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Proposal for the development of climate scenarios

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ABSTRACT: Climate scenarios are important tools for the description of climate developments. A proposal for the construction of climate scenarios is presented in this paper. The idea consists of the calculation of possible climate developments on the basis of coupling the safest hypothesis on the development of the future climate (for instance from climate model results) for a selected region with observed data from this region. Therefore, a statistical algorithm was developed by maintaining the stability of the main statistical characteristics (variability, kind of frequency distribution, annual cycle, persistence). Using a special cluster analysis algorithm, complex scenarios could be calculated which guarantee temporal, spatial and physical consistency of the considered meteorological parameters. The quality of the method was demonstrated by calculation over an example data series. In addition, the practicability of the algorithm was demonstrated for a selected region of Germany by using different scenario examples.

KEY WORDS: Climate change · Climate scenarios · Cluster analysis

1. INTRODUCTION

The climate system of the earth is strongly nonlinear. This means that its development can be forecast only to a very limited degree (Lorenz 1963). Nevertheless, a possible means of obtaining predictions about possible climate developments and the impacts they are likely to have is the construction of scenarios. In this sense, a scenario describes an adjusted climate situation in which defined changes are made to selected driving forces over a limited time period. (A well-known example is increasing the concentration of greenhouse gases in the atmosphere.) The kind of each scenario depends on the alteration of the parameters which are investigated, the selected scale, and the question to be answered. Tools for the construction of scenarios are climate models [energy balance models, general circulation models] and statistical models. These 2 types of models can also be coupled. In the following, a statistical model for the development of climate scenarios is presented.

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2. PROBLEM DEFINITION

If climate changes are to be expected, then it is of particular interest to know what the regional impact of these changes will be. Current global climate models (GCMs) are still unable to deliver applicable results to describe the climate within a selected region (IPCC 1995). Therefore different ways of creating meteorological data must be used to describe climate developments in such a region. It is also important that consistency in space and time and also among the various meteorological parameters not be violated.

A number of different types of climate scenarios are currently being discussed within the scientific community. Three important types can be described as follows:

In the first method a regional climate model is embedded in a global model. In this case the global model supplies all large-scale information to the regional model (Machenhauer et al. 1996). The advantage of this procedure is the physical coupling of large- and small-scale processes. The disadvantage is that up to now the coupling and the processes have been reproduced inexactly. This leads to defects in the results which do not allow them to be used further in small-scale impact studies.

The second method is based on climate model results which are transformed into smaller scales using statistical methods (Zorita et al. 1993). With this method one can directly use the results of the GCM so that the physical propagation of defects into a regional model is avoided. One important disadvantage is that the defects of the climate model are transmitted directly into the scenario

The third method is based on the assumption that GCM results reflect mean large-scale climate changes more exactly for a defined region than for a number of grid points. Based on this assumption, long-term observed time series are prepared using statistical methods in such a way that they reflect the changes calculated by the GCM in a given scenario. The advantage of this method is that the defects of the GCM are reduced to a minimum. At the same time the consistency between the meteorological parameters can be ensured. A disadvantage is the lack of a physical connection between the GCM results and the given scenario.

In the following, an attempt is made to develop a scenario model on the basis of the third method to achieve improved results.

3. SCENARIO CONSTRUCTION: BASIC IDEA

The basis for the construction of a scenario is formed, on the one hand, by observed time series of meteorological parameters and, on the other hand, by information about the future development of climate (expressed by a selected climate parameter) calculated by the GCM. (For instance, the expected trend of an increase in temperature can be defined as such a parameter.) According to these conditions the expected changes (in general, a trend) are imposed on the observed values of the climate parameter (henceforth called the reference quantity). Using a special algorithm, the other observed meteorological parameters are adapted consistently to these changes. It is important to remember that the statistical characteristics have to be kept intact. Fig. 1 shows the complete scheme of the scenario calculation. It can be outlined as follows:

Step 1– Selection of information about a meteorological parameter from GCM results (for instance, trend of temperature over n years within a defined region).

Step 2– Making observed data available (for instance, a long time series of all available meteorological daily data for a number of stations in the investigation region).

