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**The impact of climate  
in Czech headwater  
catchments**

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# The impact of climate change on hydrological patterns in Czech headwater catchments

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## Abstract

The aim of this study was to estimate the impacts of anticipated global climate change on runoff and evapotranspiration in small-forested catchments. The investigated Lysina and Pluhův Bor catchments are situated in the Slavkov Forest in the western part of the Czech Republic. To forecast hydrological patterns for the period 2071–2100, outputs from two general circulation models, HadAM3H and ECHAM4/OPYC3, were down-scaled by an RCAO (regional climate model) which ran the SRES emission scenarios A2 and B2 for each model. Bias-corrected RCAO daily outputs were used in combination with the hydrological model Brook90. Annual runoff is predicted to decline by 6–45%, and impacts on the distribution of monthly flow are predicted to be significant, with summer-autumn decreases of 29–96%, and winter increases of up to ~48% compared to mean flow from 1967–1990. Mean daily flows are estimated to decrease by 63–94% from August to November. These changes would have serious ecological consequences, since streams could regularly dry-up for short periods of time.

## 1 Introduction

Increases in surface air temperatures during the 20th century have been well documented on both global (e.g., Houghton et al., 2001; Salinger, 2005) and regional scales (in Central Europe e.g., Weber et al., 1997; Huth and Pokorná, 2005). Data from the Czech Republic show an increase in surface temperature during the 20th century of  $0.6 \pm 0.2$  °C with a steep warming rate since the 1970s (Pišoft et al., 2004). However, although increases in temperature may be the clearest indicator of ongoing climate change, changes in the amount, variability and spatial distribution of rainfall may have the largest impact on future hydrological patterns. Assessing future climate and its potential impact on the hydrological cycle still remains an important issue for research, since water availability affects both society and ecosystems (Prudhomme and Davies, 2009).

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Recently, many regionally-oriented projections have been done, focusing mostly on changes in the future runoff of large European rivers (Shabalova et al., 2003; Andréasson et al., 2004; Graham, 2004; Jasper et al., 2004; Lenderink et al., 2007; Graham et al., 2007). In addition, some studies have been focused on smaller catchments from tens to hundreds square km (Horton et al., 2006; Fowler and Kilsby, 2007; Horáček et al., 2008). These studies were based on results from regional climate models (RCMs), and demonstrate a rising interest in the impact of expected climate change on hydrological patterns on a regional scale. The application of RCM outputs presents a different approach than the usage of results from global general circulation models (GCMs) that prevailed in earlier studies (Gellens and Roulin, 1998; Arnell, 1999; Middelkoop et al., 2001; Menzel et al., 2006).

RCMs use large-scale and lateral boundary conditions from GCMs to produce higher resolution outputs. These typically encompass a scale of approximately  $0.5^\circ$  latitude and longitude, and parameterize physical atmospheric processes (Déqué, 2007). Thus, they are in principle able to realistically simulate regional climate features such as orographic precipitation (e.g., Frei et al., 2003). However, it is difficult to represent all influences caused by topographical features in RCMs, especially in micro-scale conditions. Outputs show still distinct systematic bias relating temperature and precipitation to the observed mean (Christensen et al., 2008). To overcome this problem, the data need to be better resolved or empirically corrected in order to represent smaller catchments, i.e. covering areas of a few square kilometres. The need for the correction of climatic variables simulated by RCMs was already suggested in the studies of Murphy (1999) and Wilby et al. (2000). More recently, the method of bias-correction has come into wide use (e.g., Fowler and Kilsby, 2007; Fujihara et al., 2008; Schoof et al., 2009).

Although RCMs include a full representation of the hydrological cycle, even the runoff component, hydrologic results are still quite rough, especially for micro-scale site-specific conditions. The typical approach in recently published studies has been to evaluate representative climate changes from climate models and introduce these changes into a hydrological model.

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This paper is focused on changes in hydrological patterns due to projected climate change in micro-scales such as headwater catchments. The effective control of headwater catchments is considered to be an important factor in the sustainable development of water resources (Cutter and Renwick, 2003). In addition, headwater catchments, which in Central Europe are often forested and located in mountainous regions, are areas of high ecological importance.

The objectives of this study can be divided into three parts. The first addresses the evaluation of hydrological patterns in a past “control period” (from 1967–1990) by means of application of the hydrological model Brook90, calibrated to site-specific conditions. The second part deals with the “downscaling” of climatic variables such as air temperature, precipitation, wind speed and solar radiation from the regional climate model RCAO (the Rossby Centre regional Atmosphere-Ocean model; Döscher et al., 2002) to micro-scale conditions.

The third part focuses on an evaluation of climate change impacts on hydrological patterns in the future (2071–2100). This includes hydrological modelling with regionally and locally downscaled outputs from HadAM3H (Hadley Centre, UK) and ECHAM4/OPYC3 (European Centre Hamburg Model, developed at Max Planck Institute for Meteorology, Germany) simulations, driven under different conditions using the A2 and B2 SRES scenario projections (Nakićenović et al., 2000).

## 2 Materials and methods

### 2.1 Site description

Two experimental catchments in the western part of the Czech Republic are situated within a large spruce forest on the plateau of the Slavkov Forest (Slavkovský les) (Fig. 1). The Slavkov Forest is a protected mountainous region with an area of 610 km<sup>2</sup>, where many small streams with varying drainage areas originate. Surface waters of the region are recovering from past industrial pollution caused mostly by coal power plants

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in the vicinity (Majer et al., 2005). Both studied catchments belong to the GEOMON network of small forest catchments (Oulehle et al., 2008).

The first investigated catchment, Lysina (LYS) (Krám et al., 1997; Hruška and Krám, 2003), lying at 829–949 m a.s.l. (50°03' N, 12°40' E; area 0.273 km<sup>2</sup>), is north-east oriented with a mean slope of 11.5%. Podzolized soils are developed on magnesium-poor granite. The vegetation is dominated by Norway spruce (*Picea abies*) that covers almost 100% of the catchment. Recent average precipitation was 945 mm yr<sup>-1</sup>, runoff 451 mm yr<sup>-1</sup> and air temperature 5.0 °C (for the period 1990–2006).

