Downscaling III: Applications to Ecosystems Modeling

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ABSTRACT

We discuss the potentials and limitations of statistical downscaling (DS) when dealing with terrestrial ecosystems studies in complex terrains, by providing examples based on a linear DS technique and the dynamic forest gap model ForClim. We show that DS is essential to assess regional ecosystem responses to global climate change in a sensible manner. However, for several applications DS needs to be complemented by additional techniques such as spatial interpolation, stochastic weather generation, the parameterization of regional climate responses as a function of atmospheric greenhouse-gas concentrations, and the estimation of the uncertainties that occur within or between future climate scenarios.

1 INTRODUCTION

Ecosystem modelers who wish to study possible regional impacts of climate change have particularly demanding requirements for climate scenarios. Typically needed are application-specific combinations of several meteorological variables, which must be provided with high spatial detail (10^0-10^1 km), and at a hourly to seasonal resolution of the annual cycle. Further, in some cases the scenarios must cover regions of several 10^2-10^3 km^2, or they must be provided for time spans of several decades or even centuries (cf. Gyalistras *et al.* 1994, 1995).

In the last years a series of techniques to statistically downscale large-scale climate changes as simulated by General Circulation Models (GCMs) to the regional scale have become available (see reviews in this volume). Here we discuss advantages and limitations of such downscaling (DS) approaches when dealing with the climate scenario requirements of ecosystem studies.

For illustration we provide examples using a DS technique which predicts local climate anomalies from large-scale monthly mean sea-level pressure and near-surface temperature anomaly fields based on Canonical Correlation Analysis (von Storch *et al.* 1993, Gyalistras *et al.* 1994). We discuss results from application of this technique to climate change experiments with the Hamburg MPI ECHAM1/LSG GCM (Cubasch *et al.* 1992, 1994) and the Canadian Climate Centre (CCC) GCMII (Boer *et al.* 1992).

On the ecosystem side we consider the dynamic forest ecosystem model ForClim (Bugmann 1994, Fischlin *et al.* 1995a), which simulates site-specific tree species compositions in function of a location's climate (Fig. 1). The climatic input requirements of ForClim (see below) are representative for several ecosystem applications, and, typically, more stringent than the input needs of empirical vegetation-climate relationships.

2 SPATIAL ASPECTS

Resolution

DS is in principle applicable to any location at which meteorological measurements are available, and thus enables to study ecosystems at a very high spatial resolution. Further it allows to coherently adjust climate parameters between different locations under a given large-scale climate change, thus reinforcing the consistency of the scenarios at the regional scale.

Fig. 1 compares the responses of ForClim at the case study location of Bever (1712 m.a.s.l., 9.9 °E, 46.6 °N, Upper Engadine valley) in the Swiss Alps under two climate change scenarios constructed with and without DS. The climatic inputs required by ForClim are the expected values, variances, and covariances of mean temperatures and precipitation totals for every month of the year, which are used to stochastically generate an annual weather cycle for every simulation year. In the first scenario (left panel) the monthly expected values for temperature and precipitation were modified based on DS. In the second scenario (right panel) the required inputs were from GCM-simulated average monthly changes from three gridpoints in the vicinity of the Alps. In both cases the monthly variances and covariances were held constant at present values.

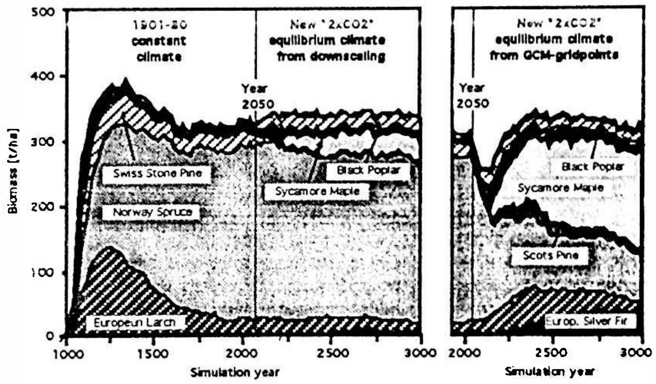

Figure 1. Comparison of average tree species compositions simulated by ForClim (Bugmann 1994, Fischlin *et al.* 1995a) at the site Bever (1712 m.a.s.l., Swiss Alps) for present climate, and under two climate scenarios derived with (left panel) and without (right panel) downscaling from a "2xCO_2"-experiment with the ECHAM1 GCM (Cubasch *et al.* 1992). All data are averages from 200 independent stochastic forest simulation runs.

It can be seen that ForClim's behaviour is sensitive to the method by which the scenario was constructed. Under the DS scenario only minor changes in the tree species composition occur. In the case of the gridpoint scenario, which specifies larger temperature and precipitation changes than the DS scenario (cf. Gyalistras *et al.* 1994), the model projects a partial forest breakdown, which is followed by significant changes in the tree species composition.