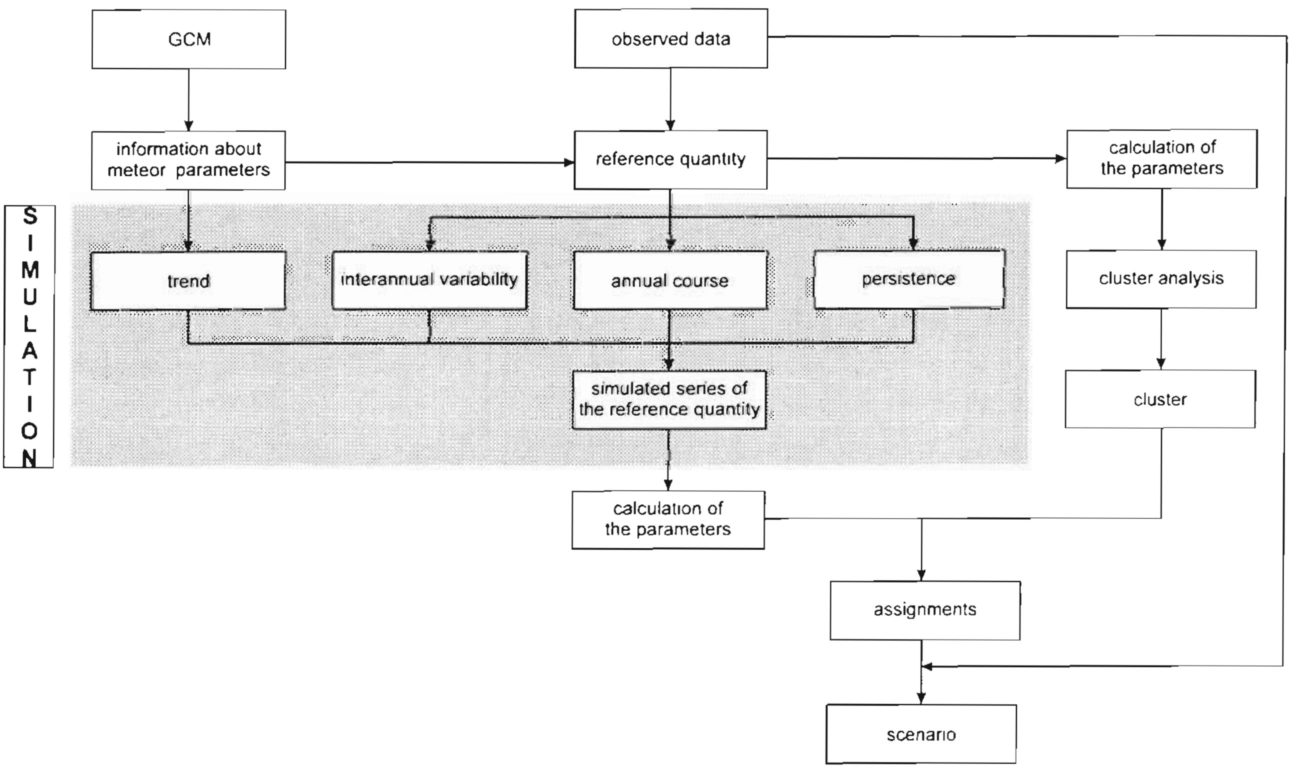


Fig 1 Scheme of scenario calculation

Step 3 – Simulation of the series of the reference quantity using the information from Step 1, maintaining the statistical characteristics of the observed data, i.e. interannual variability, annual course and persistence.

Step 4 – Cluster analysis based on those parameters which describe the reference quantity as exactly as possible. In general, these are the parameters with the highest degree of information (for instance, mean temperature can be described optimally using 3 parameters: maximum, minimum and daily range; Gerstengarbe & Werner 1992).

Step 5 – Calculation of the same parameter combination as in Step 4 for each time step (day) of the simulated series and assignment to the most similar cluster using the Mahalanobis distance.

Step 6 – Each parameter combination of the simulated series calculated in Step 5 can be completed with the observed data set which best corresponds to it.

In the following sections the basic idea will be described in greater detail.

4. DESCRIPTION OF THE OBSERVED CLIMATE

4.1. Statistical characteristics

The main condition of the method is that the statistical characteristics of the simulated climate not be different from those of the present climate. The first step is therefore to determine the statistical characteristics of the observed climate. These are the mean value of the reference quantity, the standard deviation, the persistence, the annual course and the interannual variability. These are well-known statistical characteristics, so a detailed description of them is not necessary. But it must be pointed out that the quality of the estimation of the characteristics depends strongly on the length of the observed time series (sample size). Also of importance is the dependence of the problem on resolution in space and time.

4.2. Inclusion of complex relations

In each time series of the reference quantity, a number of equal values normally exist. In addition, the causes which produce these values can be quite different. (For instance, equal daily mean temperatures can have different daily ranges because of different daily maximum and minimum temperatures, while the same daily ranges can be produced by different maxima and minima.) This has influences on the values of the other meteorological parameters which occur at the same time. Therefore the reference quantity must be characterised by 2 or more descriptive parameters in order to obtain a realistic consideration of the complex relations that exist. In the case of temperature these are, for instance, the daily minimum, the daily maximum and the daily range. If seasonal variations are considered, an additional parameter is necessary to describe these (this could be, among other things, the astronomically possible duration of sunshine).

After defining these parameters they can be exactly classified with the help of multivariate statistical procedures. For the present model an extended non-hierachical cluster analysis procedure is used.

Cluster analysis procedures enable several coherent parameters to be evaluated on a distribution-free basis and patterns to be identified. This is due to the transparency of these procedures and the multifarious ways in which they can be applied. The following investigations are carried out using non-hierarchical cluster procedures (Steinhausen & Langer 1977). The principle of this analysis can be described as follows:

– Definition of each element e_i by a number n of parameters p.
– Determination of an initial partition by sorting the elements on the basis of the parameters into a defined number k of clusters.
– Calculation of the group centroid $\bar{e}_m$.
– Euclidian distance calculation of the target function $z(g)$ for each grouping step g:

$$z(g) = \sum_{m=1}^{k} \sum_{i \in m} |e_i - \bar{e}_m|^2$$

– Realisation of grouping; a grouping step can be understood as the shifting of the elements e_i into the cluster with the nearest centroid $\bar{e}_k$, with respect to the Euclidian distance.
– Minimisation of the target function $z(g)\ \forall\ g \Rightarrow min.$

The target function reaches a local minimum if 2 successive grouping steps are equal. In this case, the iteration procedure is stopped, as the optimum classification to the given number of clusters has been obtained. Now, each cluster contains a number L of elements which, in general, differs from cluster to cluster. Although the cluster analysis has been completed, the number of clusters is not yet necessarily optimal. This requires an extension to the cluster analysis (Gerstengarbe & Werner 1997). Normally an absolute separation of the clusters is not possible under the condition of a well-defined number of clusters. In this case so-called 'overlaps' between the parameters of the clusters in the n-dimensional space exist. These 'overlaps' can serve as a starting point to answer questions as to the quality of the cluster separation and, in connection with this, as to the optimum number of clusters. The basic idea is as follows:

First, the number of 'overlaps' $U_{a,b}$ between 2 clusters a and b can be calculated as

$$U_{a,b} = \sum_{ia=1}^{L_a} \sum_{ib=1}^{L_b} \sum_{j=1}^{n} u_{ia,ib,j}$$

where $a = 1, \ldots, k-1$; $b = 2, \ldots, k$; the condition $\bar{e}_1 > \bar{e}_2 > \ldots \bar{e}_k$ applies; $u_{ia,ib,j} = 1$ for $p_{ib,j} \geq p_{ia,j}$; $u_{ia,ib,j} = 0$ for $p_{ib,j} < p_{ia,j}$; and an absolute separation exists for $U = 0$. Second, the maximum possible number of 'overlaps' is estimated by $U_{max} = n(L_a L_b - 1)$. Finally, using this previous knowledge, the quality of cluster separation and the optimal number of clusters can be statistically determined in the following steps:

Step 1 – Calculation of the mean number of maximum possible or actually existing 'overlaps' for all cluster combinations.

Step 2 – Testing whether the calculated mean values have the same basis (Student's t-test). If the zero hypothesis, which states that the mean values have the same basic sample, is not rejected, a statistically based separation of the clusters from each other will not be possible. Otherwise, it is possible to proceed as follows:

Step 3 – A corresponding ratio number related to the maximum possible number of 'overlaps' is determined by $v_{a,b} = U_{a,b}/U_{a,b\,max}$ for each actual number of 'overlaps' among the clusters.

Step 4 – Calculation of the mean value $\bar{v}$ over all $v_{a,b}$.