The second study site, Pluhův Bor (PLB) (Krám et al., 1997; Hruška and Krám, 2003), is a catchment with elevation from 690 to 804 m a.s.l. (50°04' N, 12°46' E; area 0.216 km<sup>2</sup>), with south-east aspect and mean slope of 13%. Cambisols cover magnesium-rich serpentine rocks. The vegetation also consists of Norway spruce (92%) mixed with Scots pine (*Pinus sylvestris*) (8%). Recent average precipitation was slightly lower, 844 mm yr<sup>-1</sup>, but average runoff was remarkably lower, 276 mm yr<sup>-1</sup>, and average air temperature was 5.7 °C (for the period 1991–2006)

Precipitation amounts and temperatures are based on data from a meteorological station at Mariánské Lázně, and runoff was measured at both study sites (see details below).

## 2.2 The hydrological model Brook90

In order to model changes in the hydrological cycle, the Brook90 model was used. Brook90 is a deterministic, process-oriented, lumped parameter hydrological model that can be used to simulate most land surfaces at a daily time step year-round (Federer et al., 2003). The Brook model was originally developed for the simulation of water budgets for small-forested areas in the eastern part of the USA, calibrated and verified using headwater catchments at the Hubbard Brook Experimental Forest, New Hampshire and the Coweeta Hydrologic Laboratory, North Carolina (Federer and Lash, 1978). The most recent model version, Brook90, has recently been used for modelling of water balance components in small-forested areas (e.g., Combalicer et al., 2008), as

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well as in studies assessing the impact of vegetation change on hydrological patterns (Armbruster et al., 2004). In the Czech Republic, the Brook90 model has successfully been used for experimental catchments in the Šumava Mts. (Buchtele et al., 2006).

Brook90 is a parameter-rich model designed primarily to study evapotranspiration and soil water movement at a point, with some provision for stream flow generation by different flow paths. Water is stored in the model as intercepted rain, intercepted snow, snow on the ground, soil water from one to many layers, and groundwater. Snow accumulation and melt are controlled by a degree-day method with cold content (Linsley, 1949). Evaporation is the sum of five components: the evaporation of intercepted rain and snow, snow and soil evaporation, and transpiration. The model uses the Shuttleworth and Wallace (1985) method for separating transpiration and soil evaporation from sparse canopies, and evaporation of interception. This method provides a potential transpiration estimate based primarily on maximum leaf conductance. Actual transpiration is reduced below potential when water supply to the plant is limited.

Required inputs to the model are daily precipitation, and maximum and minimum air temperatures. Additional desirable inputs are daily solar radiation and wind speed, average vapour pressure for the day, and measured runoff.

### 2.3 Derivation of input data

Meteorological data for the studied catchments (minimum and maximum daily air temperature, daily precipitation depths, average daily wind speed and length of daylight) for the period 1967–2006 were taken from a climatic station of the Czech Hydrometeorological Institute located at the Mariánské Lázně – Water Treatment Facility (700 m a.s.l.). Gaps in meteorological time series (mainly in length of daylight, representing 7% of days from 1967–2006) were estimated based on linear regression relationships between the Mariánské Lázně station and another meteorological station at Karlovy Vary – Airport (603 m a.s.l.) that is situated within 20 km of the investigated areas. Air temperature data were corrected based on a lapse rate of 0.65 °C per 100 m (Barry and Chorley, 1987), in order to represent the average catchment altitudes. Daily pre-

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precipitation amounts were corrected by a factor calculated from the difference between average annual precipitation amounts measured by bulk precipitation collectors at the investigated catchments and precipitation amounts from the Mariánské Lázně station (for 1994–2006). The daily precipitation amounts were therefore increased by 12% at Lysina, while those from Mariánské Lázně were used for Pluhův Bor unchanged because the difference was negligible (1%). Daily global radiation was calculated from the length of daylight (Klabzuba et al., 1999), which provides reliable results especially for the vegetation season in Central Europe conditions (Trnka et al., 2005). The daily average vapour pressure data were estimated by the Brook90 model using saturated vapour pressure at minimum temperature. Both catchments are equipped with mechanical water-level recorders, installed in combination with V-notch weirs.

## 2.4 Calibration and validation of the hydrological model

The calibration of Brook90 and validation of model performance were based on daily discharge data from the catchment outlets. Seventeen years of observation (1990–2006) were used for setting Brook90 for the Lysina catchment. Data from the period 1990–1999 were used for calibration, and the interval 2000–2006 was considered as the validation period. The same approach was also applied at Pluhův Bor except for the use of shorter periods: 1992–2001 for calibration and 2002–2006 for validation.

The model was calibrated using daily resolution, and calibration success was evaluated based on several approaches. Visual inspection of the measured and simulated discharge curves was one of the indicators for model performance. Testing the significance of the correlation between simulated and measured stream flow also helped in model validation. The Nash–Sutcliffe criterion (Nash and Sutcliffe, 1970) was applied as well, based on determination of the square of errors, for testing of general agreement in monthly means. In each case, the efficiency of simulations was related only to the whole calibration period, i.e., individual events were not considered for parameter optimisation.

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## 2.5 Regional climate model data

The climate model data used were obtained as a result of dynamical downscaling by the regional climate model RCAO. This model emphasizes the simulation of air circulation between ocean and continent, and the resulting changes of meteorological variables correspond with the east-west gradient across the Czech Republic (Horáček et al., 2008). The RCAO model uses large-scale lateral boundary conditions from two GCMs: HadAM3H (hereafter RCAO-H) and ECHAM4/OPYC3 (hereafter RCAO-E), each run with A2 and B2 emission scenarios. These future climate scenarios are based on the IPCC (Intergovernmental Panel on Climate Change) A2 and B2 SRES (Special Report on Emissions Scenarios) anthropogenic CO<sub>2</sub> emissions scenarios (Nakićenović et al., 2000). The A2 scenario assumes continued emissions growth while the B2 scenario is based on an expectation of CO<sub>2</sub> emission decreases during the 21st century. The A2 scenario, the more severe case, corresponds to a change in equivalent CO<sub>2</sub> content (CO<sub>2</sub> plus other greenhouse gases) from 353 ppm, corresponding to 1990 levels, to 1143 ppm in the future (2071–2100). The equivalent CO<sub>2</sub> content for the B2 future climate scenario is 822 ppm.

Simulated daily maximum and minimum temperatures, daily amounts of precipitation, global radiation, and average daily wind speed were downloaded from the PRUDENCE project (Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects) (Christensen et al., 2007). More detail on this project and its results can be found in Christensen and Christensen (2007), Déqué et al. (2007) and Jacob et al. (2007).

These datasets are available for 50×50 km grids for a control period from 1961–1990 and a predicted period from 2071–2100. Simulated meteorological data were used for the grid including the Slavkov Forest, with center at 50°15'25" N and 12°50'18" E (PRUDENCE latitude and longitude, 37–47). The average elevation of this grid was 579 m a.s.l.

