Europ.J.Hort.Sci., **77** (6). S. 241–248, 2012, ISSN 1611-4426.

High Resolved Simulation of Climate Change Impact on Greenhouse Energy Consumption in Germany

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Summary

Increasing energy costs are a main concern in greenhouse plant production. At this it is uncertain, how the expected climate change will affect this problem regionally. Therefore the future greenhouse energy consumption was simulated with the help of climate realizations of high spatio-temporal resolution from the regional climate model REMO (UBA-Runs), based on the IPCC climate projections A1B, A2 and B1. Simulations were conducted for each hour of the periods 2001–2015 and 2031–45 on a 100 km × 100 km grid for Germany, as well as continuously for each hour from 1951 to 2099 on a 10 km × 10 km grid for the federal department Lower Saxony (Germany), employing the energy simulation system HORTEX. Furthermore the influence of a consistent 2-d bias correction on the projected signal was tested in a case study (53° 03' N, 08° 48' E). The results consistently show a strong mean decrease of greenhouse energy consumption for all scenarios by 2038 and up to 45 % for the area of Germany, diverging regionally. Higher absolute reductions in energy consumption can be expected in warm greenhouses, while low temperature set points result in higher relative energy consumption reduction. The latter might influence future utilisation concepts.

Key words. bias correction – climate change – energy consumption – greenhouse

Introduction

The increase of energy costs of the last decades to a present crude oil price of above one hundred dollars per barrel (Useia 2012), as well as the influences of the increasing scarcity of resources or environmental standards along with pricing policy are indicators of a lasting trend. Being potentially existence-threatening, this is a main concern to energy-intensive sectors. Since the energy consumption of German greenhouse production is up to 0.5 % (calculation based on data from Statistisches Bundesamt 2006, 2012) of the total industrial energy, it is important to analyse possible changes of greenhouse energy use in relation to climatic change effects. Besides fluctuating energy costs it is further unknown, how climate change will affect the energy consumption of greenhouses regionally in the long run. At this, changes in driving forces as temperature or radiation will influence future energy consumption. While climatic warming can be expected to reduce the energy demand for greenhouse heating in the mean, particular attention should be paid to the utilisation concepts of greenhouses regarding cold and warm temperature strategies, as well as to the regionally varying climatic impact. Despite Hoffmann and Rath (2009) investigated the climatic impact on greenhouse energy consumption, no literature has been published so far concerning simulation studies with different spatial resolution and optimization of the input data.

Objectives

Highly resolved simulations of future greenhouse energy consumption are necessary to consider regional climatic changes. For this uncorrected and locally bias corrected climate data should be consequently applied and interpreted in case studies to simulate the pattern of energy consumption.

Material and Methods

Simulation input: Greenhouses

In order to estimate the impact of the regional climate change, future greenhouse energy consumption was simulated with the help of the greenhouse energy simulation system HORTEX (Rath 1994, 2006). Three different simulations were conducted with year-round lower temperature set point values (day/night) of 5/5 °C and 18/16 °C. Greenhouse settings for energy simulation are shown by Table 1.

Table 1. Basic simulation input settings for HORTEX.

Domain	Input parameter	Unit	Setting
Climate	hourly ambient air temperature[a]	°C	varying sim. parameter
	hourly global radiation	W m^{-2} s^{-1}	varying sim. parameter
	average wind speed	m s^{-1}	4
Greenhouse	construction	–	Venlo-type
	U'-value	W m^{-2} K^{-1}	7.6
	ground area	m^2	10000
	greenhouse cover	–	single glazing
	energy screen	–	one-layer standard
	side wall height	m	4
Control	heating set point (day / night)	°C	5/5; 18/16
	venting set point	°C	30
	energy screen threshold	W m^{-2} s^{-1}	0.1[b]
	assimilation lighting	–	none
	heating system	–	mixed

[a] in 2 m height above ground
[b] global radiation

Simulation input: Climatic Data

Regional projections based on simulated climate time series were conducted to investigate the impact of a climate change on greenhouse energy consumption. Climate data from realizations (first run) from of the regional climate model REMO (driven by the general circulation model ECHAM5) of the Intergovernmental Panel on Climate Change (IPCC) climate projections A2, B1 (simulation 1) and A1B (simulations 2 and 3) were used (Mpi 2012). Hereby the IPCC-scenarios, resulting in different greenhouse gas emission scenarios (SRES) on which climate projections are based, assume either a heterogeneous world with continuously increasing population and regionally oriented economic development (A2), or a convergent world with a population that peaks in mid-century and declines thereafter as well as fast changes in economic structures (B1, A1B). Hence the present findings follow the chain of information: IPCC scenario > emission scenario > climate projection > climatic impact simulation.