Since DS is the climatologically more consistent procedure, we concluded that the simpler gridpoint-based method yields misleading results – at least in a topographically complex region such as the Alps.

Spatially Extended Scenarios

The locations of interest to ecologists rarely coincide with climatological stations. For example, Bever is located at the valley floor, whereas most forests in the vicinity of this station grow on the surrounding slopes.

Consequently, the forest simulated at Bever contains a large fraction of Norway Spruce (Fig. 1), and the model can not reproduce the dominance of European Larch, which is actually found on the much warmer, south-facing slopes (Bugmann & Fischlin 1994, Bugmann 1994). Hence the point estimates available from measurements or downscaled climate scenarios need to be extended by means of an appropriate procedure into space.

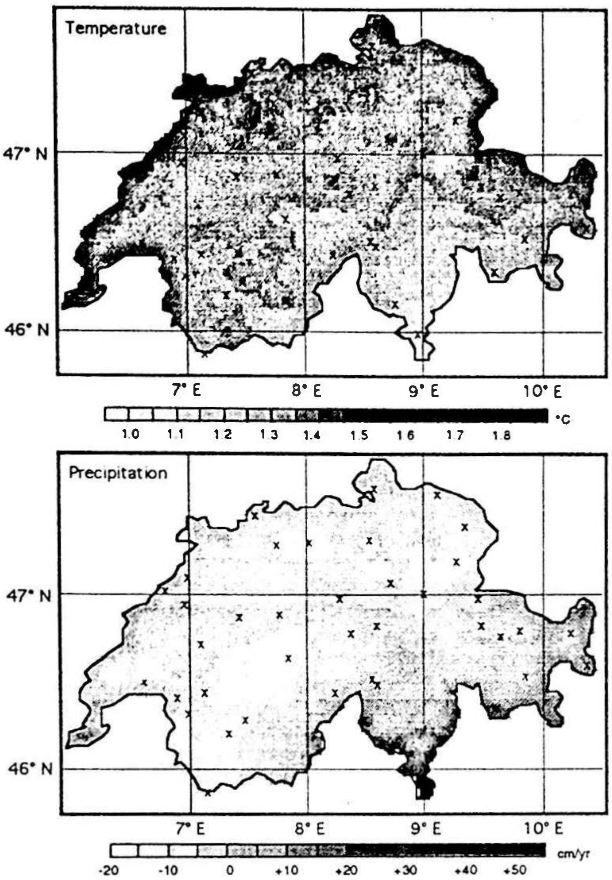

Figure 2. Interpolated maps of changes in annual mean temperature (top) and precipitation (bottom) in the Swiss region as downscaled (Gyalistras *et al.* 1994, Gyalistras 1940, Gyalistras & Fischlin 1995b) from a "2xCO_2" simulation with the ECHAM1 GCM (Cubasch *et al.* 1992). Dots signify the 40 long-term climatological stations at which monthly temperature and precipitation changes from downscaling were available. For interpolation 68 additional stations with at least 20 yr of data available were used (not shown). The main ridge of the Alps crosses Switzerland between 46 and 47 °N in a W/SW-E/NE direction.

A procedure which combines DS with spatial interpolation was proposed by Gyalistras & Fischlin (1995a). First, the baseline (present) climate at any location of interest is estimated from the application of empirical altitude-climate dependencies, plus an inverse-distance weighted mean of altitude-detrended measurements from adjacent climatological stations. DS is carried out at all nearby stations where at least 50 years of data are available ("base" stations), and the downscaled anomalies are then interpolated by means of linear regressions to all remaining "secondary" stations. Finally inverse-distance weighted means are again used to estimate the climate anomalies at the interpolation site from all surrounding base and secondary stations.

This method was applied to a "2xCO2" experiment with the ECHAM1 GCM to construct on a 2.5 km x 2.5 km latitude-longitude grid maps of changes in annual mean temperature and total precipitation for the Swiss region. The maps provide spatial details (Fig. 2) which are at present not available from simulations with regional climate models. Their salient feature is a strong N-S gradient, which is caused by different patterns of change at the northern vs. the southern slope of the Alps (cf. Gyalistras *et al.* 1994, 1995).

Crossvalidation experiments with ForClim showed that for the simulation of present tree species compositions the interpolation of monthly long-term mean temperature and precipitation in several cases falls short of the required precision. However, if a few years of measurements are available to improve the estimation of the baseline climate, the accuracy of the interpolated anomalies is in most cases sufficient to project scenarios of future forest responses (Gyalistras & Fischlin 1995a).

