

Exposure to climate change in Central Europe: What can be gained from regional climate projections for management decisions of protected areas?

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Abstract Climate change is expected to become an important driver influencing biodiversity. To protect biological diversity in the long term, nature conservationists must include potential climate change impacts in their management decisions. In order to incorporate effective climate change adaptation strategies in the management of protected areas, potential threats of climate change need to be identified. In this study, climate model projections have been evaluated to derive information about the future exposure of nature parks to climate change. Indicators reflecting climate boundary conditions were selected in a cooperative process, considering both scientifically reliable climate scenario analysis and the requirements of park managers. The evaluation exhibits large uncertainties depending on the indicator. While for temperature, a warming trend is projected for all the regions, future projections for precipitation show the largest inter-model uncertainties. The Climatic Water Balance reflects the potential water availability and aids clarification to

stakeholders, as it incorporates the temperature trend. The analysis robustly indicates a prolongation for the climatic growing season. The main challenges related to climate model information for decision-making are the uncertainties, different scales of climate and ecosystem processes and the finding of a common communication level for knowledge transfer. The results are useful for climate-influenced decision-making and provide one part of evidence for making adaptation decisions.

Keywords Bioclimatic indicators · Climate change · Climate models · Nature parks · Decision-making · Climate services

Introduction

In the next decades, climate change is expected to become an important driver influencing biodiversity (Bellard et al. 2012; Thomas et al. 2004). Range shifts of plant species as well as phenological responses to climate change have already been recorded (Walther et al. 2002). Climate change not only creates new stresses to biological diversity, but also exacerbates already existing ones (Jeltsch et al. 2011). This raises new challenges for nature conservation and its management (Vohland 2012). According to the EU Habitats Directive, protected areas are required to ensure the long-term survival of Europe's most valuable biodiversity. Especially for Nature 2,000 sites, they need to maintain or where appropriate restore to a "favourable" conservation status of their natural habitat types and species (Article 3). To protect biological diversity in the long term, nature conservation must include potential climate change impacts in the management planning decisions. In order to incorporate effective adaptation strategies in the

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protected area management, potential threats of climate change need to be identified.

The HABIT-CHANGE project (03/2010–06/2013, <http://www.habit-change.eu>) focused on the adaptation of existing management and conservation strategies in protected areas to enable conservation managers to proactively respond to likely impacts of climate change. The project brought together conservation managers, conservation agencies, and research institutions from nine different countries and fourteen protected areas in Central and Eastern Europe. In the framework of the project, users from protected area management actively requested information about potential impacts of climate change for their area.

Generally, the impacts for a system to climate change can be described as a function of exposure and sensitivity (Schneider et al. 2001). Hence, explicit data on the exposure to climate change and on the sensitivity of species and habitats are needed to include potential impacts of climate change in the planning process. In this study, information about the exposure, defined as the nature and degree to which a particular unit is exposed to climate change, was obtained by analysing climate projections. To this end, regional climate model results were analysed for the areas under investigation using suitable bioclimatic indicators to derive information about the potential exposure to climate change in the future. In many cases, however, users face problems interpreting climate model scenario results in the context of underlying uncertainties; this makes it difficult to understand what kind of information can be provided by climate models.

Uncertainty about future changes does not mean a complete lack of information—it simply means that there is more than one outcome possible as a result of climate change (West et al. 2009). Uncertainties about the future state of the climate system arise from different sources (Le Treut et al. 2007). One part of the uncertainty is seen to be inherent to the climate system, including the problem of scaling, and to the undetermined path that society follows in terms of future emissions of greenhouse gases (Collins 2007). An additional source of uncertainty is the natural variability or sampling uncertainty of the climate system, which is inherent and seen as the biggest contribution to the overall uncertainty in the climate (Giorgi 2010). Another part of the uncertainty in climate projections is correlated with imperfections in the climate models itself due to computational constraints on model resolution, numerical approximations, imperfect understanding of key climate system processes, or imperfect observation coverage of key climate system parameters (Johnson and Weaver 2009). If climate projections on a regional level are required for specific purposes, the results of the atmosphere—ocean global circulation models are often downscaled by high-resolution regional climate models (RCMs), which

increases the model's uncertainty in favour of a higher data resolution (Déqué et al. 2007).