According to these scenarios, air temperature in Central Europe will rise by 2.5 °C (B1) and 3.7 °C (A1B, A2) by the end of the century as compared to 1961–1990 (Roeckner et al. 2006). Hereby increases of temperature will mainly occur during the 2nd half of the century with temperature increases for Germany during the period investigated (simulation 1) of 0.1 °C (B1) and 0.9 °C (A2) by 2038 as compared to 2008 (both 15-year- mean).

For the simulation the air temperature (in 2 m height above ground) was corrected for altitude (–0.0064 °C m^{-1}). Global radiation was calculated from the net down- and upward surface radiation of the REMO data (Mpi 2012). Wind speed was set constant to 4 m s^{-1}, both in order to account for regional/small scale effects and to ensure the comparability of the results.

Simulation 1: Greenhouse energy consumption in Germany

Simulated hourly climate data from the periods 2001–2015 and 2031–2045 of approximately 10 km (0.088°) resolution was aggregated to 57 areas in Germany of approximately 100 km × 100 km by taking the mean of all grid points inside the corresponding area. Subsequently, the mean of each of the 8760 hours of the year was calculated for each period (see also Hoffmann and Rath 2009).

Simulation 2: Greenhouse energy consumption in Lower Saxony

A second simulation was conducted for each hour from 1951 to 2099 on higher resolution for the area of Lower Saxony (Germany). The spatial mean of areas consisting of 3 × 3 grid points (~30 km × 30 km) was calculated for 783 adjacent grid points, hence obtaining the spatial floating mean of 783 overlapping areas with a grid resolution of 10 km × 10 km. Unlike simulation 1, simulation 2 was conducted using each hour of each year of the climatic data instead of taking the mean of each hour over the years. Final results of energy consumption were brought to a regular grid by ordinary kriging (Wackernagel 1995) for the purpose of visualization.

Simulation 3: Greenhouse energy consumption simulated with bias corrected climatic data (case study Bremen)

In order to estimate the influence of the simulated climate data quality on the computed energy consumption, the latter was additionally computed with bias corrected climate data in a case study. For this, hourly climate data (1951 to 2099) at 53° 03' N, 08° 48' E from the German Meteorological Survey (DWD) was used to remove the bias of the simulated data by applying distribution based bias correction (Quantile mapping), established by Ines and Hansen (2006) and Piani et al. (2010). To restore the necessary climate variable consistency, quantile mapping was applied 2-dimensionally as described by Hoffmann and Rath (2012). For this, correction or transfer functions from simulated to measured data were obtained by mapping air temperature and global radiation non-parametrically by applying a gaussian kernel with bandwidth h = 0.1 (Bowman and Azzalini 1997) and a optimization factor K = 0.5 (see Hoffmann and Rath 2012). Hereby transfer functions were derived from 1977–2010 and applied further to REMO data from 1951–2099.

Results

According to simulation 1, greenhouse energy consumption will decrease in the mean, regardless of temperature setting or scenario. For Germany, area average reductions up to 45 % and up to 45 kWh m^{-2} $year^{-1}$ were found, depending on greenhouse temperature settings and on the chosen climate scenario (Fig. 1, 2). At this, stronger decreases were found in the warmer scenario A2 than in scenario B1. Further, stronger absolute but lower relative reductions (average 10 %) were found for higher greenhouse temperature settings of 18/16 °C (Fig. 2), while settings of 5/5 °C led to area average reductions of up to 50 % (Fig. 1). Unlike these mean tendencies, regional variation ranges from reductions of 89.6 % to an increase of 3.5 %, although no increases were found for the warmer scenario A2. Hereby low temperature settings led to a stronger decrease in south-east of Germany (which exhibits higher altitude) than in the north. This pattern was also found for higher temperature settings within in the scenario B1, but not for scenario A2. The latter shows an 'east-to-west distribution' with higher reductions in the east.