Step 5 – For the reasons given in Step 2, it must be true for any $v_{a,b} < \bar{v}$ that the cluster separation be statistically significant. This is not valid for any $v_{a,b} > \bar{v}$.

Step 6 – Testing of the frequency of occurrence $U_{a,b}$ against the mean frequency of occurrence U_m of 'overlaps' by means of an adjusted χ^2-test with the degree of freedom df = 1:

$$\chi^2 = [(U_{a,b} - U_m)^2 \cdot (2U_{a,b\,max} - 1)] / [(U_{a,b} + U_{a,b\,max}) \cdot (2U_{a,b\,max} - U_{a,b} - U_m)]$$

If the calculated χ^2-value is above a given significance value, the frequency of 'overlaps' above the mean value significantly deviates from it. That means that the separation between the clusters is not statistically valid. Otherwise, the separation is statistically valid.

Step 7 – Now, the initial number of clusters must be varied until at least a single statistically reliable separation between one cluster and the rest exists. If this is fulfilled, the elements of the separated cluster are noted as being a partial final result, and the initial series can be reduced by the separated cluster elements. This algorithm must be repeated until all clusters are separated. The optimal number of clusters is a result of the amount of clusters separated per algorithm step.

With this extended cluster analysis algorithm it is possible to calculate cluster patterns which are separated in a statistically valid manner. Similarly, one can estimate the optimum number of clusters. Clustering is carried out using a given number of elements to obtain the optimal number of clusters containing different quantities of elements (for instance days of a time series). It is then possible to relate the values of the other meteorological parameters to the elements within the clusters. This step is described in Section 6.

5. CONSTRUCTION OF THE SIMULATED CLIMATE: HANDLING THE REFERENCE QUANTITY

The simulated series of the reference quantity (temperature) is constructed in several steps. Once the daily mean values of a long-term observed time series are obtained, it is then possible to impose the given change (trend) onto the observed time series and to create the simulated series [although preliminary investigations showed that doing this in the reverse order (see Steps 1 and 2) led to better results]:

Step 1 – Calculation of annual means from the observed data series;
- estimation of interannual variability;
- classification of the annual means into 3 groups: below, within and above the standard deviation (we found that this categorisation could better capture the climate characteristics of each year).

Step 2 – Generation of a randomly distributed series of simulated annual temperature means using the statistical characteristics of the observed time series;
- classification of the annual means into 3 groups based on standard deviation as described above.

Step 3 – Imposition of the given change (trend) onto the simulated series.

Step 4 – Calculation of the time series of anomalies between daily and annual values for each year of observed data.

Step 5 – Random fitting of the anomalies to a simulated year based on the standard deviation classification (see Step 1);
- calculation of daily values by summing the annual mean, the given change and the anomaly.

Step 6 – Control and correction (if necessary) of the imulated time series (to assure that the statistical characteristics of the observed time series are preserved).

Step 7 – Calculation of the parameters defined for cluster analysis based on the simulated values (in order to fall back on the observed data).

Remark: when applying this algorithm, physical laws must be considered as well as the statistical characteristics. This means, for instance, that the simulated time series should contain no abrupt breaks.

6. LINKING THE OBSERVED AND SIMULATED CLIMATES

The simulation of the reference quantity is finished once Step 6 in Section 5 is completed. Next, the other meteorological parameters are related to the reference quantity using the parameter combinations calculated in Step 7 (see Section 5). Each of these parameter combinations can be assigned to exactly 1 cluster of the observed time series (see Section 4.2) if one uses the Mahalanobis distance as a criterion (Weber 1980). Then an element (day) is selected from the cluster. The other meteorological parameters can thus be related to a specific day of the simulated series while preserving their physical consistency.

It is also possible that values of the simulated series of the reference quantity occur outside the range of observed data. In this case it is assumed that the values of the meteorological parameters have nearly the same range as observed values in extreme clusters. Earlier investigations have shown that the error is much smaller using this assumption than when using a very conditioned extrapolation (Gerstengarbe & Werner 1987). It is thus possible to separate the elements which must be related to the reference quantity from those clusters that describe extreme regions.

A completely simulated climate scenario characterised by all given meteorological parameters is thus obtained for 1 station. However, more than 1 station is necessary to describe the spatial structure of the climate. If more stations exist, the observed spatial structure must be preserved for the climate simulation. To guarantee this one can proceed as follows:

For the description of regional climate changes it is permissible to assume that the investigation area can be regarded as a uniform climate region within a larger scale. A reference station is thus selected which represents the mean climate conditions of this region. Generally, the criteria are the mean, the standard deviation, the frequency distribution and the annual cycle of the reference quantity. If necessary, additional conditions can be defined. For this station the simulated climate is created as described above. Using this method each element (day) of the observed series which was introduced into the simulated series is known. It is therefore possible to define appropriate simulated series for each of the other stations simply by classifying the given observed data on the basis of each element (day). Thus the spatial consistency of the large-scale climate conditions is preserved.

7. EVIDENCE OF THE EFFICIENCY OF THE MODEL

7.1. Procedure

To test the efficiency of the model, 2 samples were selected from the complete (i.e. 1893–1994) observed data series from the Potsdam station: a so-called training sample (1893–1922) and a test sample (1965–1994). The temperature trend of the test sample was calculated (0.8 K) and used to develop a scenario for the time period 1965–1994 based on the training sample. Then the calculated values of the scenario were compared with those of the observed data from the test sample. The most important results are discussed here.

7.2. Results

The results of a simulation can be considered to be good if the mean and the standard deviation of the single parameters of the test sample and the scenario correspond well and if the structure of the frequency distributions and the persistence are preserved. This does not mean that the simulated and observed parameters must be from the same basic sample. Table 1 shows the means and standard deviations of the parameters used (observation and scenario). One can see that in each case the differences are very small and have no statistical significance (except the standard deviation of precipitation).