Nevertheless, climate models are excellent tools for providing insight into the range of climate system behaviour and its sensitivity to greenhouse gas emissions (Vohland et al. 2014). Generally, scientific results should not anticipate decisions, but rather support the decision-making process and should be “credible” in terms of transparency of the methods used (Cash and Buizer 2005). While it is not possible to predict the quantitative changes that will occur, managers can get an indication of the expected range of changes using scenarios, and they can use that range to develop appropriate responses (West et al. 2009). The identification of a single “most likely”, probabilistic outcome or a single “best” climate model is not feasible. That a climate model can simulate the past and present correctly does not guarantee that the models will be correct in the future, as they could be right for the wrong reasons or under incorrect modelling assumptions (Tebaldi and Knutti 2007). Hence, a variety of different climate models have to be included when assessing climate scenario projections as multi-model ensembles have the advantage of sampling structural uncertainties (Collins 2007). The level of agreement among multiple climate models indicates what aspects of climate change may be understood more robustly and what aspects might only be characterised by examination of the widest range of possible futures (Johnson and Weaver 2009).

Climate-related indicators for biodiversity are often mentioned in the literature in the context of climate envelope models which use complex statistical relations (e.g. Araujo et al. 2011). For habitat niche models, Loehle (2011) criticised that only a few studies compare multiple climate simulations and ecosystem models, leading to a false impression of precision and potentially arbitrary results due to high inter-model variance. To evaluate climate model results with regard to environmental management, a combination of statistical meteorological summaries and agro-metrological metrics are useful for stakeholders (e.g. Rivington et al. 2008; Matthews et al. 2008). Matthews et al. (2008) concluded that agro-metrological metrics were more effective than pure meteorological summaries in assisting their stakeholders to interpret what climate changes could mean for them and increased the likelihood that they used the research-derived information.

The aim of this article was to demonstrate the kind of information about potential exposure to climate change that can be gained from a multi-model climate data set for biodiversity and conservation management, especially in protected areas. The evaluation is carried out on the basis of a set of climate-related indicators representing the relevant hydro-climatic boundary conditions, which should

bridge the gap between climate science and nature conservation planning, considering the inherent uncertainty in scenario projections. A selection of the bioclimatic indicators was carried out together with environmental experts from 14 nature parks located in nine different countries in Central and Eastern Europe, where the indicators were further used to enhance the existing management of protected areas with regard to climate change adaptation (Grygoruk et al. 2013). The study presented here can help to inform practitioners and local environmental planners about the benefits and challenges of state-of-the-art climate predictions so they can make full use of ensemble information, despite the existing uncertainties.

Materials and methods

Ensemble climate models

For this study, we evaluated a set of high-resolution climate model simulations performed by several state-of-the-art GCMs and RCMs within the framework of the EU-FP6 ENSEMBLES project (van der Linden and Mitchell 2009). Fourteen GCM/RCM combinations all for the SRES A1B emission scenario with a resolution of ~ 25 km have been considered. The multi-model data set consists of four GCMs (HadCM3, ECHAM5, Arpege and BCM), including three different realizations of HadCM3 and eight different regional models (RCA3 (C4I), HIRHAM5, CLM3.21, HadRM3 (three realizations: Q0, Q3, Q16), REGCM3, RACHMO2, M-REMO and RCA3 (SMHI)). For more details, please see the Electronic Supplemental Material (Online Resource 1). Jacob et al. (2007) showed that the models' main systematic biases vary across different models, seasons and regions. The ensemble mean of different climate models performs better than the individual models in terms of systematic bias and produces more representative results than single RCMs (Kysely et al. 2011; Jacob et al. 2007; Kjellström et al. 2011). In addition, the mean model tends to have a similar quality for most areas and is less prone to feature large deviations in particular areas (Jacob et al. 2007).

Selection of indicators

In close cooperation with the HABIT-CHANGE project partners from nature park management, we selected five bioclimatic indicators (see Table 1). They can be directly calculated out of climate model data and were seen to be relevant for nature conservation planning. We defined the "user needs" in a cooperative process and met for the selected indicators between fit for purpose and scientific feasibility considering the inherent uncertainty of the

scenario projections. The limitations and uncertainties in the use of climate model information were made explicit in the discussions, and stakeholders' expectations for a 'predict-then-act framework' were managed with care.

The indicators should apply to the quality and uncertainty of climate scenario data. For that reason, simple extreme and threshold values like, e.g. length of dry spells, number of frost days or date of first autumn frost, which were seen as very relevant for habitat sustainability by the stakeholders, were excluded. Thresholds are not assumed to be robust information from climate models due to their systematic model errors. Those systematic biases generally affect mean climate as well as climate variability. To account for these biases, the differences in climate between a reference period and the future scenario periods are analysed. This method does not work for indicators including thresholds, as a threshold may introduce a strong nonlinearity (Persson et al. 2007).

Simple climatic indicators: mean surface air temperature and precipitation

As important determinants for ecosystem processes, the variables of surface air temperature and precipitation were chosen. They were evaluated on a seasonal and monthly basis to also reflect changes in the intra-annual seasonality. Temperature is one of the main determinants of biological diversity in general (Hawkins et al. 2003), and changes in precipitation regimes are likely to impact species richness, especially in areas where water is a primary limiting resource (Adler and Levine 2007).