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## 2.6 Transferring climate change from the RCM to hydrological models

5 Simulated RCM atmospheric data for the control period (1967–1990) differed notably from measured data, and therefore had to be transformed for hydrological modelling purposes. We applied the widely used method of bias correction (e.g., Fowler and Kilsby, 2007; Fujihara et al., 2008; Schoof et al., 2009). Daily minimum and maximum temperature, rainfall, wind speed, and global radiation data series were “bias-corrected” by monthly factors, so that the downscaled monthly average of the present climate matched the observed monthly average over the period 1967–1990. The future temperature (corrected to mean catchment elevation) and rainfall time series were  
10 adjusted by the same factors as for the control climate.

## 2.7 Trends in observed data

For testing trends in monthly data, the non-parametric Yue-Pilon method was applied (Yue et al., 2002a). This removes serial correlation components such as the lag-one autoregressive (AR (1)) process from the time series. The magnitude of the trend is  
15 computed by the Yue-Pilon method using the Theil-Sen approach. If the slope differs from zero, then it is assumed to be linear and the data is detrended by the slope; the AR (1) is then computed for the detrended series. The residuals should be an independent series. The trend and residuals are then blended together. The Mann-Kendall test (Yue et al., 2002b) is then applied to the blended series to assess the trend significance.

## 20 3 Results

### 3.1 Performance of the models

In general, Brook90 well reproduces the discharge conditions in the investigated catchments, including both individual flood events and long-term runoff. A plot of the Nash-Sutcliffe  $R^2$  for individual years over the period 1990–2006 (Fig. 2), demonstrates high

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model performance for both study sites, with  $R^2$  values mostly ranging from 0.6 to 0.9. The only exceptionally low  $R^2$  values occurred in the year 1996, and were caused by an unusually large spring runoff after an extremely cold and long winter.

For the validation period (2000–2006) at the Lysina catchment, the correlation coefficient was 0.93 ( $r_{\text{crit}}=0.2199$ ,  $n=84$ ,  $p=0.05$ ) for monthly data and 0.67 ( $r_{\text{crit}}=0.1966$ ,  $n=2557$ ,  $p=0.05$ ) for daily data. In the case of Pluhův Bor, the correlation coefficient was 0.87 ( $r_{\text{crit}}=0.2542$ ,  $n=60$ ,  $p=0.05$ ) for monthly data and 0.64 ( $r_{\text{crit}}=0.1966$ ,  $n=1826$ ,  $p=0.05$ ) for daily data during this same period.

### 3.2 Bias-corrections of climatic variables

A comparison of long-term averages of climatic variables (2 m temperature, precipitation, wind speed, global radiation) for observed and RCAO simulated data exhibited significant differences for the period 1967–1990. The average observed minimum air temperature was markedly lower than elevation-corrected RCAO data in the control period, differing by from 0.5 °C to 3.7 °C. However, elevation-corrected maximum temperature deviated much less from observed data, ranging from 0.1 to 1.6 °C higher. Differences in temperature values were less than 0.4 °C after bias-correction. The relative differences between measured and simulated RCAO data before and after bias-corrections were the same for both catchments because the same RCAO datasets were used.

There were also marked differences between the observed and RCAO simulated precipitation data. Compared to observed data, mean annual precipitation amounts simulated by RCAO for the control period (1967–1990) were approximately 20% (RCAO-H) and 40% (RCAO-E) higher. Simulated seasonally distributed precipitation values were also significantly overestimated, particularly in spring months (April, May) for RCAO-H, and in almost all months except for August, September, and December for RCAO-E. Long-term seasonal distribution differences ranged within 5% for both models after bias-correction.

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The RCAO-simulated wind speeds from both models,  $3.3 \text{ m s}^{-1}$  (RCAO-H) and  $3.4 \text{ m s}^{-1}$  (RCAO-E), were on average twice higher than observed data in the control period ( $1.6 \text{ m s}^{-1}$ ). The long-term average of bias-corrected wind speeds varied from observed data by less than 2%.

5 Global radiation data from the RCAO-H model were overestimated by 24% on average ( $6.1 \text{ MJ m}^{-2}$  compared to  $4.9 \text{ MJ m}^{-2}$  calculated for catchments) and from the RCAO-E model by 14% ( $5.6 \text{ MJ m}^{-2}$  compared to  $4.9 \text{ MJ m}^{-2}$  calculated for catchments). The models especially overestimated global radiation in summer months, by up to 40%. Differences between the RCAO simulated data and the observed data after  
10 bias-correction ranged within 2%.

### 3.3 Runoff modelling in the control period

The bias-corrected RCAO data were used for runoff modelling by the calibrated Brook90 model in the control period (1967–1990). The seasonal runoff distribution calculated from the bias-corrected RCAO model input data show similar patterns as the  
15 simulation based on observed data (Fig. 3). The mean annual runoff from the Lysina catchment (based on observed climatic variables) was 415 mm in the control period. The mean annual runoffs calculated from the RCAO bias-corrected climatic data were slightly smaller: 392 mm from RCAO-H and 372 mm from RCAO-E runoff. The mean  
20 annual runoffs from the Pluhův Bor catchment were 266 mm based on observed data and 239 mm calculated from both RCAO bias-corrected models. However, RCAO bias-corrected simulated runoffs were usually lower than that based on observed data from July–October, with differences ranging from 11% to 45%.

### 3.4 Recent changes in air temperature, precipitation and runoff

25 Annual temperature means for the Slavkov Forest from 1990–2006 were  $0.5 \text{ }^\circ\text{C}$  higher than those from the control period (1967–1990), resulting in a mean annual temperature increase from  $4.5 \text{ }^\circ\text{C}$  to  $5.0 \text{ }^\circ\text{C}$  at the Lysina catchment and from  $5.2 \text{ }^\circ\text{C}$  to  $5.7 \text{ }^\circ\text{C}$

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at Pluhův Bor. However, the trend in annual temperature increase from 1967–2006 was not significant. The only significant changes were in changes of the maximum monthly temperatures in April and May (+2.3°C for the period 1967–2006). The mean annual amount of precipitation did not change significantly from the control period (936 mm yr<sup>-1</sup>) to the present (945 mm yr<sup>-1</sup> for 1990–2006) at Lysina or at Pluhův Bor (from 821 to 844 mm yr<sup>-1</sup>). However, a significant increasing trend was found in monthly amounts, with an increase of 30 mm mo<sup>-1</sup> in February during the period 1967–2006.