The magnitude of the calculated trend of the test sample is 0.8 K. This value was used to calculate the scenario. As an example, the annual mean of the daily maximum air temperature is presented in Fig. 2. One can notice that the 2 trends (observation 0.80 K and scenario 0.75 K) are statistically in agreement. The interannual variability of the scenario is slightly lower than the observed variability (minimum value: observed –1.4 K, scenario –2.3 K; maximum value: observed 1.9 K, scenario 2.0 K; standard deviation: observed 0.79, scenario 1.0). The non-synchronous course (resulting from the random selection of the

Table 1. Statistical characteristics for the comparison between observations (O) and simulations (S) for the period 1965-1994 for the Potsdam station (annual mean values). TMAX = maximum air temperature, TMEAN = mean air temperature, TMIN = minimum air temperature, PREC = precipitation sum, RELH = relative humidity, PREA = air pressure, PREV = vapour pressure, CLOU = cloudiness, SUND = sunshine duration

Parameter	Mean value		Standard deviation	
	O	S	O	S
TMAX (°C)	13.3	13.3	0.88	0.81
TMEAN (°C)	8.9	9.0	0.74	0.71
TMIN (°C)	5.0	5.1	0.70	0.68
PREC (mm)	594.6	592.7	102.68	80.20
RELH (%)	78.4	77.7	1.79	1.90
PREA (hPa)	1004.7	1004.8	1.17	1.18
PREV (hPa)	9.5	9.6	0.30	0.38
CLOU (1/10)	6.8	6.4	0.38	0.31
SUND (h)	1699.6	1715.9	139.36	150.55

years) is desirable and is unimportant for the description of the mean climatological conditions.

Fig. 3 shows the 2 frequency distributions (observation and scenario) of maximum air temperature. The 2 peaks in the observed distribution are among the most important characteristics, and the simulated distribution reflects these peaks very well. The deviations of the relative frequencies within some classes occur because the 2 time series are not from the same basic sample. Therefore, the null hypothesis that 'the 2 distributions are from the same basic sample' cannot be confirmed statistically.

A further statistical property is persistence, which can be shown by the frequency distribution of the duration of time during which various thresholds are exceeded and by the autocorrelation function. For both

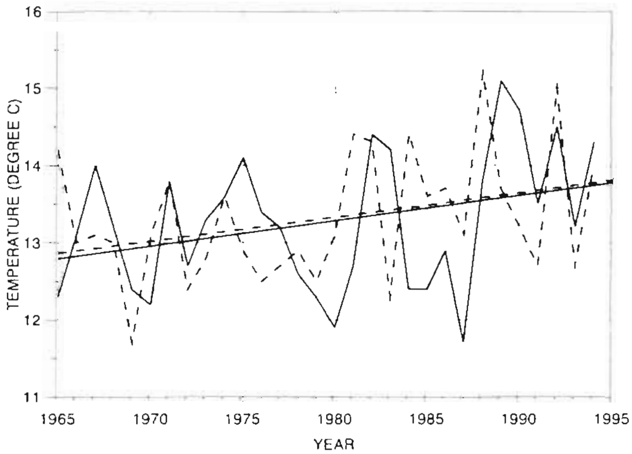


Fig. 2. Annual mean of daily maximum air temperature for Potsdam, 1965-1994. Solid line: observed; dashed line: simulated; straight lines: trends calculated by least-squares fit

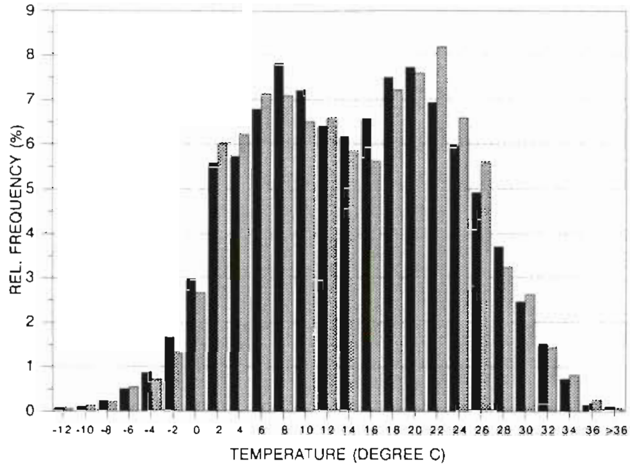


Fig. 3. Relative frequency of daily maximum air temperature for Potsdam, 1965-1994. Black: observed; grey: simulated

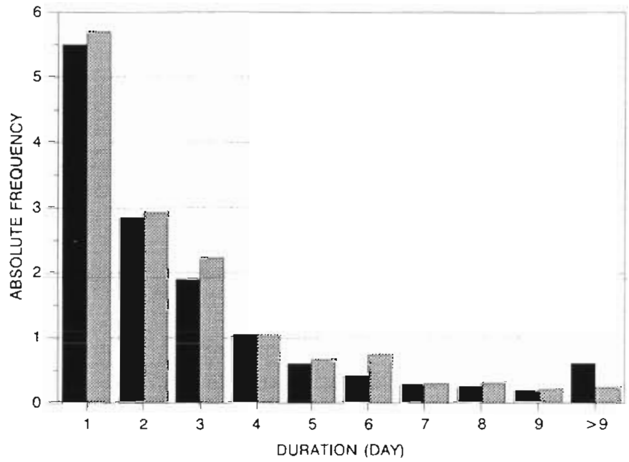


Fig. 4. Frequency distribution of the duration of days per annum with TMAX ≥ 25°C, for Potsdam, 1965-1994. Black: observed; grey: simulated

of these, results relating to daily maximum air temperature are presented in Figs. 4 & 5. In each case, observation and simulation are statistically in agreement. The results for other parameters of temperature are of similar quality (not presented here).

Because temperature was selected as the reference quantity, the scenario development for the remaining meteorological parameters is carried out by cluster analysis and cluster relation as described above. Methodologically this is not an identical procedure as that used to simulate temperature, so the results must be examined separately. The results of the precipitation simulation are presented as an example. Precipitation was chosen because it has only a slightly conservative nature (i.e. in a meteorological sense, relating to temporal and spatial occurrence).