Aggregated climatic indicators: climatic water balance and length of growing season

As the third indicator, the Climatic Water Balance (CWB) was selected. The CWB (precipitation minus potential evapotranspiration) refers to the potential water availability. Identifying the inter-seasonal changes in potential water availability proved to be very useful for stakeholders, as it provides an overview about the possible future hydroclimatic conditions in the areas. The potential evapotranspiration was calculated with the TURC-IVANOV method by DVWK (1996) and the monthly correction coefficients by Glugla and König (1989):

$$ET_p = \begin{cases} 0.0031 \cdot M \cdot (R_n + 209.4) \cdot \left(\frac{T}{T + 15}\right) & \text{for } T \geq 5 \\ 0.000036 \cdot (T + 25)^2 \cdot (100 - rF) & \text{for } T < 5 \end{cases} \quad (1)$$

With ET_p : daily potential evapotranspiration (mm); M : monthly coefficients; R_n : daily net radiation (J/cm^2); T : daily mean temperature ($^{\circ}C$); rF relative humidity (%).

Table 1 Selected bioclimatic indicators reflecting inter-model uncertainty

Indicator	Type	Metric	Uncertainty maps	Uncertainty region
Surface daily mean air temperature	Δ absolute, monthly	\emptyset Tave	$C_v = \sigma/\mu$	range, median, quartiles
Precipitation	Δ %, monthly	\sum Pave	σ	range, median, quartiles
Climatic water balance	Δ absolute, monthly	\sum Pave – \sum Epot		range, median, quartiles
Growing season length 5 °C	Δ days	after Carter*		range, median, quartiles
Growing season length 10 °C	Δ days	Start > 6 days > 10 °C; End > 6 days < 10 °C		range, median, quartiles

The climatic growing season lengths (GSL) for 5 and 10 °C were considered to be very useful for stakeholders. The GSL determines the thermal period, which is considered to be the main limiting factor for plant growth in temperate zones. The actual biological growing season varies from species to species and depends on local micro-climatic conditions. Generally, different plant species have different cardinal temperatures for growth, development, and survival. When the temperature rises, the rate of plant processes accelerates to a maximum and then declines beyond a specific optimum temperature for the plant species (Malone and Williams 2010). A simplified criterion to estimate the beginning of the growing season from meteorological parameters is calculated as the number of consecutive days in which a specific daily temperature is exceeded. However, the evaluation of long-term trends is sensitive to the definition of the growing season (Brinkmann 1979; Menzel et al. 2003). Out of different possible definitions, we selected the index after Carter (1998) which starts after five consecutive days >5 °C after last frost and ends when the 10 days running mean falls below 5 °C. Comparing growing season indices for the Greater Baltic Area, Walther and Linderholm (2006) found this index to be most suitable especially in the south-western parts. The running mean smoothes the T mean to some extent, which also applies to biases in climate model results. Additionally, the inclusion of a frost criterion can prevent early starts of the GSL (Walther and Linderholm 2006). Nevertheless, the mean trends for measurements of the phenological and climatic growing season as defined by single-value thresholds match quite well for Germany (Menzel et al. 2003). Menzel et al. (2003) also applied them in other European Countries (Austria, Switzerland, Estonia). One problem with using a 6-day spell <5 °C as end criterion for the GSL is the incidental occurrence of “never ending” growing seasons (especially in the southern parts of Central Europe), which occurred more frequently in the simulation of the far future. In those cases, the growing season was

stopped in the evaluation at the end of the year. By applying the index after Carter (1998) for Central Europe the number of “never ending growing seasons” was found to be significantly lower.

However, many crops and deciduous forests require temperatures >10 °C. This growing season length is estimated from continuous daily mean temperatures exceeding 10 °C, as a period with vegetal and generative growth for a majority of plants. In this study, the 10 °C GSL is defined as the number of days after the first 6 days in a row in which the daily mean temperature is above 10 °C, lasting until the first six continuous days after July 1 in which the daily mean temperature is below 10 °C (Walther and Linderholm 2006). For the beginning of xylem growth, the running mean 10 °C-index after von Wilpert (1990) was found to be the best abiotic variable (Menzel et al. 2003). A comparison of the index using of 6-day spells single values >10 °C with the beginning of xylem growth, after von Wilpert (1990), exhibited a very good agreement (0 ± 1 day).