Simulation 2 for Lower Saxony confirmed the findings from scenario A2 on a 100 times finer grid for scenario A1B (Fig. 3, 4). Hereby energy consumption reflects the orography of the region, e.g. with the higher elevated south-east of Lower Saxony displaying higher energy consumption. Past to present energy consumption is apparently dominated by a periodicity of cold and warm climate cycles (Fig. 3, 4), fluctuating around the present level. Nevertheless the downward trend in energy consumption arises by the mid of the 21st century, manifesting further in the distribution of the annual sum of greenhouse energy consumption (Fig. 5). As shown, a stronger mean shift of the distribution is found from 2011–2040 to 2061–2090, than from 1961–1990 to 2011–2040. Furthermore, regarding the extremes of the distribution, a shift of the mean is

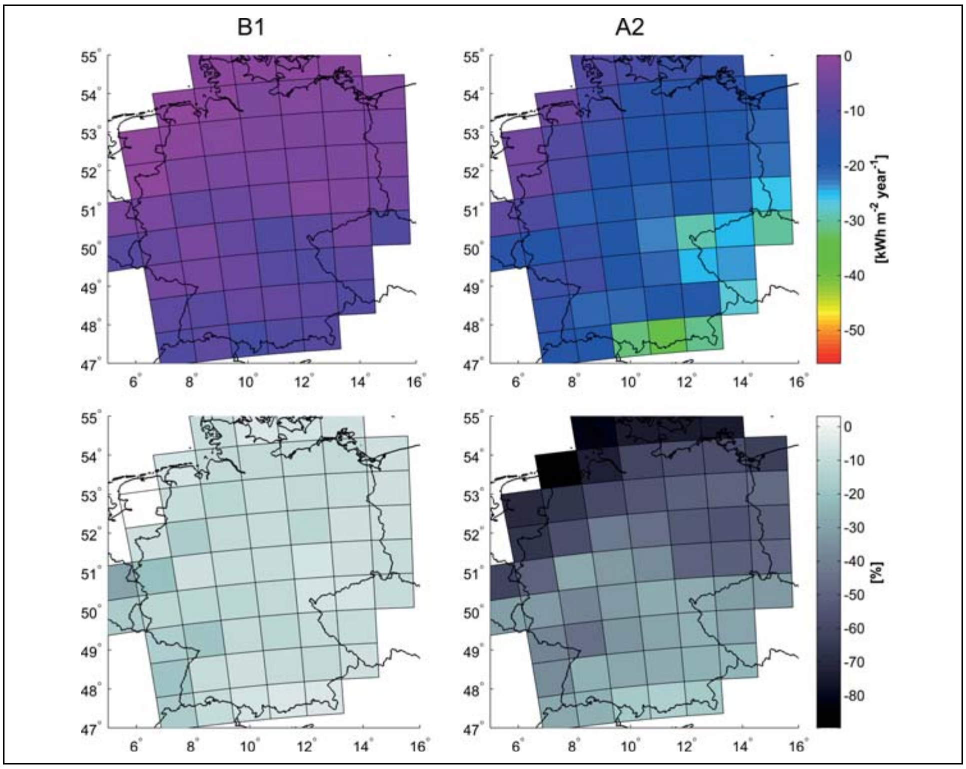

Fig. 1. Projected changes in greenhouse energy consumption in Germany by 2031–2045 as compared to 2001–2015 for scenarios B1 and A2 and temperature set-points 5/5 °C.