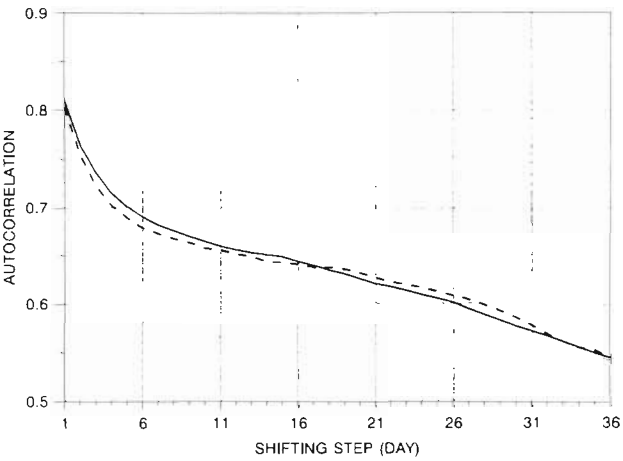


Fig. 5. Autocorrelation function of daily maximum air temperature for Potsdam, 1965–1994. Solid line: observed; dashed line: simulated

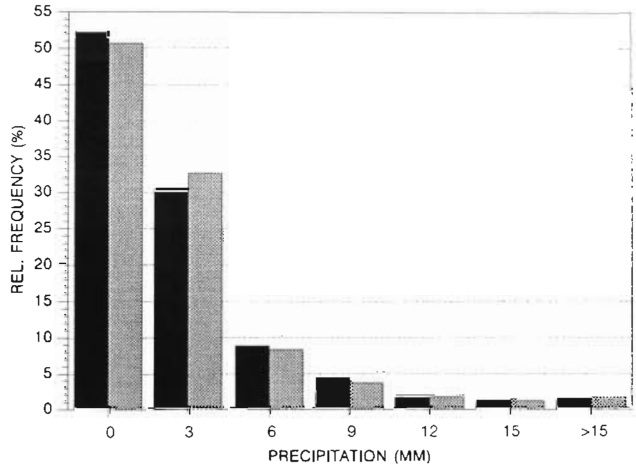


Fig. 7. Relative frequency of the daily sum of precipitation for Potsdam, 1965–1994. Black: observed; grey: simulated

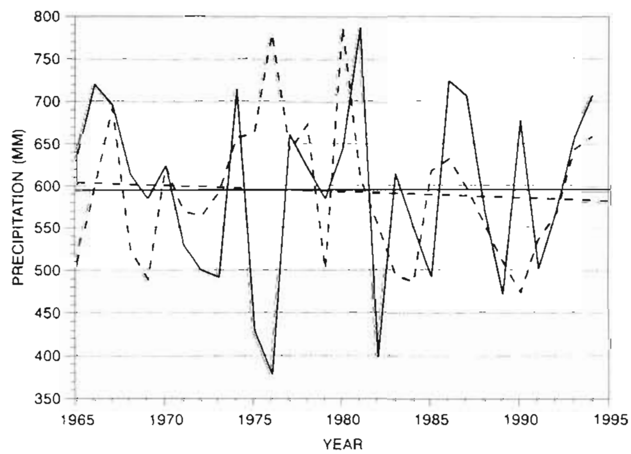


Fig. 6. Annual sum of precipitation for Potsdam, 1965–1994. Solid line: observed; dashed line: simulated; straight lines: trends calculated by least-squares fit

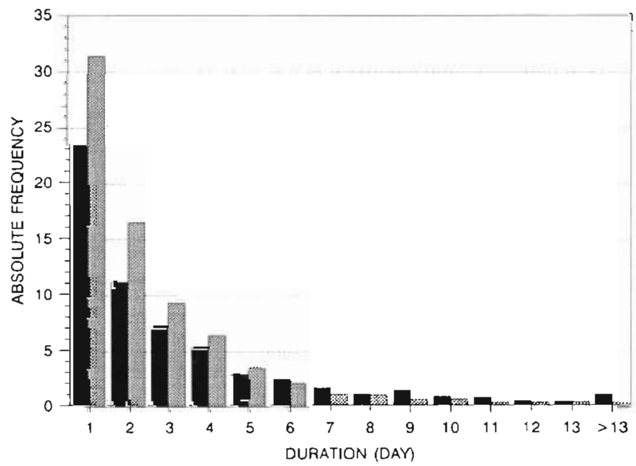


Fig. 8. Frequency distribution of the duration of days per annum without precipitation for Potsdam, 1965–1994. Black: observed; grey: simulated

Fig. 6 shows the time course of the annual precipitation. Simulated and observed values are in good agreement. This is shown by the means in Table 1. The standard deviation (see Table 1) and the interannual variability of the scenario are less than those for the observed data. A comparison of the relative frequency distributions (Fig. 7) shows that there is more than a 95% probability that they are from the same basic sample. Precipitation normally has only a very small persistence, so that an analysis of the autocorrelation function makes no sense. Only the results of the frequency distribution of the duration of days without precipitation can be analysed (Fig. 8). One can see that for durations up to 3 d the simulated values are clearly greater than the observed values and that very long durations are underestimated. The main cause is the loss of information during the classification algorithm, and an improvement of this is in principle impossible.

For all other investigated meteorological parameters (not presented here) the simulation values are of similar accuracy as those for precipitation. This test simulation therefore shows that the model is an acceptable tool for performing scenario-related tasks.

8. REALISATION OF DIFFERENT SCENARIOS

8.1. Basic conditions

The task considered here is the development of different climate scenarios for the state of Brandenburg up to the year 2050.

The following starting conditions are assumed:

Most investigations for the description of the future climate are carried out using GCMs. In the case of a further unlimited increase of the concentration of carbon dioxide in the atmosphere, these models calculate a global warming of between 1.5 and 4.5 K by the year 2100 (IPCC 1995). This warming is stronger over the continents and the regions near the poles than over the oceans and the equatorial zones. This means that an increase of temperature of about 2 to 4 K can be assumed for the Central European region within the next 100 yr. For the calculations this trend is defined as linear.

The discussed statements about future climate development can be treated as relatively safe in contrast to other meteorological parameters (Enquete-Kommission 1991). Therefore it makes sense to define the air temperature as the reference quantity. In this case daily values are necessary because this time scale is typical for many models used in climate impact research. The given trend is used for all parameters of temperature (daily mean, maximum and minimum) because they correlate closely with each other. In addition, there are no indications that the assumed trend is different for these 3 parameters within the Brandenburg region.

8.2. Scenarios

As mentioned in Section 8.1, the calculated expected warming varies over a relatively wide range. It therefore makes sense to calculate several scenarios in order to get a broad overview of possible developments. The following scenarios were calculated:

Basic scenario—BASC. This reflects the present climate over the period 1951–1990. It serves as the reference point for the evaluation of the changes within the simulations and is also used to calibrate the climate impact models.

Transient scenarios—ST04, ST15, ST30. For these, different linear trends were assumed for the time period 1996–2050 (0.4 K in ST04, 1.5 K in ST15, 3.0 K in ST30). The data for the first 2 trends are derived from the scenario runs of the GCM ECHAM-T21 of the Max Planck Institute for Meteorology, Hamburg, Germany (Cubasch et al. 1992). ST04 represents a scenario with a strong reduction of CO_2 emissions. With ST15 the 'business as usual' case is simulated. ST30 was additionally considered to investigate possible extreme impacts, and it should be noted that 3.0 K is within the range of the results of different climate models.

