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DERIVATION OF CLIMATE CHANGE SCENARIOS FOR MOUNTAINOUS ECOSYSTEMS: A GCM-BASED METHOD AND THE CASE STUDY OF VALAIS, SWITYERLAND[1]

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A method is proposed and tested which allows to obtain on scales of 1-100 km in complex terrain climatic change scenarios from transient General Circulation Model (GCM) simulations. The procedure consists of a) definition of scenario requirements, b) selection of local climate stations and construction of actual scenario region, c) derivation of climate change estimates at a "base station" where long observational data sets are available, and d) interpolation of climate and climatic changes to locations of interest. As a case study we derive scenarios for changes in monthly and seasonal mean temperatures (T) and pecipitation sums (P) in the region of Valais, Switzerland for every month (season) of the year. Definition of the region for which sensible scenarios may be specified is discussed based on correlations found between 41 Swiss climate stations. Climatic change estimates at the base station of Sion are obtained by linking local T and P by means of Canonical Correlation Analysis (CCA) to global-scale observed sea-level pressure and near-surface temperature anomalies and than applying the statistical models to anomaly fields simulated in a GCM experiment. Changes of T and P at locations with shorter observational data-sets are obtained by means of a linear regression from the base station. For all other points of interest an interpolation procedure is tested which estimates a) long-term mean T and P as weighted averages from altitude-corrected means observed at adjacent climate stations and b) changes in T and P as weighted averages of the changes obtained within the scenario region. The uncertainties entering the different steps of our case study are compared and an outlook to the needs of future scenario development is given.

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1. INTRODUCTION

Ecosystem impact and sensitivity studies need scenarios of possible future climatic change.

Best climatic change information is available from General Circulation models (GCMs) which are most reliable on scales ≥ 10^3 km. In spite of this fact several studies have used gridpoint-simulated data (e.g. LEEMANS & CRAMER, 1991; MONSERUD & LEEMANS, 1992). This is certainly not meaningfull in a complex topography such as the Alps, where local climates may vary largely on scales of some 10^0 - 10^2 km.

One approach to obtain regional climate change information from scales at which GCMs operate consists in the usage of higher-resolution numerical models nested within GCMs (e.g. GIORGI *et. al*, 1990; GIORGI & MEARNS, 1991). This is computationally intensive and results are not immediately available. A much cheaper way to obtain local climatic change estimates consists in emprically relating by means of a "downscaling" procedure global and local climatic changes to each other.

Several possibilities exist to establish such a link, ranging from simple analogues (e.g. WIGLEY *et. al*, 1980; HULME *et. al*; 1990) to more elaborate statistical relationships as proposed by STORCH *et al.* (1993). The latter method has been extended by GYALISTRAS *et al.* (1994) to derive from GCM-simulated climatic change regionally differentiated scenarios on a sub-grid scale for several climate parameters at 5 locations in the Alps.

However this procedure can only be applied at climate stations where a sufficient long record, e.g. 50-80 years is available. Ecosystem research often requires climatic data where no or only a few measurements are available. For example, climate-vegetation relationships are investigated along an altitudonal gradient. According to these needs, in this paper we present a procedure allowing to obtain scenarios of possible climate change at any point within a region of interest.

We test the method by means of the case study of temperature and precipitation scenarios for the inner-alpine province of Valais, Switzerland. Our results suggest that, when using the downscaling procedure proposed by GYALISTRAS *et al.* (1994), the uncertainties inherent to the scenarios are mostly larger than regional differences obtained on a scale of 10^2 km, and in the same order of magnitude as uncertainties due to the interpolation of climate change estimates to ecosystem locations on a scale of some 10^1 km.

2. METHODS AND DATA

Monthly and seasonal mean temperatures (T) and precipitation sums (P) have been calculated for each month and season of the year from daily measurements based on data extracted from the database of the Swiss Meteorological Agency (SMA), Zurich (SMA, 1901-80; BANTLE, 1989). The seasons are defined as follows: Winter = (Dec, Jan , Feb), Spring = (Mar, Apr, May), Summer = (June, July, Aug), and Autumn = (Sep, Oct, Nov).

The main station considered is Sion (7˚ 21' E, 46˚ 14' N, 542 m.a.s.l.), in a pronounced valley location in the central part of the Valais (upper Rhône Valley). As additional climate stations used to test the extrapolation of climate change estimates in more detail we consider Montana (7˚ 29' E, 46˚ 19' N, 1495 m.a.s.l.), on a S-exposed slope of the , Lausanne (6˚ 39' E, 46˚ 32' N, 618 m.a.s.l.) in the western part of the Swiss middle-land, and Neuchatel (6˚ 57' E, 47˚ 00' N, 487 m.a.s.l.) on a SE-exposed slope at the southern side of the Jura mountains. These additional stations are located at increasing distance, namely at 12 km NE, at 63 km W/NW and at 90 km N/NW from Sion.

For testing of the interpolation procedures we consider for T and P a network of 41 climate stations over entire Switzerland, and for P allone an additional network with center at Sion containing a total of 80 stations within a radius of ca. 90 km. Distances between stations range from 4 km to 280 km with a mean of 90 km for the first network and from 2 km to 172 km with a mean of 63 km for the second. For the first (second) network 12 (14) stations are found below 500 m, 13 (38) between 500 m and 1000 m, 9 (19) between 1000 m and 1500 m, and 7 (9) above 1500m.

The variables chosen to describe the large-scale atmospheric state are monthly and seasonal means of sea-level pressure (SLP) prepared by NCAR (JESSEL, 1991) and of near-surface temperature (2mT) from the VINNIKOV (1986; JESSEL, 1991) data-set. The fields considered extend from 40˚W to 40˚E and 30˚N to 70˚N on a 5˚ x 5˚ latitude by longitude grid (GYALISTRAS *et al.*, 1994).

Global and local climate variables are linked to each other by means of Canonical Correlation Analysis (CCA) performed in the empirical orhtogonal function (EOF)-space (ANDERSON, 1984; BARNETT & PREISENDORFER, 1987; KUTZBACH, 1967). Climatic change estimates are derived based on simulations under current and future atmospheric greenhouse-gas concentrations by the ECHAM1/LSG coupled atmosphere-ocean climate model (CUBASCH *at al.*, 1992).

Variant	CCA-Model estimation period (π)	CCA-Model verification period
A1	1901-47	1948-77
A2	1916-62	1901-15, 1963-77
A3	1931-77	1901-1930
B1	1931-57	1958-77
B2	1941-67	1931-40, 1968-77
B3	1951-77	1931-50

Table 1: Variants of data sets used.

Since climate change estimates obtained by means of CCA have been found to be sensitive to the period of data used for CCA-model estimation (GYALISTRAS *et al.*, 1994), we consider six different variants of data sets according to the availability of local T- and P-data (Table 1). Variants A1-A3 which consist of 47 and 30 years for model estimation and verification, respectively have been applied to Sion only. Variants B1-B3 (27 and 20 years for model estimation and verification, respectively) have been applied to all four main locations mentioned above.