The mean annual runoff increased slightly from the control period (1967–1990) to the 1990–2006 period, from 415 to 433 mm yr<sup>-1</sup>, and from 266 to 293 mm yr<sup>-1</sup>, at Lysina and Pluhův Bor, respectively (simulated runoff based on measured input data). However, the overall trend from 1967–2006 was not significant. Significant seasonal distribution trends were found for runoff in February and November. Monthly runoff means for 1967–2006 increased by 22 and 18 mm mo<sup>-1</sup> in February, and decreased by 25 and 13 mm mo<sup>-1</sup> in November, at Lysina and Pluhův Bor, respectively. Maximum monthly runoff shifted from April to March at Lysina, while remaining in March at Pluhův Bor, between the periods 1967–1990 and 1990–2006.

**3.5 Predicted future changes in air temperature and precipitation**

The RCAO models estimated an increase in mean annual 2 m air temperatures of between 2.5 and 5.8°C for the Slavkov Forest (2071–2100 compared to the control period 1967–1990). This represents an increase in mean annual 2 m temperatures to 7.0–10.3°C at Lysina and to 7.7–11.0°C at Pluhův Bor.

An increase in 2 m maximum and minimum temperatures throughout the year was projected for 2071–2100 for all months (Fig. 4), with largest changes in August maxima. A predicted increase of 7.0–10.7°C would increase the mean 2 m daily maximum temperatures in August to 25.3–30.5°C at Lysina and 26.0–31.2°C at Pluhův Bor. However, a noticeable increase of temperature is also predicted for the winter months, with a possible rise of between 1.5°C and 6.4°C in the minimum temper-

ature. Increased temperatures in November (by 3.0–4.9 °C) would shift the average daily minimum temperatures above the freezing point, to 0.5–2.4 °C (LYS) and 1.2–2.7 °C (PLB). The RCAO-E based predictions also show a rise in mean minimum daily temperatures above the freezing point in other months: to 1.0–2.2 °C at Lysina and 1.7–2.8 °C at Pluhův Bor in March; and 0.4–0.5 °C at Pluhův Bor in February. These increases in winter minimum temperatures above the freezing point would be reflected in changes to the period of snow cover. The past average snow cover period (1967–1990) lasted from the end of November to the middle of April at Lysina, and from the beginning of December to the end of March at Pluhův Bor. These periods would be significantly shorter: from the second half of December to the beginning of March at Lysina, and from the second half of December to the second half of February at Pluhův Bor. In a related way, the mean lengths of snow cover are also predicted to decrease, from 133 days to 46–110 days at Lysina (control period versus 2071–2100), and from 121 days to 30–90 days at Pluhův Bor. According to these RCAO-E A2 and B2 scenarios, snow cover will not be continuous, but the shorter overall snow cover periods will be interrupted by complete melt downs.

Minor differences in the annual amount of precipitation (2–9%) are expected in the future, with simulated changes from 936 mm yr<sup>-1</sup> (1967–1990 control) to 879–957 mm yr<sup>-1</sup> (2071–2100 projected, bias-corrected) at Lysina, and from 821 mm yr<sup>-1</sup> to 771–840 mm yr<sup>-1</sup> at Pluhův Bor (Table 1). However, significant changes are projected in the annual distribution of precipitation (Fig. 5). The magnitude of these changes differs from month to month, but both models with scenarios A2 and B2 showed a similar pattern: a drop in summer precipitation from July to September and an increase from December to March. The maximum predicted decrease is in August (24–43%), with changes from 105 mm mo<sup>-1</sup> to 60–80 mm mo<sup>-1</sup> at Lysina and from 92 mm mo<sup>-1</sup> to 52–70 mm mo<sup>-1</sup> at Pluhův Bor. The highest increase was predicted in December (17–51%), rising from 89 mm mo<sup>-1</sup> to 105–135 mm mo<sup>-1</sup> at Lysina and from 78 mm mo<sup>-1</sup> to 92–118 mm mo<sup>-1</sup> at Pluhův Bor.

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### 3.6 Future changes in evapotranspiration and stream flow

The increase in annual evapotranspiration based on model predictions was estimated to be 12–18% at the Lysina catchment. This would be a change from 406 mm yr<sup>-1</sup> in the control period to 455–481 mm yr<sup>-1</sup> in the future (Table 1). Changes in seasonal distribution showed an increase for almost all months (Fig. 6a). The highest absolute increases, by about 11 mm mo<sup>-1</sup> on average, are from May to July, with a maximum increase from 67 to 75–83 mm mo<sup>-1</sup> in June. In general, changes in August and September are expected to be only minor, though according to the RCAO-E/B2 scenario estimated evapotranspiration might decrease by 14% in August (Fig. 6a). This could result in actual evapotranspiration being limited by water availability. Evapotranspiration is also estimated to increase by 11–54% in spring months, probably as a result of a shift in the vegetation season.

At Pluhův Bor, simulations predicted an even larger increase in annual evapotranspiration by 15–27%. This would result in a rise from 441 mm yr<sup>-1</sup> in 1967–1990 to 509–561 mm yr<sup>-1</sup> in 2071–2100 (Table 1). Changes in the seasonal distribution showed increases for all months (Fig. 6b). The highest absolute increases of ~15 mm mo<sup>-1</sup> are from June to August, with a maximum increase in July from 72 mm mo<sup>-1</sup> to 86–93 mm mo<sup>-1</sup> in the future.

Annual runoff at Lysina was predicted to decrease from 415 mm yr<sup>-1</sup> in the control period to 298–369 mm yr<sup>-1</sup> in the future, or between 11% and 28% (Table 1). The main decrease is expected from April to November (by 12–95%), with a maximum absolute decline from 75 mm mo<sup>-1</sup> to 25–48 mm mo<sup>-1</sup> expected in April (Fig. 7a). This clearly indicates shifts in snow melt and spring runoff maxima. The RCAO-H predictions based on the A2 and B2 scenarios showed the mean monthly maximum in March, while the RCAO-E predictions showed the maximums in December for both scenarios. Runoff from December to February is mainly predicted to rise (except for the November runoff based on RCAO-H/B2), with the maximum change in February from 26 mm mo<sup>-1</sup> in the control period to 43–63 mm mo<sup>-1</sup> in the future.