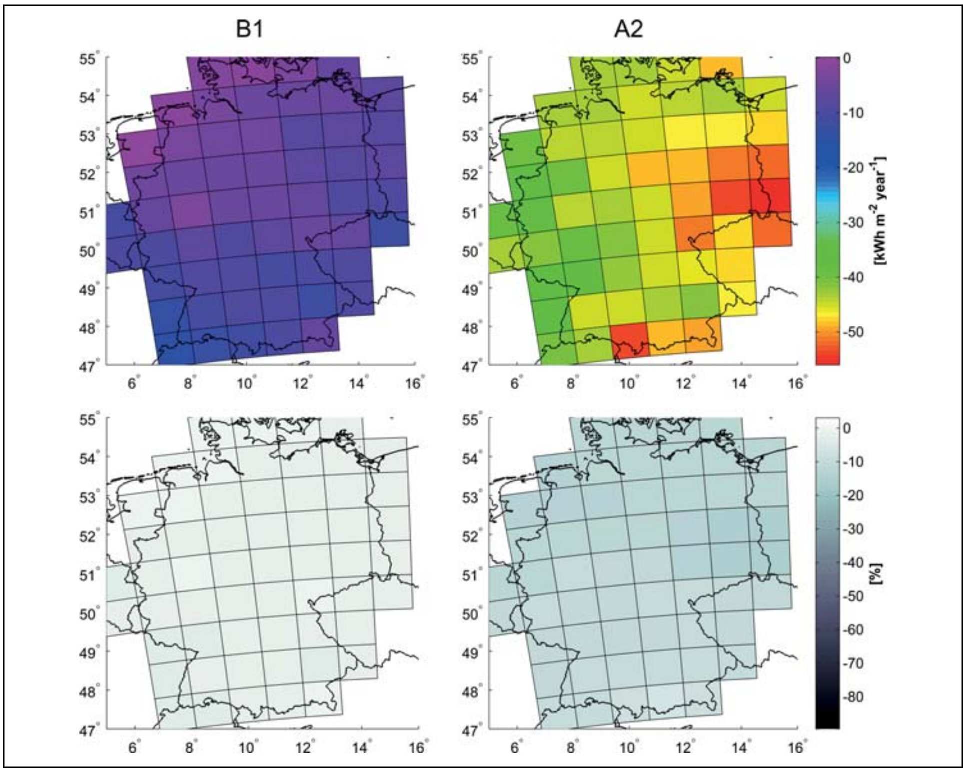

Fig. 2. Projected changes in greenhouse energy consumption in Germany by 2031–2045 as compared to 2001–2015 for scenarios B1 and A2 and temperature set-points 18/16 °C.

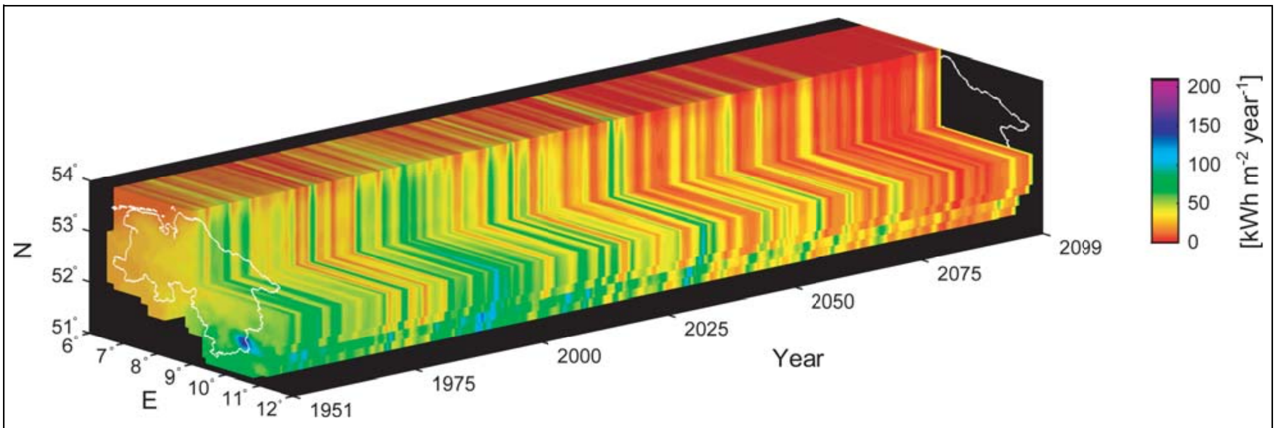

Fig. 3. Projected greenhouse energy consumption in Lower Saxony simulated for the climate scenario A1B and temperature set-points 5/5 °C (day/night).

observed prior to the reduction of the upper extreme, resulting in an increased variance.