3. RESULTS AND DISCUSSION

3.1. GENERAL PROCEDURE

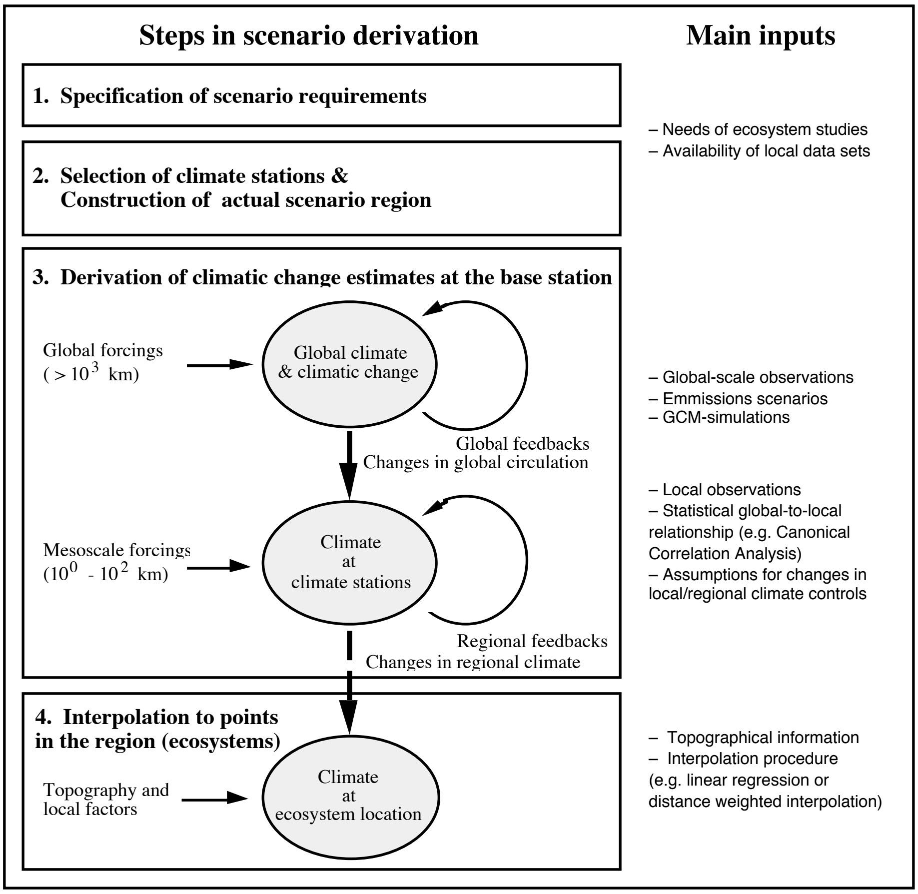


Fig. 1: Procedure for the derivation of climate change scenarios in a complex terrain. *Global forcings* are e.g. solar radiation, atmospheric greenhouse-gas concentrations and land-ocean distribution; *global feedbacks*: e.g. changes in oceanic circulation, responses of bio- and cryosphere; *mesoscale forcings*: e.g. topography, surface characteristics, inland water; *regional/local feedbacks*: e.g. albedo-temperature or moisture-temperature feedback; *topography and local factors*: e.g. altitude, slope, exposition, vegetation cover and soil characteristics.

The methodology proposed in this paper consists of the four steps summarized in Fig. 1. In the first two steps the scenario needs are specified and the actual region for which climate change estimates may be obtained – as constrained by the spatial behavior of climatic elements and by the availability of observations – is determined. In Step 3 changes in the global circulation obtained from GCM-simulations based on particular assumptions for changes in global forcings, are downscaled by means of an empirical relationship to a base climate station. From this location climatic change scenarios at the ecosystem locations are derived using a spatial interpolation procedure (Step 4).

3.2. SPECIFICATION OF SCENARIO REQUIREMENTS

3.2.1 Method

Needs for scenario data may vary widely, according to the particular climate impact or sensitivity study considered (e.g. ROBINSON & FINKELSTEIN, 1991). In order to construct appropriate scenarios, the following information needs to be specified first:

1. Region of interest, e.g. a climatic subregion or an area bounded by topograpphy;

2. Meteorological variables of interest, e.g temperature, precipitation, wind, solar radiation etc.;

3. Time of the year to be considered, e.g. a particular season;

4. Statistical parameters and temporal resolution for each variable, e.g. daily temperature extrema, monthly mean wind speed, number of days exceeding a precipitation threshhold within a month etc.;

5. Time horizon to be considered, e.g the next few decades.

We do not differentiate between steady state and transient scenarios since our procedure has been designed to provide time-dependent information; changes in the long-term mean values or the year-to-year variability of local climate parameters can, in principle, be estimated based on any sub-period contained in the transient scenario.

3.2.2 Results

As a case study we are interested in obtaining climatic change estimates for the Rhône Valley (Valais) in Switzerland. The main part of this valley extends over ca. 50 km from W/SW to E/NE and is characterized by an inner alpine climate. Precipitation shows two maxima occurring in the winter and summer seasons and the annual sum in the bottom of the valley is only 600 mm but increases rapidly with altitude, reaching at Montana 900 mm. The Valais represents an ecologically interesting region because under current climatic conditions vegetation at lower elevations is already limited by water availability and seems therefore particularly susceptible to climate change.

The local climate parameters considered are monthly and seasonal temperature means (T) and precipitation sums (P) for every month (season) of the year. Temperature and precipitation are the main parameters commonly used to describe the effects of climatic change on terrestrial ecosystems, in particular vegetation, on timescales of decades to centuries. They are needed by statistical approaches relating vegetation communities to climate (BRZEZIECKI *e al.*, 1993), as well as in dynamical models of forest succession (BUGMANN & FISCHLIN, 1996). In the Valais, relatively small changes in both parameters are likely to sensitively affect potential evapotranspiration, a commonly used measure for plant water stress (e.g FISCHLIN *et al.*, 1995).

The chosen monthly or seasonal resolution has several advantages: First, it corresponds to the resolution of the available large-scale surface temperature data which are used to estimate the CCA-models. Second, GCMs are considered to perform more reliably on these time scales rather than on a daily basis; and, third, due to the smaller storage requirements monthly data may be more easily obtained for different GCMs.

According to the time constants of forest ecosystem models (FISCHLIN & BUGMANN, this volume) scenarios for transient climatic change over ceveral centuries would be most appropriate. However, since the GCM simulation considered below extends only over the next 100 years, in this paper we restrict scenario derivation to this time horizon only.

The choice of climate parameters and of their temporal resolution in Step 1 depends also on how well a particular local parameter may be linked to global-scale climate. Fig. 2 compares the predictability of year-to-year variations of seasonal versus monthly T and P at Sion when using the downscaling procedure described in Chapter 3.4. The results are similar to those found for Montana, Lausanne and Neuchatel as well: for T no systematic variation within the year is found, but P is not well predicted for the months April to July. This could be due to stronger convective activity occurring during this time of the year. P is however better predicted for the whole Winter than for the individual Winter months, possibly because precipitation averaged over a shorter period is biased by short-lived weather systems which are not adequately represented in the monthly mean SLP- and 2mT-fields.

