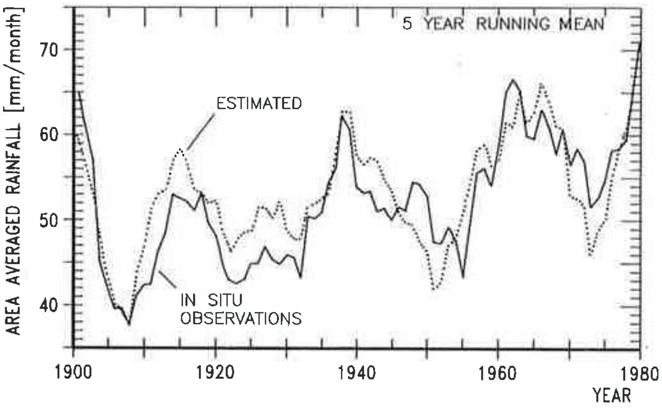


Fig. 6. Winter mean rainfall averaged for Iberian rain gauges. Full curve labelled "in-situ": calculated from local measurements. Dotted curve labelled "estimated": derived indirectly from variations of the North Atlantic air-pressure field. From VON STORCH et al. (1993).

Abb. 6. Zeitliche Entwicklung des winterlichen Niederschlages gemittelt über Stationen auf der Iberischen Halbinsel. Die durchgezogene „in-situ" Kurve ist abgeleitet aus den lokalen Beobachtungen. Die gestrichelte „estimated" Kurve repräsentiert das Ergebnis des „downscaling" und ist ausschließlich aus der Variation von Druckfeldern über dem Nordatlantik abgeleitet worden. Von VON STORCH et al. (1993).

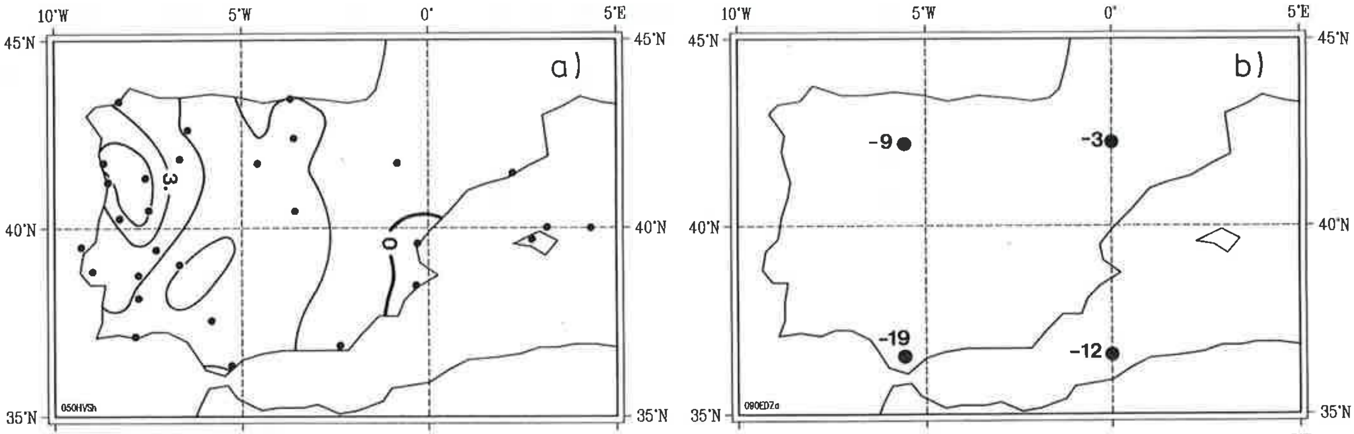


Fig. 7. Downscaled (a) and grid-point (b) response of Iberian precipitation in a "$2 \times CO_2$ experiment". Units: mm/month. From VON STORCH et al. (1993).

Abb. 7. „$2 \times CO_2$"-Szenarien für veränderte Niederschlagsverteilungen auf der Iberischen Halbinsel abgeleitet aus einem „$2 \times CO_2$" Gleichgewichtsexperiment mit dem Hamburger Klimamodell. — a: Aus den modellierten Druckdaten vermittels „downscaling" abgeleitetes Szenario. b: Szenario abgeleitet aus der Gitterpunktsinformation. Einheiten: mm/Monat. Von VON STORCH et al. (1993).

Correlation Analysis a couple of spatial patterns $\overline{\mathbf{P}}$ and $\overline{\mathbf{Q}}$ and of time coefficients $\alpha(t)$ and $\beta(t)$ are identified such that $\alpha(t)\ \overline{\mathbf{P}}$ represents a significant part of the Iberian rainfall variance in winter und $\beta(t)\overline{\mathbf{Q}}$ monitors the large-scale state of the atmospheric circulation over the North Atlantic. Moreover, the time series $\alpha(t)$ and $\beta(t)$ are optimally correlated so that the information given by $L(t) = \beta(t)\overline{\mathbf{Q}}$ may be regressed on $R(t) = \alpha(t)\overline{\mathbf{P}}$.