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At Pluhův Bor, the predicted decrease in annual runoff is larger, from 266 mm yr<sup>-1</sup> to just 145–215 mm yr<sup>-1</sup> in the future (19–45%, Table 1). The magnitudes of seasonal changes are similar to those at Lysina (Fig. 7b). The major decrease is expected from July to November, with changes from 38–95%, with maximum decline in November with a change from 17 to 1–7 mm mo<sup>-1</sup>. In winter, the maximum predicted increase in runoff is in February (by 28–76%) rising from 24 mm mo<sup>-1</sup> in the control period to 30–41 mm mo<sup>-1</sup> in the future (2071–2100). The RCAO-H predictions based on the A2 and B2 scenarios showed a mean monthly maximum in March, while the RCAO-E predictions showed a maximum in February for both scenarios.

The simulated future mean daily discharges from both catchments showed a significant decline (Fig. 8). Simulations indicated that both streams could dry up completely for short periods, especially during September and October. Based on the RCAO-E scenario, mean daily flow from August–November could decline by 61–99% (A2) or 8–93% (B2) at Lysina, and by 82–99% (A2) or 41–89% (B2) at Pluhův Bor. Moreover, decreases based on the RCAO-H scenarios were 11–92% (A2) or 27–87% (B2) at Lysina and 35–86% (A2) or 31–86% (B2) at Pluhův Bor for the same period.

## 4 Discussion

Comparing measured data with outputs from the RCAO models, there was a clear shift in absolute magnitude and seasonality, making the direct use of modelled data impossible. The fact that measured data and the regional climate model simulated data differ during the control period is not surprising, considering that meteorological station data represents local climate within a radius of few kilometres, while the RCAO data represent an average over an area of 2500 km<sup>2</sup>. These results emphasise the need for the correction of all input data series on a month-by-month basis. Fowler and Kilsby (2007) successfully used the method of bias-correction for several catchments smaller than 50 km<sup>2</sup> in the UK. Bias-correction is more consistent with RCMs than it is with other methods based on adding a climate change signal to an observational

database (Lenderink et al., 2007), such as the delta approach (Hay et al., 2002). It is necessary to correct both the absolute magnitude and seasonality with respect to observed data (especially for precipitation) in order to obtain realistic runoff series from hydrological modelling. However, this method assumes that future rainfall distribution will remain unchanged compared to the past control climate period (Fowler and Kilsby, 2007).

RCM simulated data are completely independent from the observed data in terms of temporal attachment (Déqué et al., 2007). Therefore, control period data and estimated changes based on different scenarios can only be compared among themselves, or with measurements using the long-term statistical behaviour of individual time series (Menzel et al., 2006).

The results of bias-correction of climatic input data series indicate that bias-corrected RCM control datasets are able to represent, by means of long-term monthly averages, the observed precipitation, temperature, global radiation and wind speed in the Slavkov Forest area in the period 1967–1990, despite the difference in spatial resolution between the simulated and observed datasets.

Mean annual cycles of runoff data from the two investigated catchments showed that the runoff simulation using bias-corrected RCM data as input for the hydrological modelling fit the runoff results based on measured climatic data in the control period (1967–1990) relatively well. Therefore, the calibrated hydrological model Brook90 should be a useful tool for estimating future changes in flow patterns at these catchments. Nevertheless, the Brook90 simulation using bias-corrected RCM inputs resulted in a slight underestimation of runoff (less than 10%) compared to the simulation with measured climatic inputs in the control period. The bias-corrected data from the RCAO model driven by HadAM3H reproduced runoff in this period better than that driven by ECHAM4/OPYC3. In general, both runoff simulations were less efficient in the control period from July to October (Fig. 3). This might be due to the fact that RCAO – HadAM3H better represents precipitation after bias correction, matching the observed data closely, while RCAO – ECHAM4/OPYC3 annual precipitation amounts

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are slightly underestimated (by 2%) and annual evapotranspiration overestimated (by 5–7% at Lysina and 7–10% at Pluhův Bor). For both simulations with RCAO bias-corrected data, summer evapotranspiration rates were slightly overestimated (by 2–10% at Lysina and 4–14% at Pluhův Bor).

5 The RCAO model (driven by either HadAM3H or ECHAM4/OPYC3) with future scenarios (2071–2100, SRES A2, B2) estimates a wide range of winter precipitation increase (by 8–51%) and summer precipitation decrease (by 10–53%) (Fig. 5). In general, the RCAO ECHAM4/OPYC3 modelling exhibited larger differences compared to the control period than did RCAO-HadAM3H. The significant long-term rising trend in  
10 observed February precipitation data could be a signal of the future precipitation distribution changes expected by the RCAO under different scenarios. Despite remarkable changes in the seasonal distribution of precipitation amounts, future changes on an annual level are almost negligible (Table 1).

Changes in the long-term seasonal distribution of evapotranspiration are mainly indicated by increases with maximum in June (by 13–25%) at Lysina and maximum in July (by 19–30%) at Pluhův Bor. The future evapotranspiration could be less limited at the lower elevation Pluhův Bor catchment than at Lysina, where based on the ECHAM4/OPYC3 A2 scenario evapotranspiration decreased in August (by 14%). This could be due to the higher content of soil water at Pluhův Bor than at Lysina (Krám et  
15 al., 2005). Our results showed a ~10% higher soil water content at Pluhův Bor than at Lysina in the summer (2071–2100). The relatively high evapotranspiration increases in March and April of 11–54% at Lysina and 14–59% at Pluhův Bor, respectively (Fig. 6), clearly indicate a shift in the beginning of the vegetation season. Changes in annual evapotranspiration are expected to be ~+15% at Lysina and ~+21% at Pluhův Bor.

25 Increases in mean monthly runoff by ~+69% (LYS) and ~+27% (PLB) in winter are expected. However, the largest changes in future runoff are estimated for summer and autumn, with reductions of 29–95% at Lysina (Fig. 8a) and 38–96% at Pluhův Bor (Fig. 8b). Significant decreases in spring runoff are also expected at both catchments. Since spring and autumn are crucial periods for recharge, these reductions could be

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important for water resources or ecological management in the future. Changes in daily mean flow are even more substantial, especially in the late summer and autumn months. Future estimations using bias-corrected RCAO – ECHAM4/OPYC3 simulations show a more severe decrease in runoff compared to bias-corrected RCAO – HadAM3H simulations. Average decreases in mean daily runoff by 63–91% at Lysina and by 68–94% at Pluhův Bor from August–November would be serious changes with consequences for catchment scale ecology and water management downstream. Changes in annual runoff are expected to be approximately –17% at Lysina and approximately –27% at Pluhův Bor.