Regarding simulation 3, a bias correction of the simulated climate data (REMO) for Bremen decreased the mean deviation from simulated to measured climate variables (Table 2). Hereby underestimation of global radiation and overestimation of mean air temperature were removed, resulting in an overestimation of global radiation by ~1 % (1977–2010). However, reduction of the previous climate model bias resulted in discrepancies of the energy consumption calculated from measured and simulated-corrected climate data (~3 %). At this, the range of energy consumption in terms of annual sums from measured data was fairly reproduced with both simulated and simulated-corrected climate data (see grey rectangles, Fig. 6). Years with elevated energy consumption exhibited further increased energy consumption after bias correction of the underlying data. While energy consumption from corrected data was underestimated in the period from 1977–2010 compared to calculations from measured data, projection for all REMO years with corrected climate data resulted in higher energy consumption compared to the projection with uncorrected climate data (Table 2, Fig. 6). Hereby energy consumption was in-

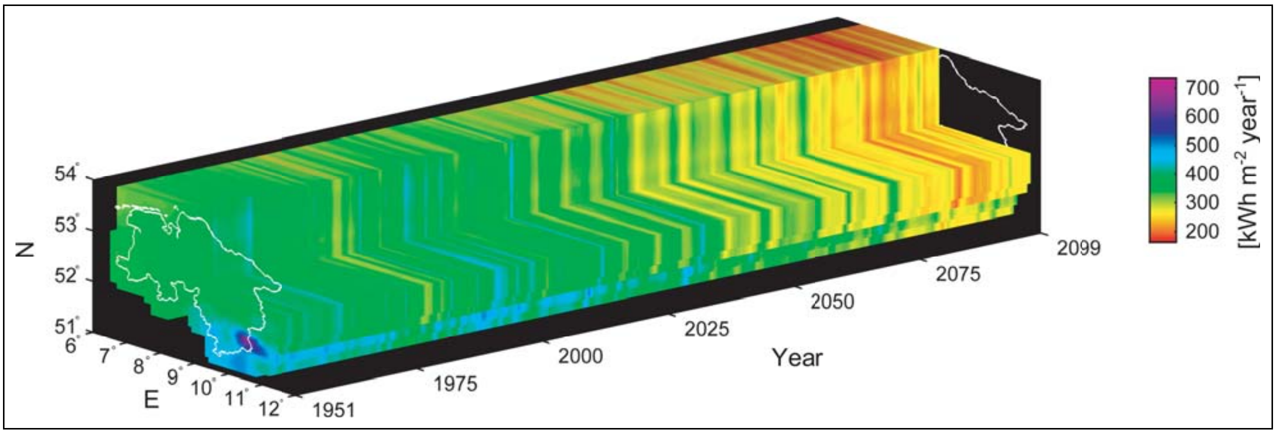

Fig. 4. Projected greenhouse energy consumption in Lower Saxony simulated for the climate scenario A1B and temperature set-points 18/16 °C (day/night).

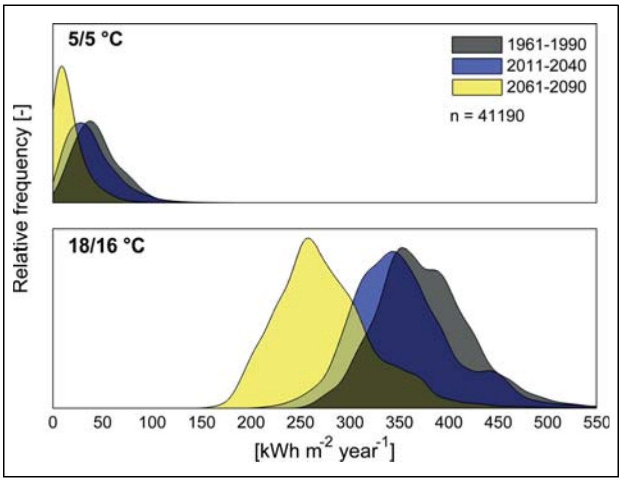

Fig. 5. Distribution of the projected yearly greenhouse energy consumption in Lower Saxony simulated for day/night temperature set-points of 5/5 °C and 18/16 °C and climate scenario A1B. The distribution was estimated by applying a smoothing gaussian kernel with bandwidth h = 8.