3 TEMPORAL ASPECTS

Resolution

Two basic approaches can be envisaged to construct scenarios with the high temporal resolution required by various ecosystem studies.

The first is to apply DS directly at the required, e.g. daily, temporal resolution. The advantage of this approach is that it uses directly the physically-based simulation of weather patterns by GCMs (e.g. Bardossy & Plate 1992, Zorita *et al.* 1995). However, at the same time it requires a sufficiently realistic performance of the climate models at this high temporal resolution, as well as the analysis of very large GCM-generated data sets.

The second approach is to use DS to adjust only the parameters of a stochastic weather generator. The latter can then be used to produce synthetic time series of weather variables at the required temporal resolution (e.g. Wilks 1992). In addition to DS-based adjustments the advantages of this approach are: (i) it can provide a large number of weather realizations, (ii) it allows to perform extensive sensitivity studies based on arbitrary adjustments of the weather generator parameters, and (iii) it relies upon commonly available (i.e. monthly) GCM-outputs. The main drawback is that the weather process is described by statistical approximations which may not necessarily hold under a changed climate.

Ecosystem modelers often need to explore in a flexible manner the relevance of different climate respectively weather parameters, as well as a wide range of possible climate changes. This is an additional reason to favour the weather generator approach.

Transient and Long-term Scenarios

The exploration of transient and/or long-term ecosystem responses (e.g. Fig. 1) by means of DS is at present limited by the fact that the currently available time-dependent GCM-simulations cover only a small sample of scenarios for future greenhouse-gas (GHG) concentrations, or cover only a relatively short future time period.

One possibility to improve this situation is to apply DS to a time-dependent GCM-experiment, and then parameterize the local climate change as a function of the GHGs used to force the GCM.

Fig. 3 shows an example of this technique for July mean temperature at Bever. First we downscaled year-to-year temperature anomalies from a transient (simulation years 1935-2084) experiment with the ECHAM1 GCM. Then we applied a 15-yr running mean filter to remove high-frequency variability, and fitted a linear response model $\Delta T_{k+1} = \lambda C_k + \alpha T_k$ to the smoothed temperature anomalies ΔT (cf. Hegerl *et al.* 1994). Here k is the simulation year; λ=0.212 and α=-0.91 are constants determined by means of a least-square fit; $C_k = \ln(GHG_k/GHG_0)$ is the forcing term, where GHG_k is the 15-year mean GHG forcing in the year k expressed in CO_2 concentration equivalents; and finally GHG_0 is the preindustrial GHG-concentration (278 ppmv).

Such a model can be used to estimate the time-dependent shift in the expected value of the local climate variable in response to an arbitrary GHG- forcing. For example in Fig. 3 we constructed a "stabilization" scenario by rescaling the IPCC "S 550" scenario (Houghton *et al.* 1995) to account for all GHGs in addition to CO_2.

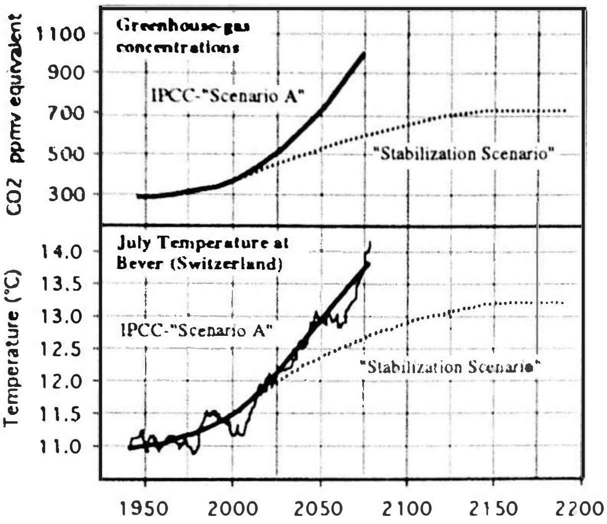

Figure 3. Use of downscaling to construct transient, long-term climate scenarios under arbitrary assumptions on future atmospheric greenhouse-gas concentrations. *Top*: prescribed profiles of equivalent CO_2 concentrations. *Bottom*: thin line: 15 year running mean of July mean temperature at Bever (1712 m.a.s.l., Swiss Alps), derived by downscaling from a transient IPCC "Scenario A" experiment with the ECHAM1 GCM (Cubasch *et al.* 1994); thick line: fitted linear response model; dotted line: application of the linear response model.

Moreover an arbitrary number of interannual monthly weather courses can be generated by assuming that the local variable is e.g. normally distributed with a time-dependent expected-value, and a constant variance (same as present). This approach can easily be extended to several local variables and more sophisticated time series models.