Essential changes in the seasonal runoff cycle represented by decreases in summer and increases in winter are more or less consistent with other studies using RCMs outputs (e.g., Fowler and Kilsby, 2007; Graham et al., 2007; Horáček et al., 2008). Fowler and Kilsby (2007) expect summer runoff reductions to be from –40 to –80% of present flows and largest at lower elevations by the 2080s (catchments in the UK with areas from 35–1300 km<sup>2</sup> and average elevations ~220–400 m a.s.l.). A decrease in summer runoff by about 40–50% for the Morava River (27 000 km<sup>2</sup>) in the eastern Czech Republic has been predicted by Horáček et al., (2008). A study of the Rhine River basin (185 000 km<sup>2</sup>) showed a decrease from July to November of about 15–35% for the period 2071–2100 (Graham et al., 2007). Comparing results of these studies shows that the impact of estimated climate change on hydrological patterns in Central European catchments will be affected by the continental nature of the climate. Annual precipitation amounts in our catchments are half (and at two-fold higher elevation) than the studied catchments in the UK (Fowler and Kilsby, 2007), which are influenced by a maritime climate. The increase in June runoff (Fig. 7) resulting from the precipitation increase expected for June based on the RCAO – HadAM3 modelling (Fig. 5), confirms that runoff will be more sensitive to redistributions of precipitation, especially in very small catchment areas such as ours. We also expect runoff to decline more in the lower elevation catchment. However, the magnitude of decrease is larger for both catchments than the results of Fowler and Kilsby (2007). The future runoff in our catchments is also

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predicted to decrease more than in the Morava (Horáček et al., 2008) and Rhine rivers (Graham et al., 2007) under the same emission scenarios and RCM. This indicates that with increasing basin area, runoff decreases less. This is in contrary to results from the UK, where the magnitude of change did not depend on basin area but on elevation (Fowler and Kilsby, 2007). The estimated climate change based on the RCMs and scenarios selected also cause a significant shift in the monthly maximum discharge to periods earlier in the year as a result of increasing temperature affecting the snow-melt process. This is in accordance with earlier published studies (e.g., Shabalova et al., 2003; Horton et al., 2006)

Mean annual changes in both our catchments are similar to results for the Czech Republic by Horáček et al. (2008). Based on the RCAO model and the hydrological model Bilan, they predicted that runoff will decrease by 8–19% by 2085 for the part of the Ohře river basin that includes our investigated catchments. Compared to these results, only our simulation based on the RCAO-E/A2 with a future decrease of 45% (at PLB) differed notably.

Our results presented here describe the impact of four plausible scenarios of climate change on two small catchments in the Slavkov Forest area in 2071–2100. We should, however, be aware of the uncertainties associated with such impact studies. In principle, the uncertainty of climate change projections consists of a chain of individual uncertainties (Mitchell and Hulme, 1999). Concerning our study, this includes uncertainty in emission scenarios driving the GCM, downscaling by the RCM, bias-correction of the RCM outputs, and finally the uncertainty caused by the hydrological model.

Selection of the GCM providing boundary conditions for the process of downscaling mostly has larger impact on the projected hydrological change than either the selection of emission scenario or RCM used for downscaling (Graham et al., 2007). One exception is summer precipitation, where selection of the RCM is the major source of uncertainty because of local processes (convection) that are marginally driven by the lateral conditions, whereas the other variables are more dependent on general circulation (Déqué, 2007). Horton et al. (2006) pointed out that quantitative assessments

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based on a small number of regional climate scenarios could result in misleading outcomes. Since the RCAO has already been successfully applied in the western Czech Republic (Horáček et al., 2008), we assume that the selection of this regional climate model in combination with two driving GCM and two emission scenarios provides a sufficient range of future climate change for the two headwater catchments investigated here.

## 5 Conclusions

We confirmed the need for bias correction of all climatic variables from the RCAO model in order to characterize site-specific conditions. For long-term monthly averages, the bias-corrected model output well represented the measured climatic data in the control period (1967–1990).

The calibrated hydrological model Brook90 provides a suitable tool for the modelling of future changes in hydrological patterns in small-forested catchments. The long-term annual cycle of runoff simulated by Brook90 with bias-corrected inputs is in accordance with results from the Brook90 simulation with measured climatic data in the control period (1967–1990).

The estimated increase of temperature, and the redistribution of precipitation with expected summer decreases and winter increases, will significantly affect evapotranspiration rates and runoff in the future period 2071–2100. Evapotranspiration is expected to increase as a result of higher temperature and prolongation of the vegetation season.

The annual runoff is expected to decrease and the annual cycle will change significantly. Winter runoff is expected to increase, the runoff maxima will shift, and runoff in summer and autumn will decrease notably.

The predicted declines in mean daily flows indicate that studied streams might regularly dry up for short periods in the summer and autumn.

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**Table 1.** Annual water balance at the Lysina and Pluhův Bor catchments in the control period (1967–1990), present (1990–2006), and future (2071–2100) according to the four modelled scenarios.

Lysina	Precipitation [mm yr <sup>-1</sup> ]	Evapotransp. [mm yr <sup>-1</sup> ]	Runoff [mm yr <sup>-1</sup> ]
Control	936	406	415
Present	945	410	433
RCAO-H/A2	954	466	369
RCAO-H/B2	924	455	354
RCAO-E/A2	879	472	298
RCAO-E/B2	957	481	359
Pluhův Bor	Precipitation [mm yr <sup>-1</sup> ]	Evapotransp. [mm yr <sup>-1</sup> ]	Runoff [mm yr <sup>-1</sup> ]
Control	821	441	266
Present	844	450	293
RCAO-H/A2	837	528	215
RCAO-H/B2	810	509	210
RCAO-E/A2	771	561	145
RCAO-E/B2	840	540	209