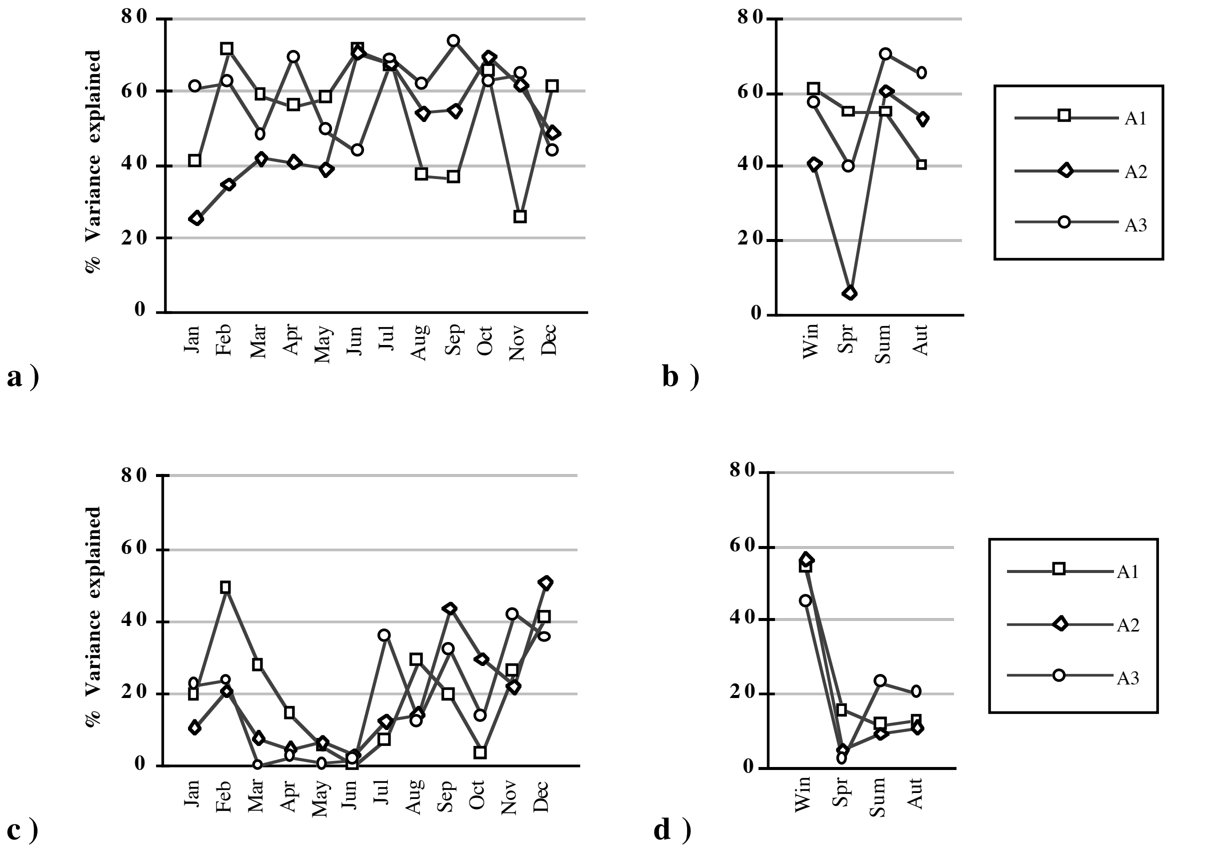


Fig. 2: Mean percentages of variances explained ($100 \cdot r^2$, n=30) for T and P by the respective 5 best CCA-models in the verification phases of data sets A1-A3. a) monthly, b) seasonal mean temperatures, c) monthly, d) seasonal precipitation sums.

Since performance of CCA on a monthly time scale is mostly at least as good as on a seasonal time scale (Fig. 2), for the derivation of climate change scenarios we will focus on a monthly resolution. We also may assume that a higher resolution allows for a more differentiated description of the variation of the global-to-local relationship throughout the year, in particular for the transition seasons. Furthermore, monthly data are more suitable for many biologic applications since they allow to more accurately estimate the timing of specific events within the year, such as the beginning and ending of the vegetation season.

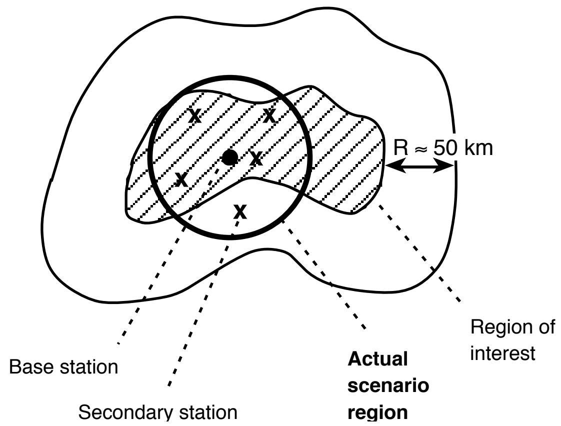
3.3. CLIMATE STATIONS AND CONSTRUCTION OF ACTUAL SCENARIO REGION

3.3.1 Method

According to the availability of observations we distinguish three types of locations which may be of interest to ecosystem studies: (a) locations coinciding with long-term climate stations, in the following named base stations, where a representative statistical relationship to global-scale climate may be established; (b) secondary stations at which some observational data are available; and (c) points in space for which no observations of climate parameters are available at all.

Since climate change estimates are obtained at base stations only, derivation of climatic change scenarios at adjacent locations depends on the representativity of a base station for its surroundings. Several characteristic numbers may be used to quantify this property (e.g. BALLING, 1984), and the results will also depend on topography, the time of the year, and the variable considered (e.g. FLIRI, 1974). In the following, the typical distance between two locations from which on realizations of the parameter X of interest (e.g. monthly mean P) become independent is abbreviated as $R_{A(X)}$. The subscript "A" denotes that this number will normally be derived from simultaneously observed anomalies of X relative to a respective mean state at different locations.

Given that R_A is known, all climate stations within a distance smaller than R_A from the margins of the region of interest and for which a minimum of, say, n_B = 50 years of data are available, are possible base station candidates for X. If no base station can be found, our method can not be used for scenario derivation, as this is the case for parts of the region of interest at a distance larger than R_A from a base station (Fig. 3).



(willl be corrected)

Fig. 3: Construction of actual scenario region. R_A: maximum distance for prediction of a variable; R^*: region of interpolation ; R_μ: distance used for interpolation.

If more than one base station exists, climate change information from all base stations should preferrably be used. This case is however not considered in our procedure which has been designed for less dense observational networks and thus only considers one base station at a time. Nonetheless, our method may always be applied by subdividing the original area of interest or using the most representative of all base stations available.

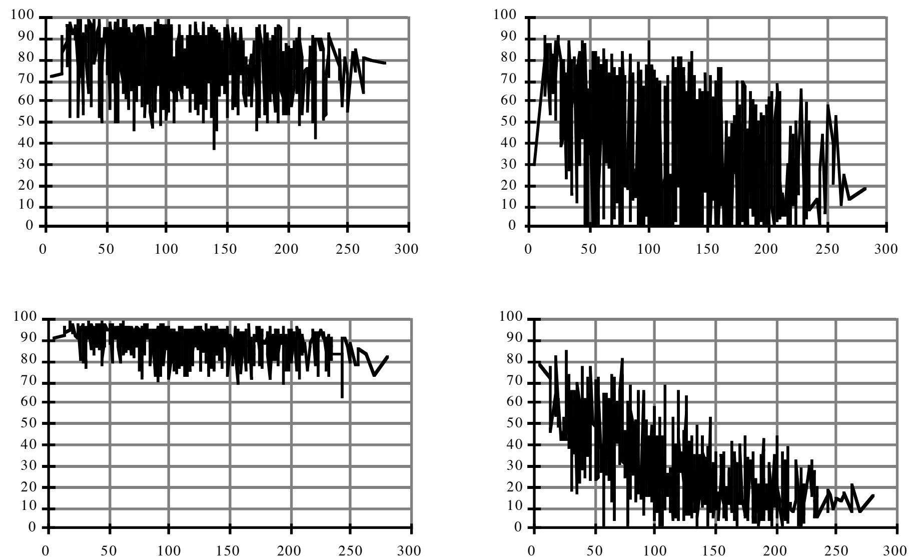
All stations within the distance R_A from the base station at which, say, n_S = 20 years of data are available are defined as secondary stations. At these locations the long-term mean of X is known and changes of X may be empirically related, e.g. by means of a linear regression, to changes obtained at the base station.

For all remaining locations L within the region of interest, the parameter X must be estimated by means of some interpolation procedure which normally will use all stations found within a typical distance R_μ from L. In principle, this can be attempted for all points within distance R_A from the base. If we assume however that, on average, climate stations can be expected to be homogeneously distributed around L, the probability that stations at a distance larger than R_A from the base are used for interpolation increases with increasing distance of L from the base. Therefore it seems reasonable to restrict the area of interpolation to some maximum distance R^* equal, say, $R_A/2$ from the base.

3.3.2 Results

Choice of $2{\cdot}R$ = 50 km: at this distance correlations of P between 39 stations distributed over entire Switzerland start to become not significantly different from zero (Fig. 4). $2{\cdot}R$ could be chosen larger for summer T, but it seems not probable that additional information from more remote stations would improve interpolation of T from the base station.