Evaluation of differences from the reference period

In order to deal with the problem of systematic climate model biases, we evaluated the indicators for the absolute or relative (depending on the indicator chosen) differences between the scenario periods and the reference period (years 1971–2000) for each climate model run. The years 2021–2050 served as the scenario period for the near future, and for the far future the years 2071–2100. For temperature, the absolute differences (°C) from the reference period for the average daily mean values were used. For precipitation, the relative changes (%) in the precipitation sums were calculated. Because the CWB already comprises a difference, the CWB indicator shows the absolute differences between the 30-year periods, as do the values of the 5 GSL and the 10 °C GSL.

Maps of Central Europe

The multi-model mean tends to have a similar quality for most areas in Europe (Jacob et al. 2007). Maps showing the multi-model mean are suitable for visualising general trends for broader areas. Several maps were generated for the extent of Central Europe, showing the results for the indicators of air surface temperature, precipitation and CWB for the summer (JJA) and winter months (DJF), as well as the GSL (5 and 10 °C) indicators. The results are shown for the scenario period 2021–2050 minus the reference period 1971–2000. To visualise the inter-model uncertainty, the uncertainty deriving from the choice of model or rather the spread of the climate model results is shown for daily T_{mean} and precipitation. For temperature, the absolute differences are displayed; the spread of the models is described by the relative variability around the multi-model mean. The coefficient of variation (%) ($\sigma/\mu \times 100$) is used as an index. Higher values mostly come with a higher variability in absolute terms than a smaller value. Hence, it is avoided that warmer and cooler European regions are incomparable in their model spread. The future changes in precipitation were calculated as the percentage of the amount of rainfall in the reference period. For changes in precipitation, the inter-model spread of these percentages is assessed with the standard deviation around the multi-model mean value.

Protected areas in different regions

For the protected areas, the ENSEMBLES climate models results were evaluated in more detail on a regional basis. The box-whisker plots on a monthly basis exhibit the projected changes in the intra-annual seasonality, as well as the inter-model uncertainty. In the HABIT-CHANGE project, climate projections were evaluated for all fourteen areas under investigation. For this paper, three protected areas in Central Europe were selected as representative examples (see Fig. 1). The selected regions in which the protected areas are located encompass an area depending on the size of the national park and the constraint of climate models to include the surrounding raster cells in the evaluation and geographical conditions of the sites. The selection of specific regions was intended to represent different climatic regimes and physiographic settings. The selected regions also represent three different environmental zones in Europe according to the Environmental Stratification of Europe for 1990 (Metzger et al. 2005).

- *Biebrza National Park (Poland)* (Continental) is located in Northeast Poland and with ~60 ha it includes forests, agricultural lands and valuable wetlands and marches most sensitive to changes in the

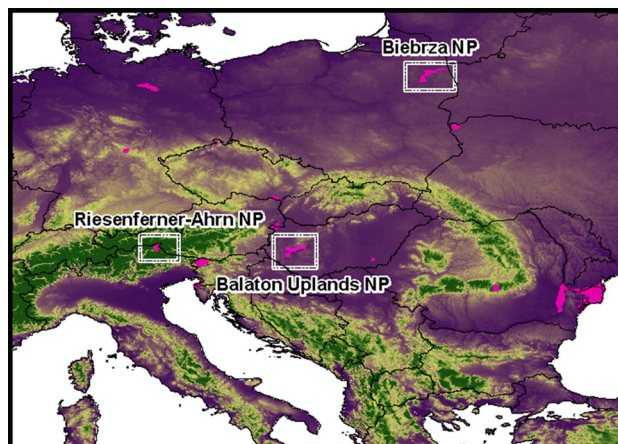


Fig. 1 Fourteen HABIT-CHANGE investigation sites (in pink) and selected regions (white frames) of Biebrza National Park, Riesenferner-Ahrn Nature Park and Balaton Uplands National Park (colour figure online)

hydrological regime (resolution: 75 km × 100 km/7 × 4 grid cells).

- *Balaton Uplands National Park (Hungary)* (Pannonian) is situated in the vicinity of Lake Balaton with an area of ~57 ha and is located in the Pannonian basin. Climate-induced problems are expected from changes in wetlands leading to a higher vulnerability of freshwater habitats and changes in vegetation patterns due to droughts (resolution: 150 km × 100 km/6 × 4 grid cells).
- *Riesenferner-Ahrn Nature Park (Italy)* (Alpine South) is located in the north-eastern part of South Tyrol in the Alps and encompasses ~31 ha. It is characterised by high mountainous habitats and glaciers and is highly sensitive to changes in temperature. Climate-induced problems are expected in terms of shifting vegetation zones and glacier retreat (resolution: 125 km × 75 km/5 × 3 grid cells).