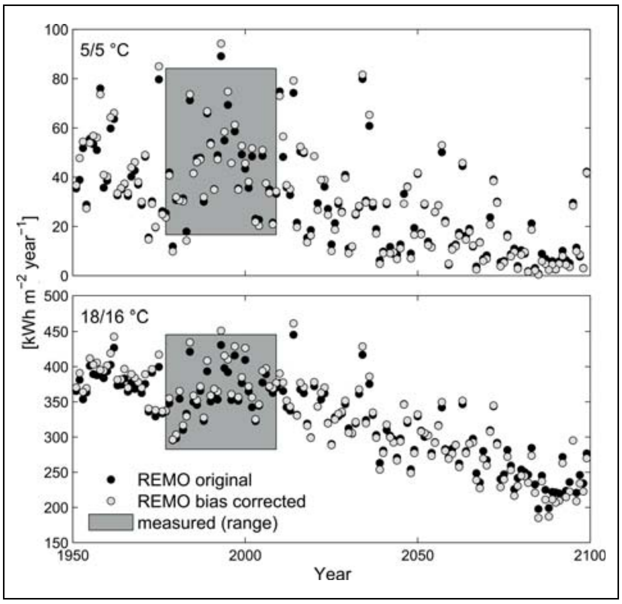

Fig. 6. Projected yearly greenhouse energy consumption for different day/night temperature set-points, calculated from original and bias corrected simulated climate data in Bremen (scenario A1B). Rectangles indicate the period and range (min, max) of energy consumption computed from measured values.

Table 2. Influence of the bias correction on climate data quality and simulated energy consumption (1977–2010).

Climate Data	Global radiation[a] [kWh m^{-2} $year^{-1}$]	Air temperature[b] [°C]	Energy consumption[a] [kWh m^{-2} $year^{-1}$]
Measured	960.8 ± 76.2	9.1 ± 1.3	354.3 ± 44.5
Simulated (original)	897.2 ± 76.0	9.4 ± 1.0	354.8 ± 36.0
Simulated (bias corr.)	970.9 ± 67.3	9.1 ± 1.0	343.2 ± 38.7

[a] mean and standard deviation of annual sums
[b] mean and standard deviation of annual means

creased in the mean by 0.1 and 2.2 kWh m^{-2} $year^{-1}$ for temperature settings of 5/5 and 18/16 °C, respectively.

Discussion

Influences of air temperature, greenhouse temperature and altitude

In detail the magnitude of expected reduction in energy consumption mainly depends on the three following factors (i) climatic data as depending on the chosen scenario and resolution, (ii) greenhouse temperature settings and (iii) orography of the domain investigated. As the projected future warming of the scenario B1 is lesser than of the scenarios A2 and A1B (Roeckner et al. 2006), future energy consumption for scenario B1 does not decrease as far as for scenarios A2 or A1B. Further, energy consumption is influenced by the site orography, as air temperature decreases with increasing altitude, leading to higher energy consumption at higher altitudes. As this influence remains constant for the different climate scenarios, it can be considered as a function of spatial resolution of the climate data or simulation. The present simulations resolved the elevated energy consumption of the low mountain range (~200–500 m altitude) on a 10 km × 10 km grid for Lower Saxony, whereas these findings could hardly be distinguished through a resolution of 100 km × 100 km. Furthermore these results reflect the stronger temperature increase in higher elevated areas, as the higher elevated south-east of Lower Saxony displays the sharpest decline in greenhouse energy consumption.