The area typically represented by a base station may be inferred by comparing geographical distances between climate stations to respective climatological distances, e.g. to correlation coefficients estimated from observations. Our findings from such an analysis in the Swiss Alps (Fig. 4) suggest that stations at a distance Ra typically up to ca. 60 km for P and more than 100 km for T may contain usefull information to describe year-to-year variations in both, monthly T and P, at a particular location.



a)

b)

Fig. 4: Percentages of pairwise explained variances ($100{\cdot}r^2$, n=30) between year-to-year variations of T (left) and P (right) at 39 Swiss climate stations, sorted by distance (in km) for a) January and b) July.

Choice of n_B = 50 years: is less than 80 years used in downscaling studies to date (Storch, Werner, Gyal). Though we have not systematically investigated this point, results for Sion suggest that 50 years are also tenable; the relatively wide ranges obtained hereby when using different data set variants for CCA-model estimation suggest however that several decades of data should be available in order to infer climatic changes based on models fitted to as many as possible different global climatic regimes (Fig. 7).

Choice of n_S = 20 years: Often no long data sets are available. Simultaneous availability of data sets at base station and secondary stations imposes additional restriction. Thus, period has been chosen shorter than 30 years used for definition of climatic subperiods (WMO) but large enough to estimate changes at secondary stations by means of a linear regression.

R≈50 from margins of the region (Martigny-Sion-Visp), data for at least ca. 50 years until 1980 for both T and P: Leysin (1931-76), Sion (1901-77), Grand-St-Bernard (1934-89), Montreux-Clarens (1931-89), Montana (1931-89), Chateau-d'Oex (1931-89), Lausanne (1931-80).

Best base station is Sion since in the centre of Valais and longest data sets. Montana would also be a possible base station. However Sion is more representative for a case study since long observational data sets are typically available in valley locations.

All other stations are located at the margins or outside the region of interest and are considered together with Montana as secondary stations. Three additional secondary stations with at least 20 years of data for both variables, Saas Fee (1931-68), Marsens (1931-68) and Interlaken (1931-70) are available until 1977, such that a total of 14 secondary stations are available. For P allone more data would be available from the precipitation data base of the SMA, but we want to simulate a situation with not too much data available.

3.4. DOWNSCALING OF CLIMATIC CHANGES AT THE BASE STATION

3.4.1 Method

Regional climate change estimates are obtained based on a relationship

$$\Delta \vec{l}_{(t)} = f(\delta \vec{g}_{(t)}) + \vec{\varepsilon} \qquad \text{Eq. 1}$$

where

$\Delta \vec{l}$	perturbation of local or regional climate parameter vector
t	time (e.g. in years)
f	“downscaling” function
$\delta \vec{g}$	perturbation of global-scale climate parameter vector
$\vec{\varepsilon}$	error accounting for variance of $\vec{l}$ which may not be explained by means of f

The downscaling function f is fitted and verified with observational data from the past. Since it is determined for a particular location or region, it also implicitely quantifies the effects of (a) mesoscale forcings, (b) regional feedbacks, and of (c) additional local factors (e.g. vegetation characteristics) on the response of $\Delta \vec{l}_{(t)}$ to variations in $\delta \vec{g}$ (s.a. Fig. 1). Certainly, the influences (a)-(c) may also determine the long-term means of the local variables relative to which perturbations are calculated (e.g. generally lower precipitation in an inner-alpine location), and which are not explicitely related to global-scale climate according to Eq. 1. Scenario derivation requires also assumptions on the residual vector $\vec{\varepsilon}$. Depending on f, the residuals may for example be best described by means of a multivariate normal distribution; under a climate change scenario, possible changes in the covariance matrice or the mean vector of this distribution need then to be specified.

3.4.2 Results

a) Specification of downscaling function

Based on a simplified version of Eq. 3 given in GYALISTRAS *et al.* (1994) the "downscaling" function *f* considered in this study is given by:

$$\Delta_\pi \vec{l}_{(t)} = \begin{pmatrix} \sigma_\pi(T) & 0 \\ 0 & \sigma_\pi(\sqrt{P}) \end{pmatrix} \sum_{i=1}^{2} \begin{pmatrix} \alpha_i \\ \beta_i \end{pmatrix} \rho_i \frac{\sigma_\pi(\vec{\gamma}_i \bullet \Delta_\pi \vec{g})}{\sigma_\pi(\alpha_i \cdot \Delta_\pi T^* + \beta_i \cdot \Delta_\pi \sqrt{P}^*)} \vec{\gamma}_i \bullet \delta \vec{g}_{(t)} \qquad \text{Eq. 2}$$

where

T	temperature (monthly or seasonal mean)
$\sqrt{P}$	transformed precipitation (monthly or seasonal sum)
π	reference period for which CCA is performed (cf. Table 1)
$\Delta_\pi \vec{X}$	deviation of $\vec{X}$ from mean state of period π
$\sigma_\pi(X)$	standard deviation of X in period π
$\vec{X} \bullet \vec{Y}$	scalar (dot) product of $\vec{X}$ and $\vec{Y}$
X^*	X standardized to unit standard deviation in period π
ρ_i	i-th canonical correlation (cf. Table 2)
α_i, β_i	elements of i-th canonical pattern of $\vec{l}$ (cf. Table 2)
$\vec{\gamma}_i$	i-th canonical pattern of $\vec{g}$ (cf. Fig. 2 a)-d), for i=1)

Vector $\vec{g}$ (size = 2·158 = 306) consists for CCA-model estimation of observed SLP and 2mT weighted such, that each field accounts for the same proportion of the total variance of $\vec{g}$ in period π. $\vec{l}$ (size = 2) is given by monthly (seasonal) T and $\sqrt{P}$. For CCA we use standardized anomalies $\Delta_\pi T^*$ and $\Delta_\pi \sqrt{P}^*$ such that the two local variables enter the procedure with the same weight. We preferably use $\sqrt{P}$ because this transformation was found to mitigate the skewness of P (given in cm/month) for all months of the year at Sion and Montana by an average of 70%.

Following GYALISTRAS *et al.* (1994), the time-dependent global anomalies $\delta \vec{g}_{(t)}$ used to estimate simultaneous local changes $\Delta_\pi \vec{l}_{(t)}$ are calculated as

$$\delta \vec{g}_{(t)} = \vec{g}_{(t \notin \pi)} - \mu_\pi(\vec{g}) \qquad \text{Eq. 3a}$$

for CCA-model verification and as

$$\delta \vec{g}_{(t)} = \vec{g}_{\text{ScenarioA}\ (t=1985..2084)} - \mu_{\text{Control}}(\vec{g}) \qquad \text{Eq. 3b}$$

for the derivation of transient climate change scenarios. Hereby μ_π denotes the mean state observed in period π, μ_{Control} is the mean state simulated in the years 9 to 49 in the "control run" (constant 1985 atmospheric greenhouse-gas concentrations) of the ECHAM1/LSG-GCM (CUBASCH *at al.*, 1992), and $\vec{g}_{\text{ScenarioA}}$ are the SLP- and 2mT-states simulated by this model under increasing atmospheric greenhouse-gas concentrations according to the IPCC "Business-As-Usual" emmissions scenario ("Scenario A"; HOUGHTON *et al*, 1991).

For each period π, month (or season), and location we fit 11 CCA-models using 2 to 12 EOFs of $\vec{g}$ and both EOFs of $\vec{l}$. For scenario derivation (Eq. 3b) we retain the 5 models for which the sum of correlations between the reconstructed (Eq. 3a) T- and P-time series and their observed counterparts in the respective verification period is maximal. We chose a maximum of

12 predictor-EOFs, because above this number no substantial increase in the second canonical correlation coefficient ρ_2 was found for models fitted at Sion (data-sets B1-3 and A1-3) and Montana (data-sets B1-3) for all months and seasons of the year. Both $\vec{1}$-EOFs are always retained for CCA because inclusion of the second canonical mode generally improved verification results, and because in the corresponding models the ρ_2 were mostly found to be relatively large (cf. Table 2e).

b) Statistical model for Sion

The results of CCA applied to Sion for seasonal mean T and $\sqrt{P}$ are shown in Fig. 5 and Table 2. Temperature anomalies at Sion are found to depend on the strength of W/SW-flow in Winter, the strength of southerly flow in Spring, of anomalously high pressure over Central Europe in Summer and of the strength of SW-flow in Autumn. The pairs of SLP- and 2mT-sub-patterns in Fig. 5 are consistent under each other, showing simultaneous positive temperature anomalies downstream of the low pressure centers in Winter, Spring and Autumn and anomalously high temperatures over Central Europe in Summer. The Winter and Summer patterns (Fig. 5a) and c)) resemble closely the results obtained by GYALISTRAS *et al.* (1994) for five other Alpine locations.