Results

The produced maps are available in the Electronic Supplemental Material (Online Resource 2 and Online Resource 3). The multi-model mean for daily mean surface air temperature displays a clear warming trend for the future in the whole area, although there are regional differences in the magnitude of the projected temperature increase (see Online Resource 2-Figure Left). For precipitation, the ensemble means values exhibit a spatially more heterogeneous trend than for temperature (see Online Resource 2-Figure Left). The inter-model spreads with the coefficient of variation (for temperature) and standard

deviation (precipitation) in relation to the ensemble mean value in the maps (Online Resource 2-Figure Right) visualises the regional differences in the agreement of the different model results. For the temperature values, the coefficient of variation shows the deviations of the different models around the multi-model mean value. Generally, the model spread for temperature is higher in summer than in winter months. Additionally, in areas with a higher multi-model mean value for temperature increase, the coefficient of variation generally has lower values. The different model projections for precipitation show higher deviations from the multi-model mean than those for temperature. For the projections of precipitation, the standard deviation tends to come out higher for summer than for winter months.

The projected future changes of the CBW in Central Europe are spatially and seasonally very diverse (see Online Resource 3-Figure). For the summer months, the multi-model mean for the CWB is to a very large extent projected to be negative with the highest decrease in the south and south-east. An opposite picture becomes apparent for the winter months, where most parts except the Mediterranean show a positive trend for the multi-model mean in the winter months. The multi-model means evaluation for changes in the length of growing season shows an increase throughout the area (Online Resource 3-Figure). Generally, lower values and a more homogenous picture are shown for the projections of the 10 °C GSL than for those of the 5 °C GSL. The highest changes of the 10 °C GSL are projected for the alpine region, as well as Southern and South-eastern Europe.

Projected changes in representative protected areas

The climate scenario data set was evaluated for regions of the three selected protected areas in Central Europe for each of the five indicators chosen. The box-whisker plots show the inter-model spreads on a monthly basis.

Biebrza National Park, Poland (see Fig. 2)

For the region of Biebrza National Park, Poland, the temperature response of the model ensemble under the A1B scenario shows for the near future a clear warming trend with a median from 1.4 °C for the whole year which is more distinct in winter (2.1 °C) than in summer (0.9 °C). For the end of the twenty-first century, a strong increase in daily mean temperature (median annual 3.0 °C) becomes apparent, particularly for the winter months (median 3.9 °C). Changes in monthly mean precipitation for the near future vary between -16 and 27 % (median 4 %) in summer, but a positive trend is distinct in winter with a median of 10 % (range -4 to 29 %). For the years

2071–2100, the range between the individual simulated changes in precipitation is large, in particular for July with a range from -42 to 45 %. The model ensemble clearly indicates a strong increase in winter (median 23 %) and spring (median 11 %) precipitation. Changes in monthly CWB show contrasting variations for the years 2021–2050 in the Biebrza region ranging from -26 (June) to 34 mm (September), with the highest model uncertainties from May to September. There is a smaller range for the winter months (median 6 mm). The results for the years 2071–2100 show that the tendencies for the near future are accelerating with a high model spread in summer from -37 to 40 mm (median -4 mm) and higher certainty for an increasing CWB in winter (median 11 mm). In line with the general increase in temperature is the projected increase of the 5 °C GSL which is slightly higher than for the 10 °C threshold (see Fig. 3). The model ensemble shows for the near and far futures a median of 16 and 36 days, respectively. The 10 °C GSL is projected to increase around 10–17 days (lower to upper quartile) for the near future and from 27 to 36 days for the far future.

Balaton Uplands National Park, Hungary (see online resource 4-figure)

For the region of Balaton Uplands National Park, the ensemble median for the near future shows a warming trend for all months (1.4 °C) and tends to be higher in summer (1.4 °C) and in winter (1.8 °C) than in the transition seasons. For the end of the twenty-first century, the ensemble median for temperature amounts to 3.7 °C, while 50 % of the models range from 2.5 to 4.0 °C. There is a very high inter-model uncertainty range for the months July to September with a maximum extent of -1.3 to 8.1 °C. The projected precipitation response for the Balaton region's near future is ambiguous (median +1 %), but with a negative tendency in summer (median -8.5 %) and a tendency for more rain in winter (median 7.8 %). Precipitation trends are more pronounced in the projections for 2071–2100, with a summer ensemble median of -23 % (range -53 to 19 %) and a winter median of 18 % (range -6 to 40 %). No clear trend and high uncertainty is visible in the transition months such as September. The evaluation of changes in the CWB for the years 2021–2050 exhibits no clear trends except a slight negative tendency for the summer months (median -6 mm). By the end of the twenty-first century, the projected changes in the CWB at the Balaton region show very clear patterns among all models with a projected reduction of the CWB in May to August/September (summer median -40 mm), and a positive trend in winter (median 13 mm). For the Balaton region, 50 % of the model combinations project an increase in the 5 °C GSL between 8 and 17 days for the near future