Equilibrium scenarios—SE04, SE15, SE30. Some of the impact models require an equilibrium climate state for their own calculations. Therefore, climate scenarios were calculated over a time period of 55 yr with an increased temperature of 0.4, 1.5 and 3.0 K.

8.3. Data

Data from 9 meteorological stations in Brandenburg, Germany, were used to describe the mean climate in this region (Table 2). The observation period covered 40 yr (1951–1990). In an earlier investigation (Lehmann & Gerstengarbe 1980), it was shown that the number of stations, the selected stations themselves and the time period comprise a complete characterisation of the Brandenburg climate. The Potsdam station was defined as the reference station because of the high quality of its data. For each station the 10 most important meteorological parameters were used (Table 3).

In addition, the astronomically possible sunshine duration was used to guarantee that equal data from different seasons were differentiated.

8.4. Realisation

With reference to the scheme for the scenario calculation (see Fig. 1) it is clear that all information is available with respect to the climate model, the reference quantity and the observed data. Subsequent to this cluster analysis is carried out. Four parameters were defined: daily maximum, minimum and range of air temperature, and the astronomically possible sunshine duration. The reference quantity was then simulated, and derived parameters from the simulated series were assigned to clusters. In this last step the complete scenario was created based on the observed data, and all stations were coupled.

Table 2. Meteorological stations used to describe the climate in Brandenburg. MSL: mean sea level

Station	Latitude	Longitude	Height above MSL
Potsdam	52° 23′ N	13° 04′ E	81 m
Marnitz	53° 19′ N	11° 56′ E	81 m
Angermünde	53° 02′ N	14° 00′ E	56 m
Zehdenick	52° 59′ N	13° 21′ E	46 m
Müncheberg	52° 31′ N	14° 07′ E	62 m
Lindenberg	52° 13′ N	14° 07′ E	98 m
Wittenberg	51° 53′ N	12° 39′ E	105 m
Cottbus	51° 47′ N	14° 19′ E	69 m
Doberlug-Kirchhain	51° 39′ N	13° 35′ E	97 m

Table 3. Meteorological parameters used in the calculation of climate scenarios for Brandenburg

Parameter	Unit	Acronym
Temperature (maximum, mean, minimum)	°C	TMAX, TMEAN, TMIN
Precipitation	mm	PREC
Relative air humidity	%	RELH
Air pressure	hPa	PREA
Vapour pressure	hPa	PREV
Sunshine duration	h	SUND
Cloudiness	1/10	CLOU
Saturation deficit	hPa	SATD

8.5. Results

8.5.1. Introductory remarks

In Section 7 it was shown that the proposed model fulfils the given requirements. Therefore, the results of only 2 scenarios (ST15, SE15) are discussed here. The evaluation focuses on the interpretation of temporal and spatial changes of the means, the durations, the frequency distributions and the extreme values.

8.5.2. ST15 scenario

The results of the ST15 scenario are illustrated by 2 examples. Fig. 9 shows the annual means of the daily maximum air temperature for 3 stations. One can see at once that the given trend (1.5 K) is exactly reproduced. The same can be said for all other parameters of the temperature and for all stations. Furthermore, one can see that the spatial structure (with Marnitz = coldest and Cottbus = warmest station in the region) is preserved. The nearly parallel course of the temperature curves indicates that the spatial characteristic of temperature in the region is also stable if climate changes of this magnitude occur. Also, the magnitude of interannual variability can be considered as stable.

The behaviour of the spatial consistency of precipitation is completely different to that of temperature (Fig. 10). On the one hand, the increase of precipitation is clearly different from station to station (an attribute confirmed by investigations carried out by Schönwiese et al. 1993). On the other hand, there are examples in which anomalies in the annual sum of precipitation are different from station to station. This can also be observed in the basic scenario.

8.5.3. SE15 scenario

The most important results of the comparison between BASC and SE15 are shown in Table 4 for all stations used. The table shows that for the parameters of temperature, the given change of 1.5 K is well reproduced, with deviations of maximally +0.3 and −0.2 K. In addition to the consistent spatial structure of the temperature distribution, the structure of the statistical parameters is also preserved. As an example of this, the 2-peak frequency distributions of the daily maximum air temperature for the scenarios BASC and SE15 are given in Fig. 11. The assumed increase of temperature of 1.5 K is reflected by the shifting of the SE15 frequency distribution to higher temperatures.

The character of the precipitation distribution can also be accepted as stable (Fig. 12). The figure shows

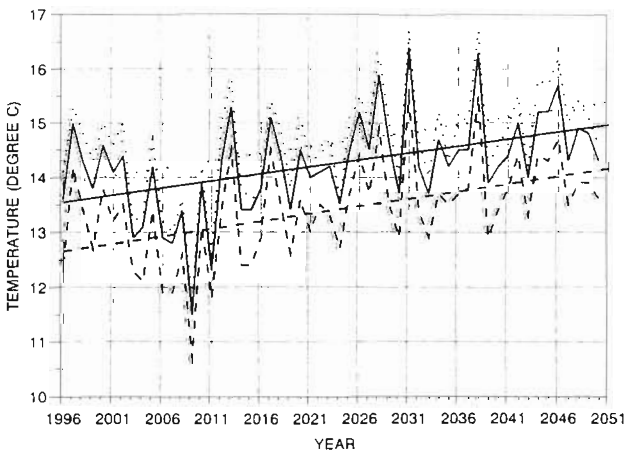


Fig. 9. Annual mean of daily maximum air temperature for scenario ST15, 1996–2050. Solid line: Potsdam; dashed line: Marnitz; dotted line: Cottbus; straight lines: trends calculated by least-squares fit

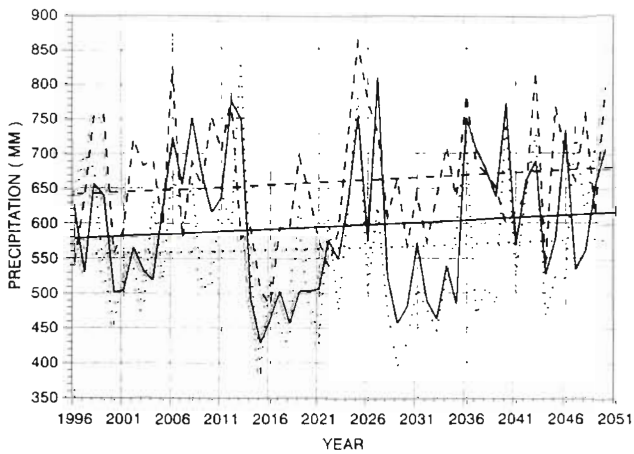


Fig. 10. Annual sum of precipitation for scenario ST15, 1996–2050. Solid line: Potsdam; dashed line: Marnitz; dotted line: Cottbus; straight lines: trends calculated by least-squares fit