4 UNCERTAINTIES

Uncertainties Within Scenarios

A particularly attractive feature of DS with regard to ecosystem applications is that it can be flexibly applied to any regional climate variable of interest. However, the reliability of the empirical link between large-scale and local climate critically depends on the season, location, and the variables considered (Gyalistras *et al.* 1994). Unfortunately, the performance of DS deteriorates for several ecologically important variables such as summertime precipitation or winds.

One resort is to try to improve the performance of present DS procedures. However, the accurracy of DS can be expected to be always be limited due to (i) physical reasons, e.g. due to the occurrence of more erratic precipitation in summer, (ii) the sampling variability which enters the estimation of the statistical DS model, and, in some cases, (iii) the need to extrapolate climate changes beyond the range of the data which were available to fit the model.

A second possibility is to quantify the uncertainties in the downscaled climate scenarios, and then explore their effect on the ecosystem models (e.g. Bugmann & Fischlin 1994).

For instance, Gyalistras (1994) used a "bootstrap" technique (Efron 1979) to estimate uncertainty intervals for downscaled changes in monthly mean temperature and total precipitation at 22 Swiss locations. For each month and location N=800 different DS models to N data sets, each consisting of 57 large-scale and local data pairs, were fitted separately. The data pairs were sampled at random (with replacement) from a 57-year observational data base. The intervals obtained from application of the DS models to four different GCM-experiments are shown in Fig. 4.

These intervals account for sampling variability in the definition of present climate and for parameter uncertainty of the DS models. Certainly, they are only valid under the assumptions that (i) regional climate variations can be described as a sum of a "signal", which is forced by the large-scale component, plus a "residual variability", (ii) the "signal" is captured correctly, and (iii) the statistical properties of the "residuals" remain unchanged under a changing climate. The last point implies corresponding assumptions on the constancy of e.g. regional climate forcings or feedback mechanisms which are not resolved by the driving GCMs.

Uncertainties Between Scenarios

The complexity of ecosystem models often prevents a systematic assessment of possible ecosystem responses. An important application of DS is thus to generate at relatively small expenses a wide range of sensible working points for sensitivity and impact studies.

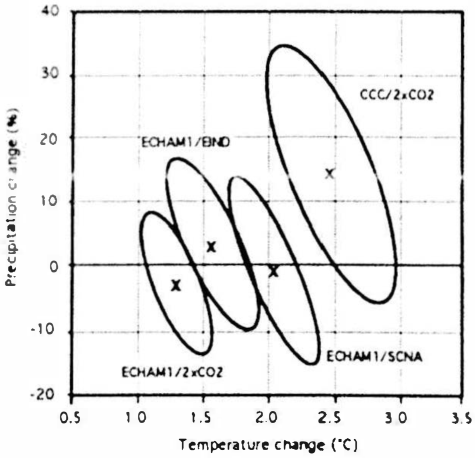

Figure 4. Comparison of changes in annually and regionally averaged temperature and precipitation for the Swiss region as downscaled from experiments with the ECHAM1 GCM (Cubash *et al.* 1992, 1994) and the CCC GCMII (Boer *et al.* 1992). 2xCO2: changes under an equilibrium CO_2-doubling; EIND, SCNA: changes for the decade 2075-84 under the transient "IPCC Scenario A" for greenhouse-gas concentrations; the GCM integrations started at 1935 (EIND) resp. 1985 (SCNA). Crosses denote best estimates, ellipses empirical 90% intervals of changes obtained from a bootstrap-procedure involving 800 downscaling models fitted separately for each month of the year and each of the 22 Swiss locations considered. After Gyalistras (1994).

This is again illustrated in Fig. 4. The overall range covered by the different scenarios reflects the different climate sensitivities of the ECHAM1 and the CCC GCMs, which respond to a CO2-doubling with a global mean temperature increase of 1.7 °C and 3.5 °C, respectively. The relatively modest regional temperature increase under the ECHAM1 EIND-experiment is because the GCM projects a cooling over the North Atlantic, which is more pronounced in the EIND- as compared to the SCNA-experiment.

Recent investigations on the role of these uncertainties for forest responses as projected by ForClim demonstrated that the sensitivity of the forest model was largest at sites close to the precipitation and temperature determined timberlines. At these locations climate scenario uncertainties in the order of ±1 °C for temperature and ±15% for precipitation already affect forest compositions significantly (Bugmann 1994, Fischlin *et al.* 1995a,b).

These results underpinn the importance to explore a wide range of scenarios, respectively the regional uncertainties resulting from inter-GCM variability. At present, this can only be accomplished by downscaling.

5 CONCLUSIONS

Statistical downscaling is a flexible and economic method to construct regionally consistent climate scenarios as required by ecosystem studies. However, many ecological modeling applications need a downscaling complemented by additional methods, such as spatial interpolation and stochastic weather generation, in order to make best use of existing theory and data.

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