Climate simulations for the state of Hesse using a weather pattern-based regionalization method on the basis of ECHAM4 OPYC 3, scenario B2, for the time frames 2011/2020 and 2051/2100

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Introduction

In the year 2003 the company “Meteo Research” in Stahnsdorf was put in charge of a research project for the assessment of regional climate change. The client was the Hessian Agency for Environment and Geology. As in studies for the states of Saxonia, Bavaria, Baden-Württemberg and Thuringia, the time frame 2021-2050 was first investigated and then extended to include decades before this time frame as well as the period 2051-2100. Comparing the results for the different regions, clearly marked and orographically induced differences of a regional climate scenario appeared within the individual states.

In order to run hydrological simulations and forestry models an extension of the simulation time frame until 2100 and the closing of the gap between 2011 and 2020 were required. The solution was developed within the “Integrated climate protection programme Hesse 2012 – component II“ based on climate model scenario runs in T42 resolution from the Max Planck Institute Hamburg's ECHAM4. A second data pillar are meteorological observation data for the region of Hesse and its surroundings which include the time interval 1961-2000 and focus on the last two decades. These data were made available by the German Weather Service (DWD). A pool of 60 climate and 503 precipitation stations was used for the simulation of the climate change scenarios.

Method

The regionalization method has been developed and refined since the 1990s by Dr. W. Enke. Using reanalysis data, objective weather types are derived and classified according to distance criteria. If a synthetically and randomly assembled sequence of weather episodes meets several boundary conditions, it is calibrated using existing weather records by prescribing a frequency distribution of weather patterns of the current climate. The next paragraphs give an overview of the method's approach.

The first step consists of an objective classification of weather patterns. These are built from normalized fields of atmospheric properties. There are 10 classes (weather patterns) for the temperature regime and 8 classes (weather patterns) for the humidity regime in the four seasons. They are conditioned to have a good agreement with empirical classes: extremely cold to extremely warm when temperature is considered and extremely dry to extremely heavy precipitation when humidity is considered.

The time series of measured data are, taking temperature as an example, divided into episodes of above- and below-normal conditions. This is achieved by using temperature, averaged over all stations that are considered, as a guiding property, removing the annual cycle and smoothing the series, temporally. Applying a random generator, a re-combination of the segments is achieved. This simulated time series is constructed under the condition that the prescribed frequency distribution of the temperature regime (derived from reanalysis data for the past and a large-scale model scenario for the future) is met as closely as possible. Moreover, successive weather situations, i.e. newly combined days in the simulated series are required to exhibit a transition probability of at least 10 %. Each day of this simulated time series contains a pointer to the weather pattern class of the temperature and the humidity regime as well as the reference to the day of the year. The annual cycle of the meteorological properties is subsequently used to further modulate the simulated time series. At that stage, the simulated data are containing the value range of the measured data, yet, these may have a different frequency distribution.

In order to enable the modelling of new extreme conditions, the time series for all meteorological properties, except precipitation, are modulated using a weather pattern-specific deviation. This is computed from a representative grid point of a GCM and reflects the change in the large-scale atmospheric fields of a given decade, relative to the decade 2001-2010. The magnitude of these modulations is determined by way of regression.

The modulation of precipitation values is carried out for the whole study area (average of all stations) by way of fitting the average distribution of the precipitation classes to the frequency distribution of the humidity regime – this fitting is done separately for each decade and each simulation run. For each precipitation class, starting with the driest one, a day is randomly selected and the amount is raised by 10 % at all stations, whereupon the frequency distribution is re-computed. This procedure is performed iteratively until the prescribed frequency distribution of the humidity regime is met – individual days are allowed to be selected more than once.

Forced by daily realizations of a global circulation model (GCM – in our case the model ECHAM4 and the IPCC scenario B2) daily data series are generated. This is carried out for the locations of the aforementioned climate and precipitation stations of the German Weather Service. Each decade is considered separately and in order to increase the statistical stability the conditions in a decade are described by 200 years of modelled data. In addition, for all climate and precipitation stations and every decade 10 simulation runs are produced to cope with the variability of the method.