Influence of climate data bias correction

Depending on the climate model, climate variable, timescale, measurements and gridding (resolution) among others, simulated climate time series may have large biases to measured data (Haerter et al. 2011, Maraun 2012). The removal of this bias is possible (bias correction), e.g. by means of quantile mapping (Piani et al. 2010). Nevertheless 1-dimensional bias correction of single climate variables separately can lead to large errors in multidimensional impact models (Maraun et al. 2010). Therefore a consistent bias correction approach (Hoffmann and Rath 2012) was used in the present study to restore climate variable consistency. In this work projected energy consumption with uncorrected and corrected simulated climate data differed in the mean by 0.3 % and 0.7 % for temperature settings of 5/5 °C and 18/16 °C respectively (case study Bremen, 1951–2099). Hence, the climate impact signal was hardly influenced by the bias correction. Nevertheless, simulated annual energy consumption with bias corrected climate data exhibited larger variation than without bias corrections, reproducing the variance simulated from measured data slightly better (1977–2010). However, bias correction of climate variables (1977–2010) improved climate variable quality (bias, consistency) but led to slight underestimation of the resulting energy consumption. Despite this discrepancy, projected energy consumption with bias corrected data are possibly more robust due to the following: i) Uncorrected simulated climate data overestimated temperature and underestimated global radiation, possibly resulting in energy consumption similar from that calculated from measured climate data. Hence, the true absolute error of the energy simulation with uncorrected climate data would be larger than from measurements, but did sum up to a smaller bias. ii) The intra-annual course of energy consumption from uncorrected data exhibits the characteristic patterns inherited from the regional climate model, being different to the pattern of the intra-annual energy consumption from measured climate data.

Influence of concatenating climate and impact models

The stated energy simulations use climate simulations (Mpi 2012) based on emission scenarios which describe possible future developments of the world (Ipcc Sres 2000). Hereby general circulation models generate climatic data, which are downscaled to regional resolution via regional climate models. To decrease deviation and inconsistencies in the data, bias correction procedures are applied. At the end impact models use these corrected data. Since this concatenation is a source of large uncertainties in projections, simulation uncertainty increases with increasing time horizon of the projection (Hawkins and Sutton 2009).

Timeline of the climatic impact on energy consumption

According to the present results, major changes in greenhouse energy consumption are not to occur before 2035. While mean reductions in energy consumption can be expected from the mid of the century on, year to year differences (variance) will increase. These findings are consistent with the stronger climatic impact in the second half of the century. Therefore, with single years until the mid of the century potentially demanding energy consumption at the present level, changes in heating strategies can be expected only concerning utilization concepts of greenhouses. Consequently changes of the employed heating systems are therefore unlikely to occur before 2050.

Conclusions

The present findings can be summarized: 1.) Climatic warming can be expected to lead to a mean reduction in greenhouse energy consumption of 10 % and 50 % for high and low temperature settings respectively. 2.) Reduction is regionally highly divergent as being dependent on site orography. 3.) Greater changes of the mean level of energy consumption cannot be expected before the mid of the century. 4.) Despite a mean reduction of energy consumption single year extremes potentially reach the present level till the mid of the century. 5.) Changes in energy consumption could lead to innovations in greenhouse utilization concepts for low temperature strategies (Akyazi and Tantau 2012). 6) Consistently bias corrected time series of dynamical-physical climate models like Remo or CLM should be used where possible. If bias correction is not possible, original data of the climate model must be used with care, since simulation results might depend on the systematic error of the climatic input. Alternatively statistical regional climate models as WETTREG (Kreienkamp 2006) could be employed.

Looking at the specific results for German greenhouse energy consumption it can be concluded that, since operation at higher temperatures usually leads to a higher portion of energy costs (which are expected to increase for the future) compared to total variable costs, innovation of greenhouse utilization concepts are more likely to occur for lower temperature settings. Therefore potential benefits of the climatic warming due to absolute energy consumption reduction in warm-house cultivation (≥ 18 °C) as for ornamental plant production, e.g. orchids, or vegetable production, e.g. cucumber or tomatoes, (Krug et al. 2007) can be expected to be diminished through increasing energy costs.

Acknowledgements

The study was supported by the Ministry for Science and Culture of Lower Saxony within the network KLIFF – climate impact and adaptation research in Lower Saxony.

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Received 07/12/2012 / Accepted 10/08/2012

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