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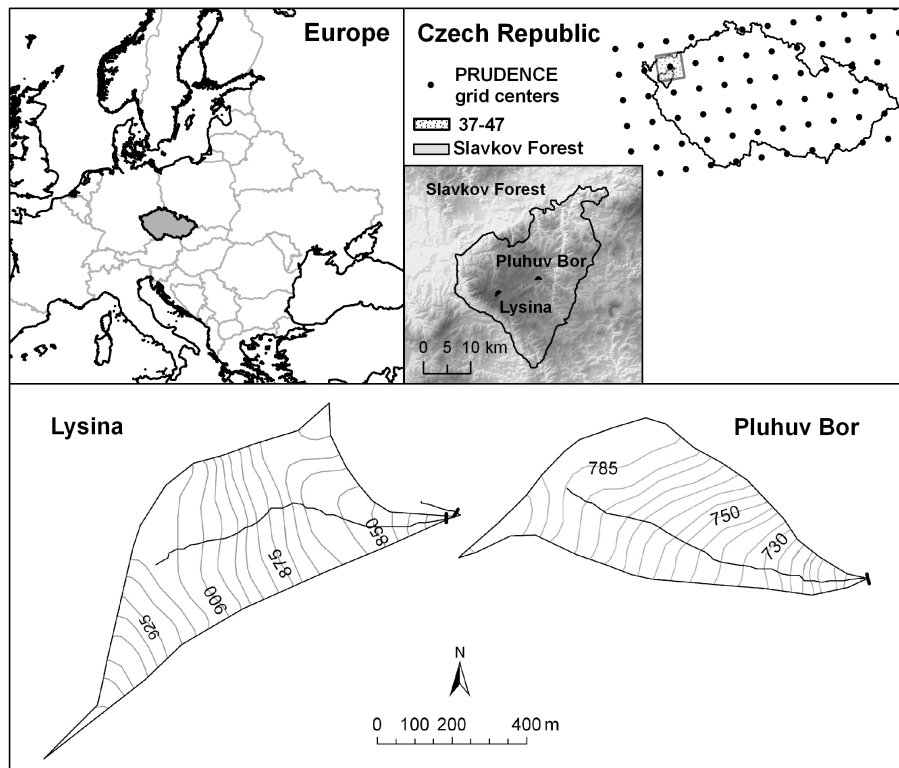
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**Fig. 1.** Map of the Czech Republic, showing the location of the Slavkov Forest and catchments of Lysina and Pluhův Bor.

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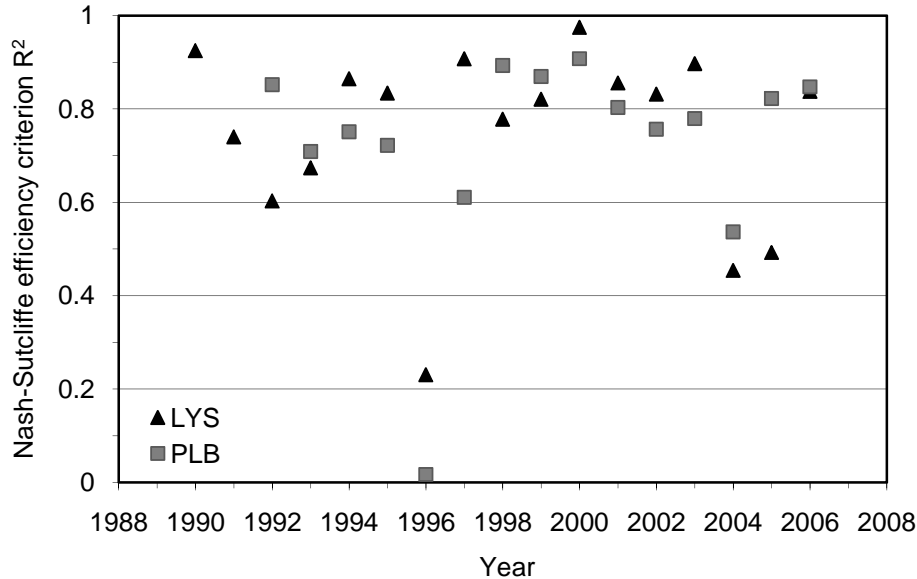
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**Fig. 2.** The Nash–Sutcliffe  $R^2$  (model performance criterion) for the two investigated catchments over the period 1990–2006.

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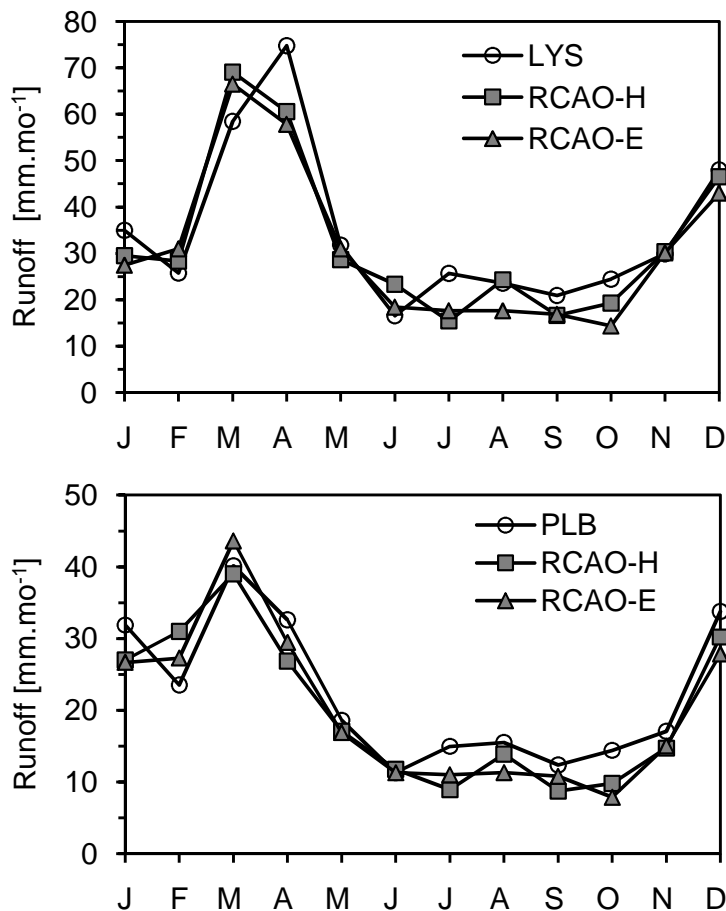
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**Fig. 3.** Runoff monthly means modelled by Brook90 using observed data and RCAO simulated data at (a) Lysina and (b) Pluhův Bor in the control period (1967–1990).