Interannual variations of T and $\sqrt{P}$ are better correlated in Winter and in Summer than in the transition seasons (Table 2c), such that the patterns shown in Fig. 5a) and c) explain only little, and the patterns shown in Fig. 5c) and d) almost none of year-to-year precipitation variability (Table 2d and e). $\sqrt{P}$ is thus mainly explained by the second canonical mode ($\vec{g}$-patterns not shown) which relates anomalously low $\sqrt{P}$ at Sion with anomalously high pressure situations over middle Europe in Winter and inhibited westerly flow in Spring, whereas positive precipitation anomalies are found to depend on the strength of W- and NW-flow in the Summer and Autumn seasons, respectively (cf. β_2 in Table 2).

	Winter		**Spring**		**Summer**		**Autumn**	
a	6		10		6		8	
b	84.7		89.1		73.3		89.4	
c	64.1		57.7		69.7		58.3	
ρ_1	0.89		0.93		0.92		0.92	
ρ_2	0.73		0.69		0.63		0.58	
	T	$\sqrt{\mathbf{P}}$	**T**	$\sqrt{\mathbf{P}}$	**T**	$\sqrt{\mathbf{P}}$	**T**	$\sqrt{\mathbf{P}}$
α_1, β_1	0.98	0.41	0.96	0.08	0.99	-0.34	0.98	-0.06
α_2, β_2	0.14	-0.90	0.24	-0.99	-0.05	0.93	-0.10	0.99
d	97.9	17.3	94.4	0.7	99.7	12.0	98.9	0.4
e	2.1	82.7	5.6	99.3	0.3	88.0	1.1	99.6

Table 2: Parameters of the CCA-models used to produce the patterns of Fig. 2. a: number of predictor EOFs used for CCA; b: corresponding percentage of total predictor variance explained; c: percentages of variances explained by first EOF of T and $\sqrt{P}$; $\rho_{1,2}$: canonical correlations of first and second canonical mode, respectively; α_1, β_1 and α_2, β_2: responses of predictands for the first and second canonical mode (in standard deviations of respective variable); d and e: percentages of predictand variances explained by first and second canonical mode, respectively.

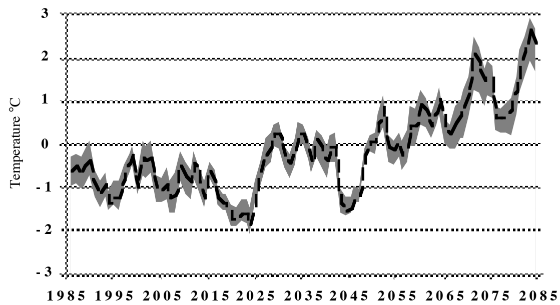
Fig. 5: First canonical corelation patterns for a) Winter, b) Spring, c) Summer, d) Autumn relating T and $\sqrt{P}$ at Sion with the large-scale state of the atmosphere as represented by the SLP and 2mT-field. *Left*: SLP sub-patterns (contour intervals 1, 0.5, 0.5 and 0.5 mb, respectively). *Right*: 2mT sub-patterns (contour intervals 1, 0.25, 0.1 and 0.2 ˚C). All CCA-models have been fitted for the years 1901-47 (data set A1) using both EOFs of T and $\sqrt{P}$ (see also Table 2).

c) Climatic change estimates

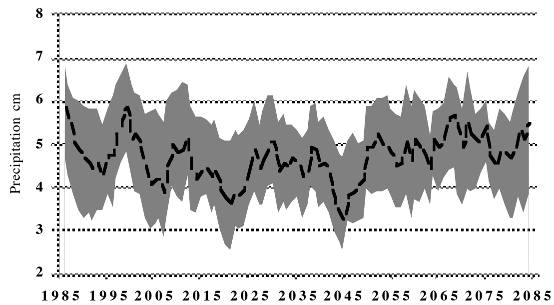
In this paper we derive scenarios considering changes in global climate forcings only. In particular we assume that under a changed global climate (a) the functions *f* specified by means of CCA remain valid, and that (b) all factors not considered in these functions remain stationary, i.e do not systematically contribute to changes in the mean or the variability of $\Delta \vec{l}_{(t)}$. This corresponds to the assumptions that local influences and feedbacks indicated in Fig. 1 remain unchanged or mutually cancel each other out, and that under climatic change the statistical parameters describing the residuals $\vec{\varepsilon}$ which account for variability due to e.g. smaller-scale erratic processes such as convective precipitation remain the same as for present-day climate.

Though P may not be well predicted for some months of the year (cf. Fig. 2), there exist two reasons why the established statistical relationships may still be applied, at least as zero-order approximations, for the derivation of scenarios: First, CCA-models based only on a small number of predictor EOFs may describe for the period of data for which they have been fitted the observed interannual variability of P under relatively high canonical correlations (Table 2) and based on plausible (Fig. 5), large-scale patterns. Second, the CCA-models may still capture the major variations of monthly P on a timescale of several years to decades. This is exemplified in Fig. 9 for Montana, but has been found to be valid for Sion as well: correlations between observed and reconstructed January and July P in the verification period 1958-77 on a year-to-year basis are 0.39 and 0.34, respectively, but for the shown 5-year running averaged timeseries (Fig. 9) amount to 0.78 and 0.57.

Fig. 6 shows the simultaneous transient changes in T and P obtained by Eq. 3b under GCM-simulated climatic change at Sion. In order to derive transient scenarios consistent with observed regional climate variability however, these time series would need to be corrected for systematical errors found in the interannual variability of the GCM-simulated SLP and 2mT-fields under current climatic boundary conditions (GYALISTRAS *et al.*, 1994). For this reason, in the following discussion we will focus on the mean states obtained for the last decade (2075-2084) of the climate change simulation.



a)



b)

Fig. 6: Projected (a) January mean temperatures and (b) January precipitation sums at Sion based on a simulation by the ECHAM1/LSG-GCM under the IPCC "Business-As-Usual" scenario for greenhouse-gas emmissions. *Dashed lines*: mean responses of 15 selected CCA-models estimated using data variants B1-B3. *Grey areas*: ranges of responses by the 15 models. The 1931-77 observed means and standard deviations are -0.29°C/2.14C and 5.64/3.58 cm, respectively.

Fig. 7 shows that climate change estimates obtained from models fitted to data set variants B1-B3 are for a monthly resolution mostly well within the range obtained with models fitted to the longer data sets A1-A3 (Fig. 7a and c). Seasonal changes seem to depend stronger on the choice of data sets, but are consistent with changes obtained from respective monthly changes (Fig. 7b and d).

The ranges of possible changes shown in Fig. 7 have been found to be mainly determined by differences between sets of models fitted to different periods of data rather than between models fitted to the same data, but using different numbers of $\vec{g}$ -EOFs. For example, Autumn T and P at Sion are more strongly cross-correlated during 1931-77 (variance explained by first EOF: 69%; 1901-47: 58%, cf. Tab. 2c), and their link to global-scale climate during this period is represented by a first SLP-pattern which is measuring the strength of southerly flow (not shown) and which is different from the more zonal pattern found for the first half of the century (Fig. 5d). Thus, the 1931-77 pattern possibly reflects more frequent southern föhn episodes reaching the valley floor during this period; under GCM-simulated climatic change the corresponding CCA models lead to precipitation changes (ranges by 5 selected CCA-models) of -35..-47% as opposed to +28..+49% estimated by models fited in 1901-47 (cf. Fig. 7d, all estimates contained in fourth bar from left).