The parameters of this regression model are fitted to data from 1950 to 1980. The scheme is tested with independent data from 1901 to 1949. The resulting mean rainfall, averaged over all stations, derived indirectly from the air-pressure distribution as well as given by local measurements are shown in Fig. 6. The overall upward trend as well as low-frequency variations are reproduced by the "downscaling model" indicating the usefulness of the technique as well as the reality of both the trend and the variations in the Iberian winter precipitation.

We have applied the downscaling model to a "$2 \times CO_2$ experiment" performed with a "T21" climate model (CUBASCH et al. 1992) and compare in Fig. 7 the "downscaled" response with the grid-point response of precipitation. The grid-point information indicates a marked decrease over most of the Peninsula whereas the downscaled response is weakly positive.

7 Example: Daily rainfall sequences

With an analogue technique, realistic sequences of wet and dry days can be specified if the large-scale air pressure distribution is known (for details, see ZORITA et al. 1995). The large-scale information L is located in the 25-dimensional phase space spanned by the coefficients of the first 5 Empirical Orthogonal Functions (EOFs) at day t, t–1 . . . t–4 of the large-scale sea-level air-pressure distribution surrounding the location of interest.

In the analogue technique, the local rainfall $R(t)$ at some time t is specified as follows. The coordinates $\overline{\gamma}(t)$ in the 25-dimensional phase space are determined and then, in the set of all historical cases we look for that time t^* which minimizes $\| \overline{\gamma}(t) - \overline{\gamma}(t^*) \|$. Then the rainfall observed at time t^* is used as an estimate of the rainfall at time t: $R(t) = R(t^*)$.

This approach hs been tested for several locations, among others Hightstown in New Jersey. Rainfall amount histograms calculated from local observations as well as derived with the analogue technique from observed air-pressure distributions (labelled NMC) and from control runs with climate models (labelled MPI and GFDL) as well as from one "$2 \times CO_2$ experiment" are shown in Fig. 8. The local information is well reproduced by the large-scale information available in the analyses and in the models; the impact of a changed atmospheric CO_2 concentration is small.

A more tricky parameter is the distribution of the *storm interarrival time* which is the time between two rainy days. The cumulative distribution functions, obtained from local observations as well as through analogue downscaling, are shown in Fig. 9. The analogue technique works well and also the models do a credible job; the climate change signal is negligible.

8 Concluding remarks

Statistical downscaling versus limited area models. From the presentation and brief discussion of the examples it is clear that there is no universal downscaling method valid for all variables and all regions. Instead, statistical downscaling requires the design of statistical models on a case-by-case-basis. This should not be too large a disadvantage for the investigator interested in a single region but it is certainly impracticable for an assesment of climate change on a detailed regional basis. In this respect Limited Area Models

Fig. 8. Histogram of rainfall amount in Hightstown, New Jersey, in winter and summer (calculated from local observations and derived from large-scale air-pressure information provided by operational analyses (NMC), by control runs with two climate models (MPI and GFDL) and by a “2 × CO_2” experiment. From ZORITA et al. (1995).

Abb. 8. Häufigkeitsverteilungen für tägliche Niederschlagsmengen in Hightstown, New Jersey, USA, im Sommer und Winter, abgeleitet aus lokalen Beobachtungen und indirekt bestimmt aus der großräumigen Luftdruckverteilung. Die Druckverteilungen sind operationellen Analysen (NMC) und Klimamodellberechnungen mit ungestörten Bedingungen (MPI und GFDL) und mit verdoppelten CO_2-Konzentrationen (MPI) entnommen. Von ZORITA et al. (1995).