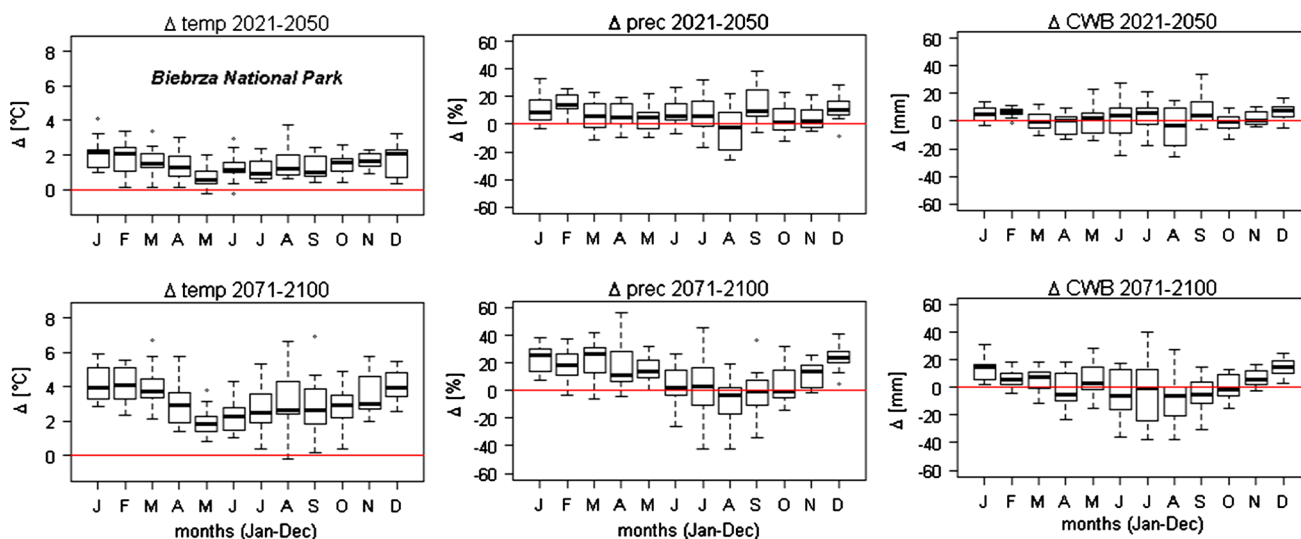


Fig. 2 Climate change projections for Biebrza NP: changes in daily mean temperature (°C), precipitation (%) and CWB (mm) for multi-year averages on a monthly basis [JAN-DEC] as box-whisker plots for the scenario period 2021–2050 and 2071–2100 each showing the

changes to the reference period 1971–2000 for the A1B greenhouse gas emission scenario with 14 different GCM-RCM combinations from the ENSEMBLES project

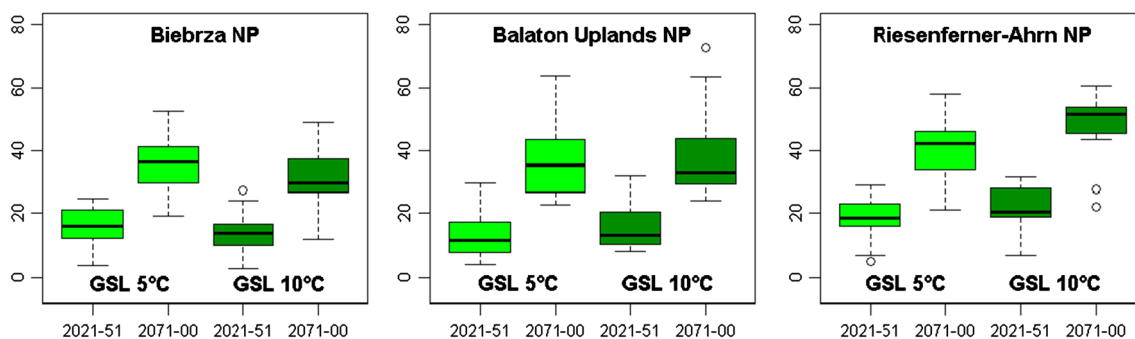


Fig. 3 Changes in growing season length for 5 and 10 °C thresholds (days) for the four selected protected areas for multi-year averages on a monthly basis [JAN-DEC] as box-whisker plots for the years 2021–2050 and the years 2071–2100 each showing the absolute

changes to the reference period 1971–2000, for the A1B greenhouse gas emission scenario with 14 different GCM-RCM combinations from the ENSEMBLES project

(see Fig. 3). For the far future, a further increase in the 5 °C GSL is projected with an upper and lower quartile of 28 and 43 days. For the 10 °C GSL, a smaller increase than for the 5 °C GSL is projected for the near and far futures, where 50 % of the scenario results range between 19 and 28 days or between 46 and 54 days (far future), respectively.