Table 4. Annual values of selected meteorological parameters and stations for BASC during 1951-1990 and the deviations (Delta) of SE15 during 1996-2050 from them. Pdm: Potsdam; Mar: Marnitz; Ang: Angermünde; Zeh: Zehdenick; Mün: Müncheberg; Lin: Lindenberg; Wit: Wittenberg; Cot: Cottbus; Dob: Doberlug-Kirchhain

Parameter	Pdm	Mar	Ang	Zeh	Mün	Lin	Wit	Cot	Dob
TMAX	13.4	12.3	12.9	12.7	12.9	13.1	13.5	13.9	13.4
Delta	1.6	1.8	1.6	1.8	1.6	1.6	1.5	1.5	1.6
TMEAN	9.0	8.5	8.6	8.6	8.7	8.8	9.0	9.2	8.9
Delta	1.6	1.6	1.6	1.7	1.6	1.7	1.7	1.7	1.5
TMIN	5.1	5.1	4.7	4.8	4.9	5.2	5.3	5.1	4.8
Delta	1.6	1.4	1.5	1.3	1.3	1.6	1.5	1.6	1.4
PREC	598.3	628.4	495.9	569.4	547.9	592.3	566.3	545.5	553.2
Delta	−4.8	30.0	32.3	−25.6	−16.2	−38.8	6.1	24.9	7.1
RELH	78.4	78.4	78.9	77.2	79.1	77.1	75.6	75.7	76.8
Delta	−0.3	1.7	0.4	1.1	−0.1	0.4	1.5	1.0	1.6
PREA	1004.9	1004.6	1008.1	1009.2	1008.5	1002.7	1003.0	1007.3	1003.5
Delta	0.0	−0.1	0.0	−0.3	0.1	0.0	0.1	0.1	0.1
PREV	9.4	9.3	9.3	9.2	9.3	9.2	9.3	9.4	9.4
Delta	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
CLOU	6.9	6.9	6.8	6.3	6.8	6.6	6.7	6.6	6.6
Delta	−0.1	−0.1	0.0	−0.1	0.0	−0.1	0.0	−0.1	−0.1

that the precipitation-free days increase within the scenario SE15. However, the number of days with a precipitation of up to 3 mm decreases while the frequencies in the classes >3 mm precipitation are unchanged. For annual precipitation, scenario SE15 notes clear changes at a couple of stations (Fig. 13). These changes are quite different from station to station. The strongest increase is seen in northeast Brandenburg, sometimes higher than 30 mm yr^{-1}. The changes are similar in the northwest. In contrast, a decrease in annual precipitation of the same magnitude (more than 20 mm yr^{-1}) can be found in north and east Brandenburg. In all other areas changes are negligible (except in the extreme southeast where there is a small increase). In spite of all the changes, the large-scale structure of precipitation is essentially preserved.

An increase in relative humidity for almost the complete region can be observed. At the same time there is an inverse trend in the development of precipitation (Table 4). That indicates a shift in the seasonal precipitation distribution.

The changes in air pressure, vapour pressure and cloudiness are unimportant. In addition to the discussed mean conditions, the extremes are of special importance. Some characteristic data are given in Table 5.

The given temperature trend is reflected most clearly for the daily minimum of air temperature (from

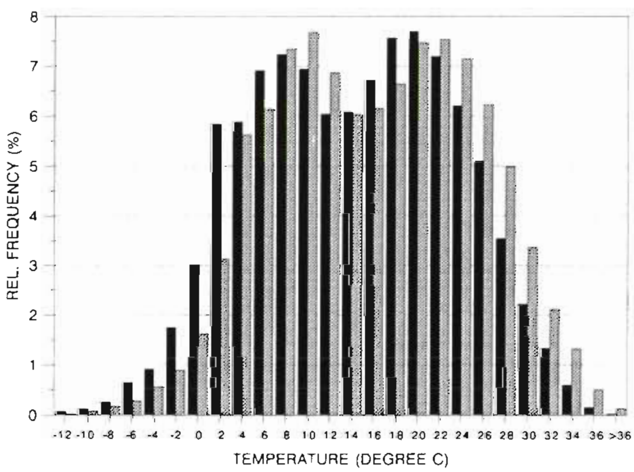


Fig. 11. Relative frequency of daily maximum air temperature for Potsdam. Black: BASC, 1951-1990; grey: SE15, 1996-2050