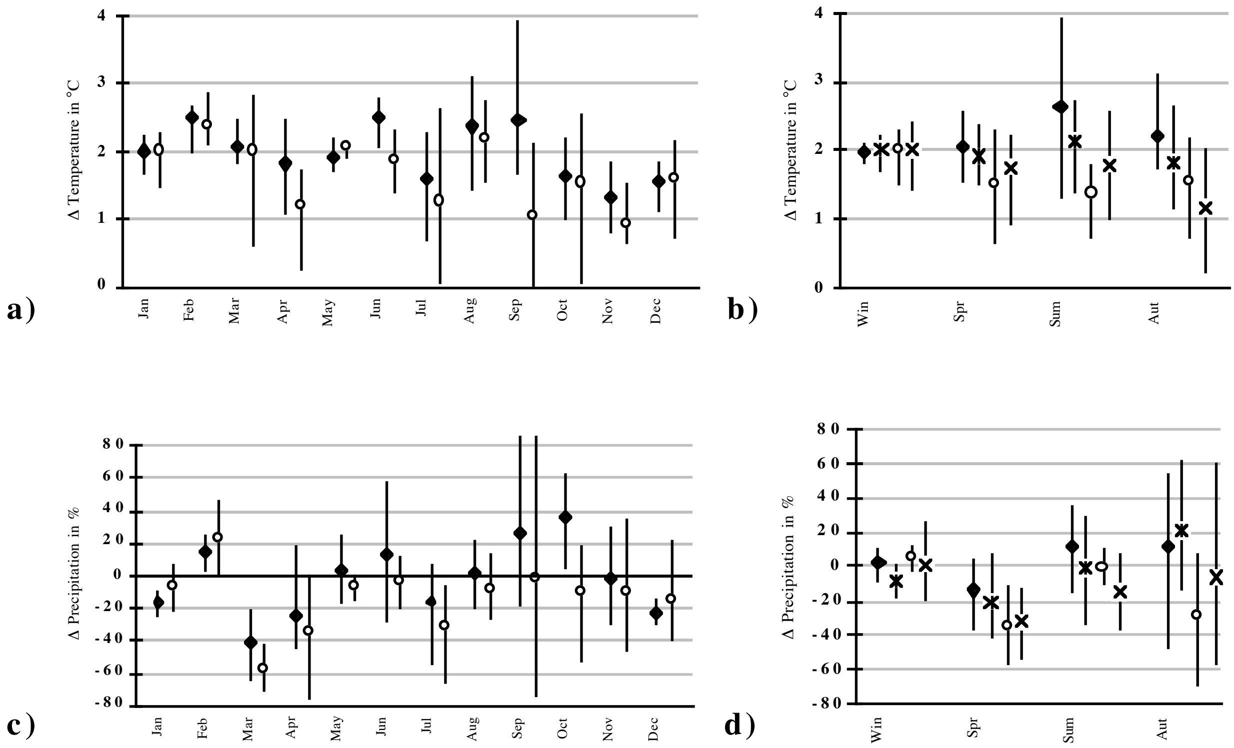


Fig. 7: Projected changes for a) monthly, b) seasonal mean temperatures and for c) monthly and d) seasonal precipitation sums at Sion downscaled from the last 10 years of the ECHAM1/LSG "Business-As-Usual"-simulation. Dots denote means, bars ranges obtained from 15 selected CC-models fitted separately for each month (season) using data set variants A1-A3 (black dots) and B1-B3 (white dots), respectively. "X"s in b) and d) denote seasonal averages derived from the respective monthly values given in a) and c).

The regional differentiation obtained between the four locations is mostly smaller than the ranges given in Fig. 7; for most months of the year however the downscaled estimates differ markedly from gridpoint-simulated changes (Fig. 8). The changes for the decade 2075-84 also differ from the changes in the range of 1.0-2.3˚C and 0..+53% (Winter), and 1.9-3.1˚C and -40..+30% (Summer) inferred by GYALISTRAS *et al.* (1994) for 5 northern, central and southern Alpine Swiss locations for the same GCM simulation.

The estimated temperature increases of 1.9˚C (Winter) and 2.0˚C (Summer) are small compared to the values of 2˚C and 2.5˚C given under the same greenhouse-gas emmissions scenario (IPCC- "Scenario A") for the area 35-50˚N and 10˚W-45˚E, but already for the year 2030, by MITCHELL *et al.* (1990). This discrepancy can partially be explained by the fact that the GCM-simulation used in our study does not account for warming that may have ocurred prior to the start of model integration (cold-start problem, CUBASCH *et al.*, 1992). The mean precipitation changes at all four locations of -3.5% (Winter) and -15% (Summer) are comparable to the values of +5% (Winter) and -10% (Summer) given by MITCHELL *et al.* (1990), but show large variations for the individual months (c.f. Fig. 8).

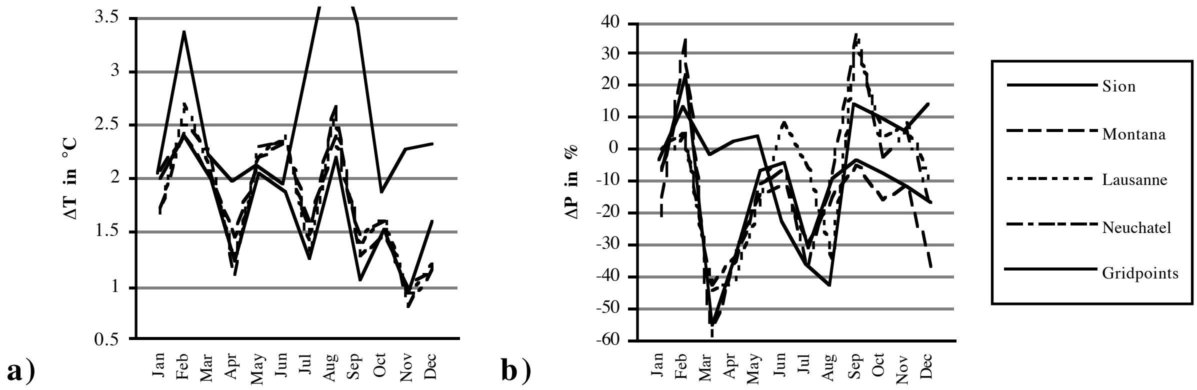


Fig. 8: From 15 selected CCA models projected mean changes in a) monthly mean temperatures and b) monthly precipitation sums at four locations in western Switzerland and gridpoint-simulated changes from three gridpoints in the vicinity of the Alps.

3.4. INTERPOLATION TO POINTS IN THE REGION

3.4.1 Method

Assuming that a linear relationship represents an approppriate first-order approximation, interpolation of a parameter X (i.e. T or P) from the base station B to a secondary station at a point $\vec{r}$ in space is accomplished by means of a linear regression

$$X(\vec{r}, t) = a(\vec{r})\; X_{B(t)} + b(\vec{r}) \qquad \text{Eq. 4a}$$

Changes in X relative to its mean state at any period π may then be estimated as

$$\Delta_\pi X(\vec{r}, t) = a(\vec{r})\; \Delta_\pi X_{B(t)} \qquad \text{Eq. 4b}$$

as can be obtained from Eq. 4 when using the approximation $\mu_\pi(X(\vec{r})) = a(\vec{r})\; \mu_\pi(X_B) + b(\vec{r})$.

In order to infer climatological or meteorological parameters at locations where no observations are available several procedures have been proposed till now (e.g. JENSEN, 1985; BENICHOU & BRETON, 1987; RUNNING *et al.*, 1987). Since development or adaptation of such methods for climate change studies is not within the scope of this paper, here we merely consider a weighted interpolation according to

$$X(\vec{r}, t) = \sum_{i=1}^{N} w_i \left(X_{i(t)} + g_{(H(\vec{r}),\, H(\vec{r_i}))} \right) \qquad \text{Eq. 5a}$$

where i counts the N stations available within a given radius R_{int} from the point of interest $\vec{r}$, w_i are the weights attributed in the interpolation to the observations X_i, and g represents a function that accounts for differences in topography H between a climate station and the ecosystem location.