Riesenferner-Ahrn Nature Park, Italy (see online resource 5-figure)

For the alpine region of Riesenferner-Ahrn Nature Park, the mean temperature response pattern under the A1B scenario is characterised by a robust and large positive trend for the whole year with a median of 1.4 °C (upper and lower quartiles: 0.9° and 1.8 °C) for the near future and

3.4 °C (upper and lower quartiles: 2.5° and 4.0 °C) for the far future. For the years 2071–2100, 50 % of the ensemble members diverge about 1.5 °C. Signs of percentage precipitation change for the near future are not robust among the models, except a tendency for precipitation decrease (median ~ −9 %) in July and August. At the end of the twenty-first century, the range between the individual simulated changes is large, but the quartiles indicate a robust positive trend in winter precipitation (upper and lower quartile: 6–15 %) and negative trend in summer precipitation (upper and lower quartile: −18 to −4 %). The signals for the CWB for the region of Riesenferner-Ahrn Nature Park show no clear trend for November to July for the near future. For July and August, the signals tend to be negative, and for September and October slightly positive. By the end of the century, the monthly CWB is projected to

change from -55 to -21 mm (inner quartile range) in summer and from 5 to 19 mm (inner quartile range) in winter. In the alpine region, the projected increase under the A1B scenario for the 5 °C GSL has a similar magnitude than the 10 °C GSL, with a median of 19 and 21 days, respectively (see Fig. 3). Differently from the other nature park regions, the 10 °C GSL (median 52 days) is projected to increase slightly more in the median value than the 5 °C GSL (median 42 days) in the far future.

Discussion and conclusions

Experiences from the HABIT-CHANGE project revealed different perceptions, expectations and knowledge about climate model projections of scientists and environmental managers. In this study, climate scenario data were evaluated according to bioclimatic indicators with a focus on nature conservation management. Stakeholders' expectations were handled with care with regard to scientific feasibility and underlying uncertainties so as not to give a false sense of certainty. Despite great uncertainties about the future behaviour of the climate system, climate scenario data provide information about potential exposure. Combined model averages exhibit tendencies in the direction of what the climate change scenarios show for the end of the century (Kjellström et al. 2011) and perform better than individual models in terms of systematic bias (Jacob et al. 2007). Maps exhibiting the coefficient of variations or standard deviation reflect the inter-model uncertainty. Even if the inter-model range of results is large, patterns in sign and magnitude give decision support to the park management, in particular for the end of the twenty-first century. For all of the climatic indicators, the evaluation shows large uncertainties, but differentiated for the parameters.

For surface air temperature, signs of warming are clearly visible for all regions. The outcomes of the climate models have to be interpreted by local managers in the context of the specific habitats and species; open areas translate temperature changes different than forests, and single species show different sensitivities towards changing temperature regimes. In particular, organisms that are already at the lower range of their distribution area will be most affected (Schwarz 2012).

For precipitation, the biggest inter-model spread appears, not only in the magnitude but also in the sign of change signals. The high uncertainties arise from the higher spatial and temporal heterogeneity of precipitation than is the case for long-term averages of daily mean temperature. The simulated precipitation patterns are strongly influenced by the RCMs. The inter-model spread for climatic processes, primarily dominated by large-scale circulation and

hence by the GCMs, is generally smaller than for RCM-dominated processes, because fewer GCMs than RCMs were considered in the analysis. For the nearer future, the evaluation does not show a distinct trend for precipitation in most of the HABIT-CHANGE project areas. Nevertheless, the pattern of projected future precipitation changes becomes more robust for the more distant future, where a shift in precipitation from summer to winter becomes visible in most of the areas. Additionally, the ensemble means exhibit the trend for a higher annual precipitation in northern parts of Central Europe and a distinct reduction in the southern parts.

The Climatic Water Balance refers to the potential water availability. The projections of different models and emission scenarios for precipitation are in part not satisfying for stakeholders, as they do not give managers a clear direction. The CWB as an integrated indicator aids clarification as it incorporates temperature trends. Just as rising temperatures especially in summer evaporation increases, projected decreasing water balances in the investigation areas provide hints of potential problems in water availability. Reduced water availability due to climate change may affect the persistence of amphibians, especially in monotonous agricultural landscapes (Piha et al. 2007). For more specifics on water relations for management purposes, eco-hydrological models should be applied, because water availability also depends on vegetation and soil characteristics (cf. Holsten et al. 2009). Eco-hydrological models provide information on a smaller scale and can integrate management options (Hattermann et al. 2008), but also add an additional source of model uncertainty.