The data of the climate change projection which are well resolved in time and space constitute a suitable basis for studies of climate change impacts, e.g. in the fields of water management, agriculture and forestry.

Applications

The method has been applied successfully to numerous regional climate studies, e.g. KLIWA, GLOWA/Elbe, as well as for Saxonia, Thuringia and Hesse. It supplies time series of meteorological elements at individual stations. The method is capable of delivering a projection of the behavior of extreme weather in a climate scenario, albeit this property is subject to some error margins (cf. paragraph on the reliability of the projections).

Results

Temperature

The daily mean temperature shows its most pronounced changes in winter, amounting to about 4 K until the end of the 21st century (all changes referred to hereafter are in relation to the averages of the 1981-2000 period). The summer season shows a major increase of the temperature, too, whereas autumn and spring are characterized by a warming of a smaller magnitude. Similar developments can be observed for the daily maximum temperature for which an increase of up to 4.5 K can be expected. In summer the amounts are up to 3.4 K and in spring and autumn the trend is between 2 and 3 K. Daily minimum temperatures do not increase so strongly: In winter, the temperature gain is 4 K, in summer around 2 K and spring and autumn between 1 and 2 K. Concerning areal distributions within Hesse, no differences could be found until the middle of the 21st century. Then, the northeast shows a stronger increase than the south. Elevated areas have a stronger temperature trend in summer and lowlands have stronger trend in winter.

Precipitation

Until the middle of the 21st century, winters become more moist (precipitation increase of up to 25 %) and subsequently drier again. By the end of the 21st century the level of wintertime precipitation approaches the levels of the reference period again. Spring and summer are characterized by a clear drier climate (up to 30 % decrease of precipitation). No significant changes can be expected in autumn. The spatial variability of precipitation is very large in summer – and increases steadily; in winter it is comparably smaller, but a pronounced luff-lee effect can be seen. The summer decrease is stronger in the northeast and the hilly regions than in the south.

Other climate parameters

Sunshine duration increases most strongly in spring (continuous increase of a magnitude of up to 1.5 hours per day until the end of the 21^{st} century). In summer this increase amounts to 1 hour per day and already occurs in the first third of the 21^{st} century, then remains at that level. No significant changes can be detected for autumn and winter.

Wind speed and relative humidity show no major trends or changes.

Extreme events

For spring and summer, the highest values of daily maximum temperature are reached around the middle of the 21^{st} century followed by a stagnation on this high level or a small decline. In autumn and winter the maximum temperatures increase permanently. The number of extremely hot days (maxima above 35°C) increases until the end of the century which is an indicator for an increase in the duration of hot spells.

Despite the dryness that increases in summer, the number of days with extreme precipitation becomes larger, too. This points to a changing climate in which dry stress is more pronounced in combination with higher damage rates to soils which are caused by runoff from intense rainfall events which could otherwise seep into the ground. On the other hand, the tendency towards high precipitation amounts decreases in the winter season.

Reliability of the projections

The statistical methods supply a range of results. Therefore, there are always ten model runs. In general terms it should be expected that results of rather robust parameters such as the daily mean temperature are subject to small errors, unlike of the results of more complex parameters such as the spatial distribution of precipitation. The largest margin of error is expected in conjunction with extreme values, because all statistical methods are facing difficulties when dealing with new states that have not been present in the existing sample.

Outlook

The climate projections of the company Meteo Research are based on the global climate model ECHAM4 and the scenario B2 which tends to be on the moderate side of affairs. In the near future there will definitely be new and substantially more comprehensive data available for climate projections. Rooted in ECHAM5 results, new climate projections are intended to be produced by the Meteo Research statistical downscaling method for the IPCC scenarios A1B, A2 and B1. This enables arriving at more reliable projections as well as covering a range of possible impacts of the changing climate.