Specification of scenarios for a point in space where no observations are available consists of two parts: First, the long-term mean of X needs to be estimated under current climatic conditions, as may be done by substituting in Eq. 5a the X_i with the respective observed long-term means $\mu_\pi(X_i)$. Second, observed or GCM-downscaled anomalies of X at the base station must be linked to corresponding deviations at the ecosystem location. If a linear approximation is chosen to this purpose, the task consists in estimating the covariance between realizations of X at the base station and at the ecosystem location, i.e. in estimating the regression coefficient $a(\vec{r})$ (Eq. 4a,b). Observed relationships between the base station and the secondary stations may be used hereby according to

$$\Delta_\pi X(\vec{r}, t) = \left\{ \sum_{i=1}^{N} w_i \, a(\vec{r_i}) \right\} \Delta_\pi X_{B(t)} \qquad \text{Eq. 5b}$$

as is obtained from Eq. 5a after substituting the X_i with the righ-hand side of Eq. 4a and subtraction of the long-term mean.

3.4.2 Results

We regressed (Eq. 4a) monthly T and P at Montana, Lausanne and Neuchatel from 20 years of observations at Sion, separately for each variable and month of the year. As could be expected from Fig. 4, predictability of P was found to decrease with geographical distance; the average explained variance ($100 \cdot r^2$) for all months of the year amounts to 84% for Montana, whereas for Lausanne and Neuchatel the average explained variances found were 65% for the Winter (Oct-Mar) and of 50% for the Summer (Apr-Sep) half-year. T may be predicted from Sion for all locations equally well from February to October with an average of 92% explained variance; correlations become however minimal from November to January and for the location of Montana (mean explained variance of 55%), confirming that local climates may depend more on exposition and on the vertical stratification of the atmosphere than on geographical distance.

Interpolation of long-term (20 years) means according to Eq. 5a was tested using a data basis of 41 climate stations distributed over Switzerland for T and P. For P allone we also considered a much denser network consisting of 80 stations around Sion (cf. Chap. 2). Each station was excluded once from the data set and its T and P were predicted from all, or a subset of, the remaining 40 (79) stations. The function g (Eq. 5a) was prescribed to account for altitudonal variation only, i.e. as the respective variable's altitudonal gradient function integrated from the height of the respective climate station to the height of the test station. Height dependencies of T and P were approximated as piecewise linear below and above 1500 m (BARRY, 1992 p. 233; URFER, 1979), the respective gradients being estimated by means of a linear regression of observed long-term means from height separately for each altitudonal zone and month. To this purpose, the respective 40 stations available for T were grouped into locations above and below 1500 m. For P, which shows regionally differentiated altitudonal gradients in the Swiss Alps (e.g. SCHÜEPP, 1978), we determined these groups using only stations found within R_{int} around the test location, but, if needed, increased this distance by 10% until at least 2 stations were available within each group.

Experiments with R_{int} = 20, 35, 55 and 110 km and with weights $w_i \propto 1/|\vec{r} - \vec{r_i})|$ and $w_i = 1/N$ yielded always the best results for the case of distance-independent weights, suggesting that the closest climate stations are not necessarily the most representative for a location of interest, and for regions of a size given by R_{int} = 55 km for T, and R_{int} = 35 km for P (when using the network with 80 stations). 90% of the differences between observed and interpolated long-term mean T were found within the empirical intervals given by ±1.7 °C (average for all months of the Winter half-year) and ±1.1 °C (average for Summer half-year), whereas 90% of the interpolated P-means were found to deviate by -34%..+75% (Winter half-year) and -32%..+61% (Summer half-year) from the respective observed values.

Interpolation of deviations (Eq. 5b) was evaluated by considering each of the 41 (80) stations as a base station and than determining as test locations all secondary stations at a maximum distance R_T = 30 km for T and R_P = 20 km for P from this station (cf. Chap. 3.3.1). The slope of the linear regression from the base to each test location was than estimated by means of Eq. 5b using all other secondary stations within the distance 2·R from the base.

Comparison of interpolated and actual regression slopes estimated from 20 years of observations showed that interpolation errors for T remain in a range of ±0.25 °C per 1 °C change at the base station, with 90% of the cases showing an error smaller than 0.2 °C/°C. For precipitation 90% of the errors remain within 4.2% of the respective test location's mean per 10% change at the base station, with a range from -6%..+9%. An increase of R_T to 75 km yielded for T the same 90%-interval as above, but a larger range of ±0.33 °C/°C. For R_P = 50 km, 90% of the estimates of ΔP deviated up to 5.4% per 10% ΔP at the base, and the range of deviations increased to -8.5%..+15%, thus confirming our more conservative initial choices for R.

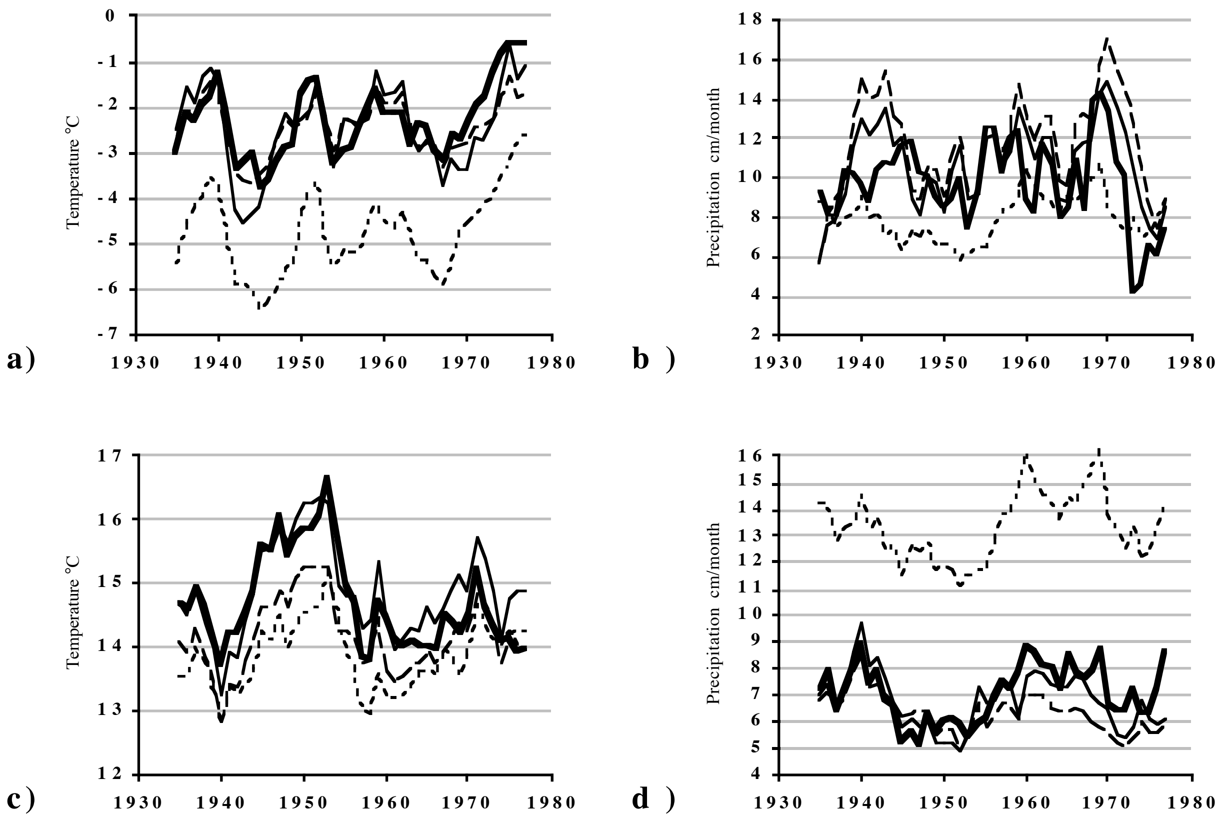


Fig. 9: Comparison of observed (thick lines) and reconstructed 5-year running averaged T and P at Montana for a), b) January and c), d) July. Thin lines: solid – mean responses of 5 selected CCA-models fitted for Montana for the years 1931-57 (data set B1); dashed – reconstruction from a linear regression based on the mean responses of 5 selected CCA-models fitted for Sion (data set B1); dotted – reconstruction based on downscaling at Sion and subsequent interpolation using Sion and additional 6 (T) and 18 (P) secondary stations.