For the climatic growing season length, the climate scenario analysis robustly indicates a prolongation. A prolongation of the vegetation period not only impacts organisms physiologically, but may shift functional relationships such as prey–predator relationships or competition (Both et al. 2010). Generally, threshold values like the GSL need to be interpreted with care, as they are strongly influenced by systematic temperature biases in the climate models, even if the analysis only focuses on the absolute or relative intra-model changes with reference to a specific time period. Thermal indices for the climatic growing season are valid in temperate areas where the growing season is mainly temperature-limited (Menzel 2002). In mountainous areas, the beginning of the phenological growing season is influenced by the melting of snow, which also depends on the amount of winter precipitation. Unfortunately, phenological observations beyond 1,000 m a.s.l. are rarely available (Menzel et al. 2003). At low latitudes also other factors like precipitation and evapotranspiration play a significant role (Linderholm 2006).

There is a variety of climatic threshold indicators related to temperature and precipitation which are highly relevant

for biological processes, such as frost events, drought periods and number of heat days that indicate climate change (Badeck et al., 2008), but can only be provided with reservations due to the climate models' systematic biases (Persson et al. 2007).

Implications for the use of scenario projections for adaptation

Even if long-term climate predictions are uncertain and incomplete, ignoring such information risks the implementation of maladaptive practices and policies (Daron et al. 2014). Climate models should not be misinterpreted as simple tools to support predict-then-act approaches focusing on a single “most likely” outcome (Weaver et al. 2013). Thus, climate model outputs are used for climate-influenced decisions where they can add a part of evidence for taking a decision, e.g. for the evaluation of adaptation portfolios. In a responsive adaptation management, where climate is embedded in a wider decision context, a range of plausible climate futures should to be incorporated in management decisions to avoid unintended consequences (Daron et al. 2014). The extent to which the multiple climate models agree exhibits what aspects of climate change might only be characterised by examination of a wide range of possible futures and what aspects may be projected more robustly (Johnson and Weaver 2009).

Generally, we recommend a holistic approach which considers the improvement of adaptive capacity and the reduction of non-climatic anthropogenic pressures. These suggestions belong to the so-called ‘no regret’ options and are in line with a precautionary approach also favoured by the convention of biological diversity. Main challenges related to climate model information in the context of environmental management are the quantification of uncertainties, the different scales (spatial and temporal) of climate and ecosystem processes, as well as finding a common communication level for knowledge transfer to stakeholders.

The communication of uncertainty related to future climate scenarios is most important to ensure scientific credibility in the sense of transparency of the methods used (Cash and Buizer 2005). Practitioners need to be supported by scientists to interpret the different outcomes of climate models in the context of climate modelling assumptions and limitations. The uncertainty should be represented in the results and communicated to the decision-makers. When interpreting the climate model results used in this study, one has to keep in mind that the inter-model range of uncertainties would be likely to increase considerably if more GCM/RCM and realizations were included in the ensemble matrix. Additionally, the range of model results would also increase significantly if more than a single emission scenario (A1B) were used as radiative forcing for

the GCMs (Kyselý et al. 2011). Hence, the ‘real’ uncertainty range is higher than the multi-model range indicates and there is no established way to fully represent the entire range of physically possible future developments.

Regional climate model results are usually available at a spatial resolution between 10 and 50 km². A higher resolution of climate data and the combination with habitat data are most relevant for ecosystem processes. A higher resolution in climate modelling also comes with higher uncertainties, limiting the provision of further information. Additionally, grid cell results are not directly transferable to standard meteorological observations or point measurements (Persson et al. 2007). Plants and animals are most influenced by their direct surroundings, by the microclimatic conditions resulting from local vegetation structure and topography (Suggitt et al. 2011). This poses a challenge for the assessment of exposure to climate change in a particular protected area. The temporal scales of climate and ecosystem processes vary significantly. Besides long-term mean values, ecosystems are sensitive to extreme events, such as a single frost days. Climate models, however, provide information about long-term mean values and probability distributions.

What is still missing is the dialogue in the protected areas affected. Stakeholder dialogue in the protected areas can increase the efficiency of climate adaptation measures as local communities may be more willing to support them and improve the general awareness of climate-induced problems in the area (Grygoruk et al. 2013). A participatory management should inform about climate change projections and their uncertainties, about possible risks for local fauna and flora, and discussing local and international responsibilities and trade-offs. This is the fundamental key to the successful adaptation and management of protected areas in the face of climate change.

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