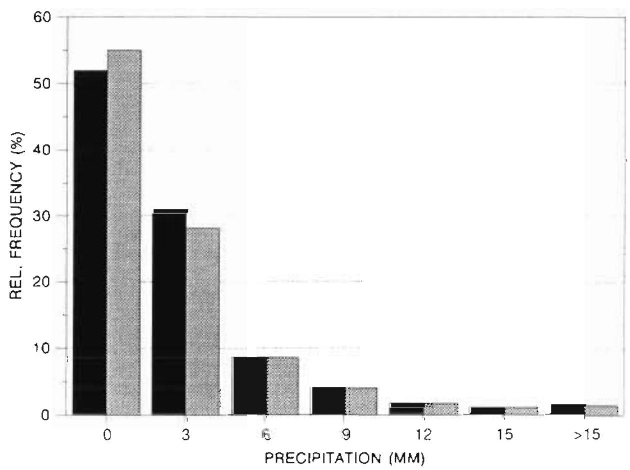
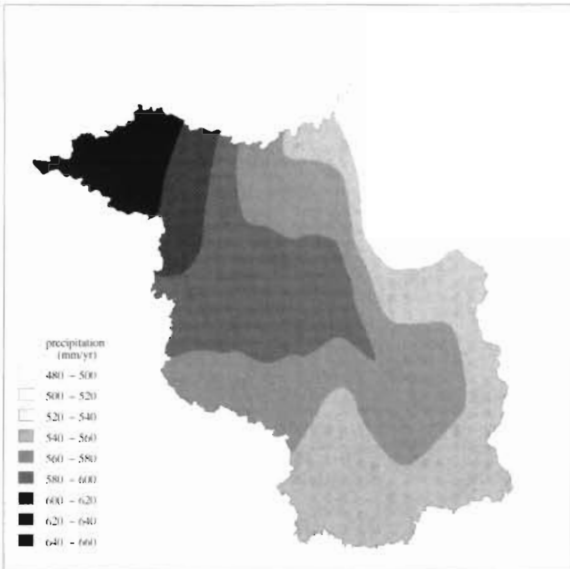
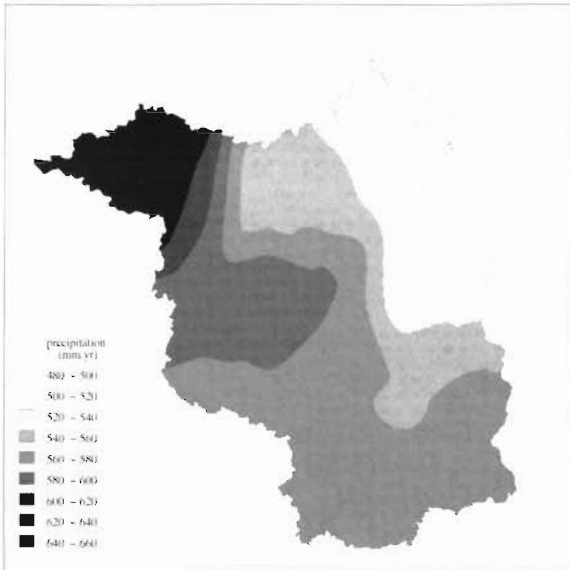


Fig. 12. Relative frequency of the daily sum of precipitation for Potsdam. Black: BASC, 1951-1990; grey: SE15, 1996-2050





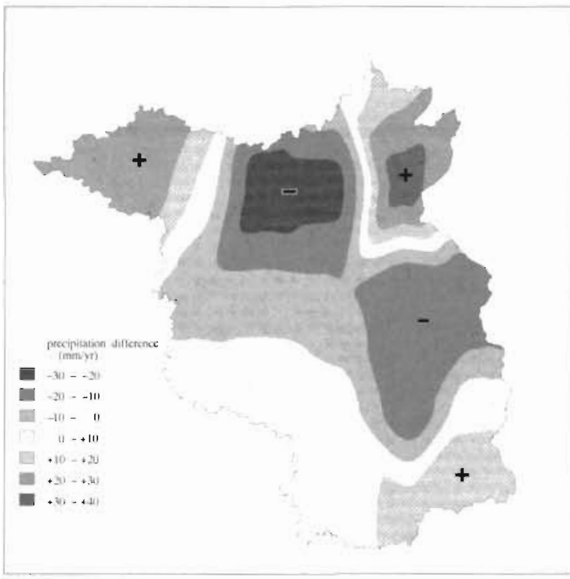


Fig. 13. Mean annual sums of precipitation for (a) Brandenburg during 1951–1990 (BASC) and (b) Brandenburg during 1996–2050 (SE15), and (c) differences of mean annual sums of precipitation for Brandenburg (SE15 – BASC)

−24.5 to −22.8°C). Strong changes were observed for the threshold of the natural extreme value region, especially for the parameters temperature and precipitation (for instance TMAX from 34.8 to 37.1°C). The most obvious changes in the behaviour of the extreme values is seen for different durations. The duration of 'hot days' (TMAX ≥ 30°C) increases by about 55% while that of 'cold days' (TMIN < −10°C) decreases by about 19%. The changes in precipitation and relative humidity are similar. The duration of days without precipitation is reduced by 13%, the duration of days with a relative humidity <60% by 25%.

Therefore, the hypothesis can be confirmed that climatic changes first become noticeable through strong changes of the extremes.

8.5.4. Climatological assessment of the results

The presented results are based on the most probable climate development up to the year 2050 (on the basis of existing knowledge). It means that for the most probable scenario (1.5 K) the expected climate development can be described as follows:

All parameters of temperature similarly reflect the given warming, while changes in precipitation are clearly different regionally. Together with this, the saturation deficit increases slightly, vapour pressure is nearly constant and relative humidity mostly increases. This means that, in general, humidity conditions are influenced by different local tendencies within the atmosphere. Strong changes can be observed in the

Table 5. Comparison of the extreme value behaviour of BASC and SE15 for the Potsdam station. Extreme value: the absolute largest or smallest observed extreme values; Extreme value region: the threshold of a natural extreme value region (which includes all values above or below a threshold which separates them in a statistically significant way from the basic sample; Gerstengarbe & Werner 1988); Duration: the sum of the 10 greatest durations for a defined threshold

Parameter		Extreme value		Extreme value region		Duration (d)	
		BASC	SE15	BASC	SE15	BASC	SE15
TMAX	(≥ 30°C)	38.4	38.7	34.8	37.1	71	110
TMIN	(< −10°C)	−24.5	−22.8	−20.8	−18.5	109	88
PREC	(≥ 0.1 mm)	104.8	104.9	41.7	36.3	208	181
RELH	(< 60%)	25.0	25.7	35.0	36.7	122	92
CLOU	(< 2/10)	–	–	–	–	66	56
	(≥ 9/10)	–	–	–	–	120	116
SATD	(≥ 20 hPa)	55.6	55.9	39.7	41.6	96	104

occurrence of extreme events, which tend to be more moderate than those observed up to now, except for the number of 'hot days'. Summarising, one can say that the simulated climate changes for the calculated scenarios are of the same magnitude as the observed climate variations within the last 40 yr for Central and Western Europe.

9. CONCLUSIONS

In the investigations presented here it was shown that the proposed model can be used very effectively to develop climate scenarios. This method produces climate scenarios under a wide range of assumptions about probable climate changes, which can be used as input for the calculations. This method allows one to return to the provided reference quantity with the safest information on its most probable future development. The condition that both the observed relationships between the different meteorological parameters and their statistical characteristics must be preserved in the case of a climate change is a certain restriction; however, in practice this restriction is unimportant because quantitative statements about possible changes in interannual variability, variations in the annual cycle, the frequency of extreme events and further characteristics are not available. This discussed method presents a practical technique for the creation of climate scenarios. This technique also makes it possible to calculate changes in the statistical characteristics of parameters under which climate change can be obtained, for instance, from GCM runs.

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