In Fig. 9 observed T- and P-timeseries are compared with results from downscaling of observed SLP- and 2mT-fluctuations at Montana, and with timeseries downscaled at Sion and subsequently interpolated to Montana. Interpolation according to Eq. 5a systematically underestimates observed January and July mean T by -2.0 °C and -1.4 °C, respectively, most probably because our interpolation procedure does not account for the slope location and southerly exposition of Montana. Systematical errors for P amount to -10% and +80% of the observed January and July means, respectively. Estimation of the means for the years 1931-57 based on regressions (Eq. 4a) fitted for the years 1958-77 yields much smaller deviations of 0.0 °C and -0.7 °C for January and July T, respectively, and of +9% and -2.5% for P.

July P regressed from Sion deviates during the verification period 1958-77 by -0.7 cm from the directly reconstructed values (Fig. 9b). This difference is larger than the error of -0.2 cm in the estimation of the 1931-57 mean based on the regression, and also larger than the range (ca. ±0.3 cm, not shown) obtained at average by the reconstruction of P by different CCA-models fitted to the same period of data. Since the measurements at Sion and Montana seem mutually consistent (no systematic trend in the ratio of observed P over the entire 1931-77 period), and since 1958-77 mean precipitation increased relative to the period 1931-57 by 17% and 12% at Sion and Montana, respectively, it is likely that this inconsistency is due to changes in the large-scale circulation of July which are differently captured by the CCA-models fitted at the two locations.

Fig. 10 climate change estimates obtained by means of downscaling at a particular location and

(*

Additional 50-year data sets available at the more remote stations Lausanne and Neuchatel which reflect northern alpine climates with maximum precipitation occurring in Summer and annual precipitation sums of 1050 mm and 980 mm, respectively, allow to test whether the climate change estimates obtained for Sion would be representative if the region of interest were the entire western part of Switzerland, but if no data were available outside the Valais.

*)

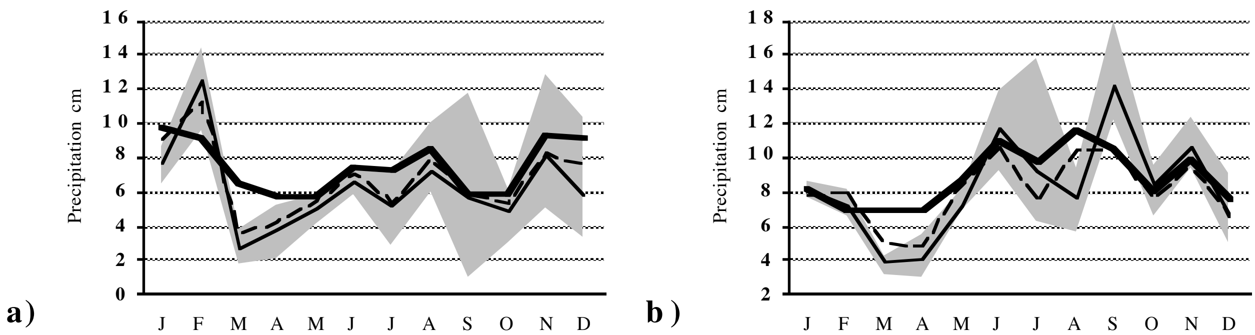


Fig. 10: a): Comparison of 1931-77 mean observed (*thick solid lines*) and of pojected monthly precipitation sums at Montana derived from the last 10 years of the ECHAM1/LSG "Business-As-Usual"-simulation. b): same as a), but for Lausanne. *Thin solid lines*: mean responses of 3x5 = 15 (data set variants B1-B3) selected CCA-models fitted for Montana (Lausanne); *grey areas*: ranges of changes projected by the 15 models; *dashed lines*: means have been inferred using Eq. 5 from changes projected by 15 selected CCA-models fitted for Sion.

4. CONCLUSIONS

Several advantages may be seen in the proposed subdivision of the overall task of scenario derivation into four well-defined parts (Fig. 1): first, the assumptions leading to a particular scenario can be more clearly specified; second, a framework is given within which the individual procedures involved may be independently improved and, as far as possible, automated; and third, each step may be considered as an entry point for iterations between the definition of requirements by ecosystem impact or sensitivity studies and the derivation of scenarios.

General rules concerning the definition of the region for which meaningfull scenarios may be specified seem difficult to find.

On the one hand climatological constraints, i.e.the representativity of climatic changes obtained at the base station for other locations is restricted by mesoscale forcings in the horizontal dimension (i.e. luv-lee effects) and discontinuities in the vertical dimension (i.e. inversion layers). Our results suggest that, as a rule of thumb for every month of the year, an upper horizontal limit in the Swiss Alps is in the order of 50 km for monthly pecipitation sums (P) and in the order 100 km for monthly mean temperatures (T).

(* Threshhold may be given by the geographical distance were correlation between realizations of a climate parameter no more different from zero *)

(* Representativity of changes along e.g. an altitudonal gradient should also be investigated. *)

On the other hand requirements of ecosystem studies setting the upper limits for the range of uncertainties that separate usefull from trivial scenarios. For forest ecosystem models this range is in the order of ±2 °C and 20% precipitation change. This is in the order of changes obtained for Sion and Montana, such that the scenarios derived in this paper may be considered as interesting inputs for forest gap models.

According to the current state of our procedure uncertainy ranges for the scenarios depend heavily on local data availability. If secondary stations with, say, 20 years of data are available, scenarios may be inferred with little loss of accurracy by means of a simple linear regression from the base station at which regionally differentiated climate change estimates may be downscaled (Fig. 10a). In this case, usefullnes of scenarios is only limited by the quality of the climate change estimates at the base station and it’s representativity for the secondary station.

The interpolation to points in space where no data are available may, the uncertainties may increase rapidly depending on the quality of the interpolation procedure. Abgesehen from the problem of the long-term means, interpolation of changes according to Eq. 5b may yield non-trivial scenarios at distances of ca. 30 km (P) to 50 km (T).

Errors are summarized in Fig. 11.

The following recommendation may be derived from this comparison

1) Better interpolation. Covers many new locations were something can be said!

Performance of our procedure which may be biased by the irregular distribution of the climate stations chosen as well as by “border” effects could be improved by a more differentiated selection of secondary stations and determination of altitudonal T and P gradients, e.g. based on expert knowledge of regional climates. Reduction of interpolation errors for T by at least 0.5 ˚C should however also be possible if slope and exposition are explicitely considered (e.g. URFER, 1979), whereas errors for P should be reduced by a more sophisticated inclusion of relief information (e.g. BENICHOU & BRETON, 1987).

2) Investigation and reduction of uncertainties inherent to scenario derivation at base station:

– Other DS-procedure, additional predictors, nonlinear

Reduction of uncertainties is particularly needed for P since this variable shows a larger spatial variability and is generally less well predicted than T.

– The uncertainties resulting from climatic change simulated under the same boundary conditions for the climate system, but by different GCMs, should however be quantified as well.

– local climate forcings

3) Investigation of usefullness of already available, shorter data sets (e.g. one or two years of daily measurements during the vegetation season) or setting up of measurements at regions of interest.

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