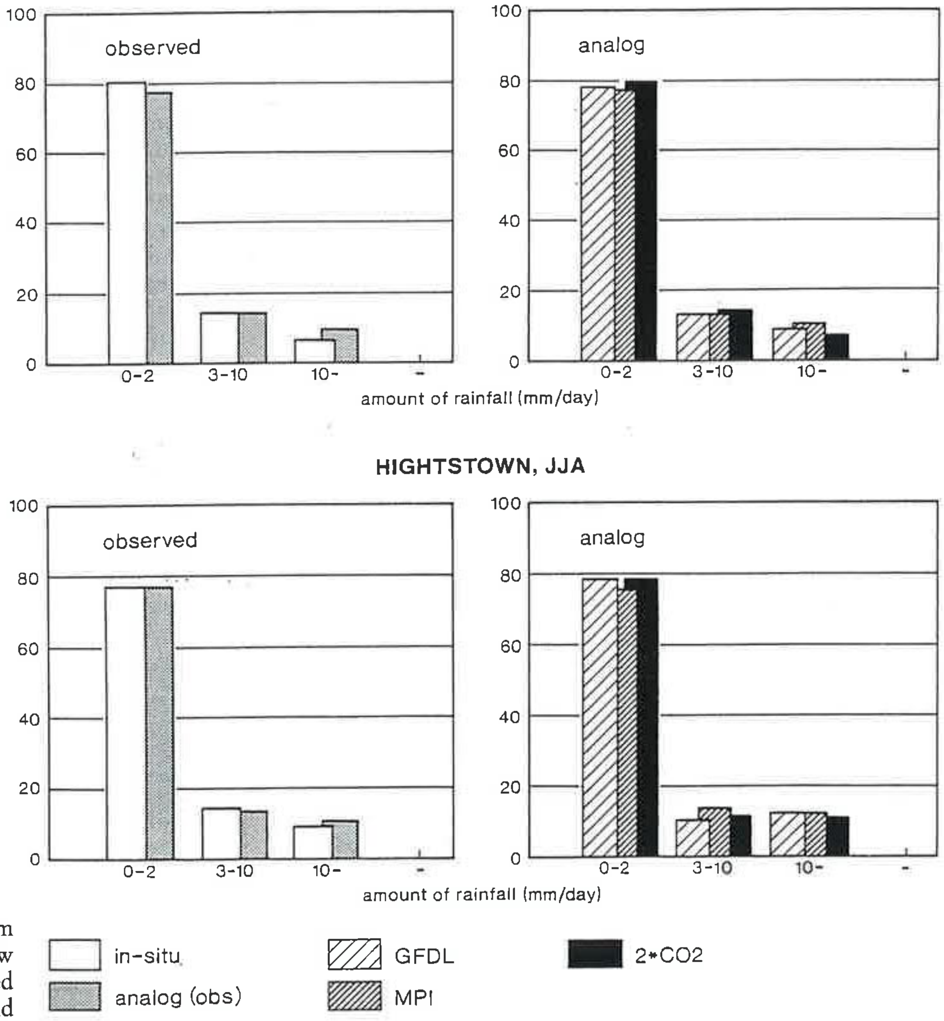
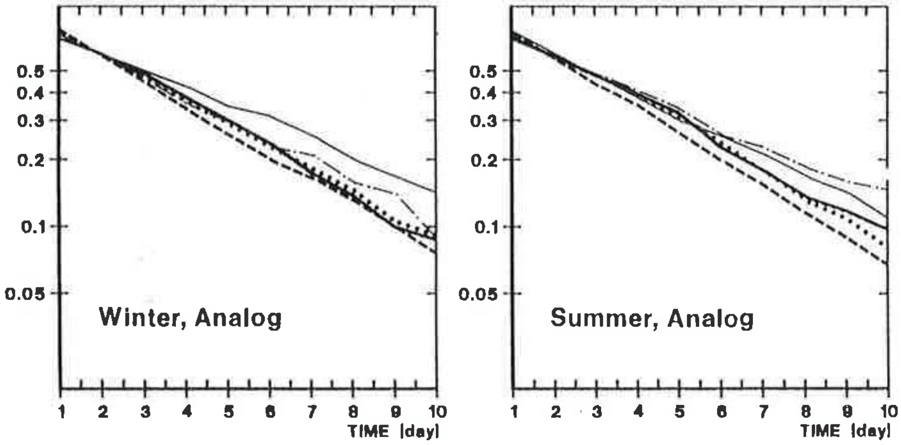


Fig. 9. Survivor functions of the storm interarrival times at Hightstown, New Jersey, in winter and summer calculated from local observations (heavy line) and derived through the analogue technique from large-scale air-pressure information available from operational analyses (dotted), from control runs with climate models (light line and dashed) and from a “2 × CO_2 experiment” (dash-dotted). From ZORITA et al. (1995).

Abb. 9. „Survivor function“ der Zeit zwischen zwei Regentagen für Hightstown, New Jersey, USA, im Winter und Sommer. Die dicke Linie repräsentiert lokale Beobachtungen. Die anderen Linien sind aus dem Zustand des großräumigen Luftdruckfeldes abgeleitet: aus operationellen Analysen (punktiert), von Klimamodellsimulationen des heutigen Zustands (dünne und gestrichelte Linie) und von einem „2 × CO_2“ Gleichgewichtsexperiment (strichpunktiert). Von ZORITA et al. (1995).



(LAMs) and “time slice experiments” with high-resolution global models are more suitable.

On the other hand, statistical models should be in most cases easy to develop and *test.* If they are able to reproduce the observed low-frequency variability of the regional climate, they will likely correctly estimate regional climate changes (provided that the GCMs correctly simulate the large-scale climate changes). LAMs are much more difficult to test. They require high-quality large-scale forcing fields which are normally available for no more than a couple of decades. This means that one cannot be sure if they can simulate regional climates other than the present one. Statistical methods can be of some help in this respect: LAMs *must* be able to represent the statistical relationship between the large-scale fields and the regional climate. A study of these relationships as simulated by the LAM can be helpful in improving the dynamical model itself.

Daily weather sequences. The daily weather sequences discussed above can be used sensibly only if the required forcing function, i.e., the daily large-scale weather stream simulated in the climate model, is realistically simulated by these models. Whether this assumption is really valid has hardly been checked so far, so that certain reserve in this respect is recommended for the time being.

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