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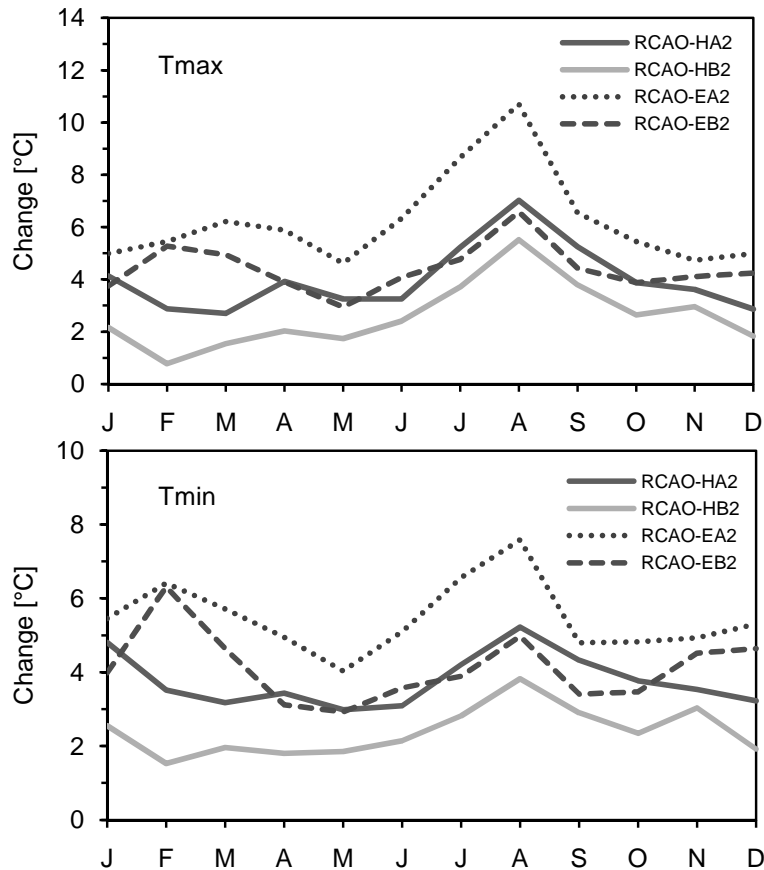
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**Fig. 4.** Mean annual cycle of 2 m maximum and minimum air temperature change between the control period (1967–1990) and the future bias-corrected RCAO model outputs for the period 2071–2100 (using HadAM3H and ECHAM4/OPYC3 with SRES A2, B2 scenarios) at the investigated catchments.

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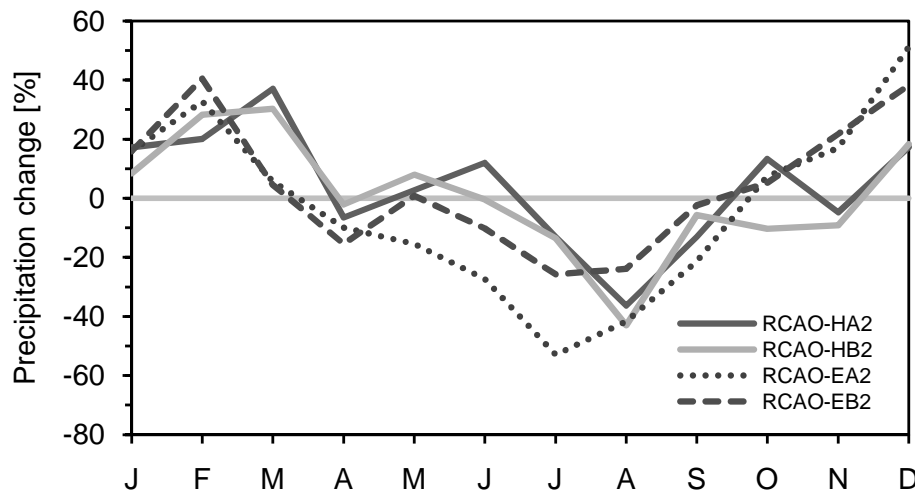
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**Fig. 5.** Mean annual cycle of precipitation change between the control period (1967–1990) and the future bias-corrected RCAO model outputs (using the HadAM3H and ECHAM4/OPYC3 with SRES A2, B2 scenarios) for the investigated catchments.

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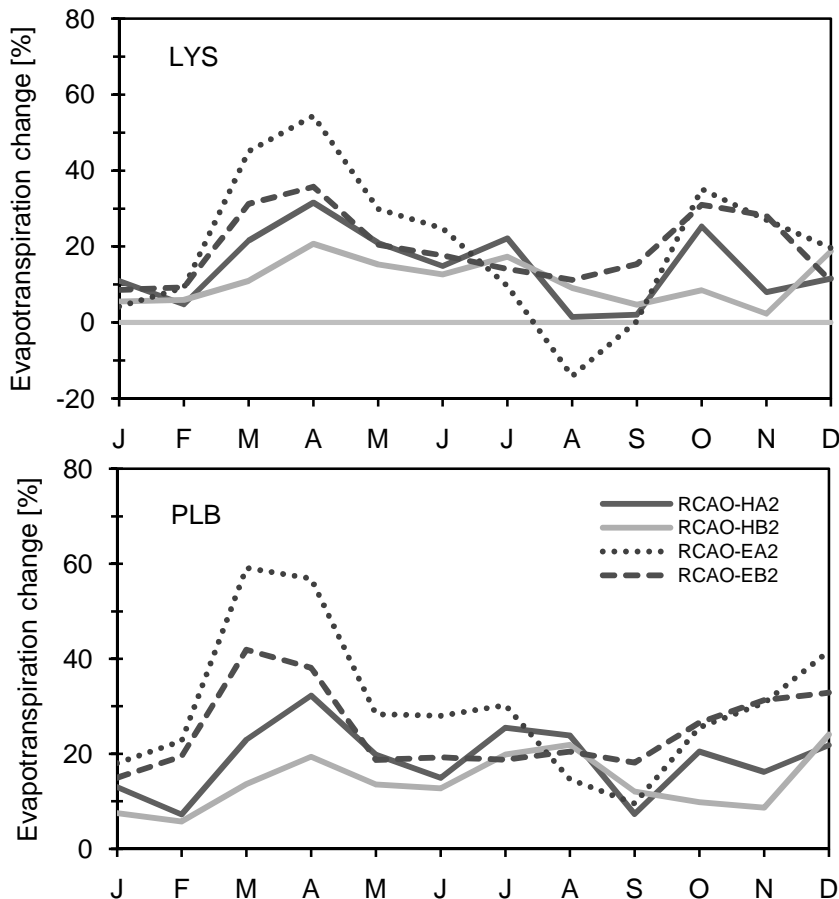
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**Fig. 6.** Mean annual cycle of evapotranspiration changes for **(a)** Lysina and **(b)** Pluhův Bor. Changes between simulations are based on observed data for the control period (1967–1990) and future evapotranspiration in 2071–2100 simulated with bias-corrected RCAO outputs (using the HadAM3H and ECHAM4/OPYC3 with SRES A2, B2 scenarios).

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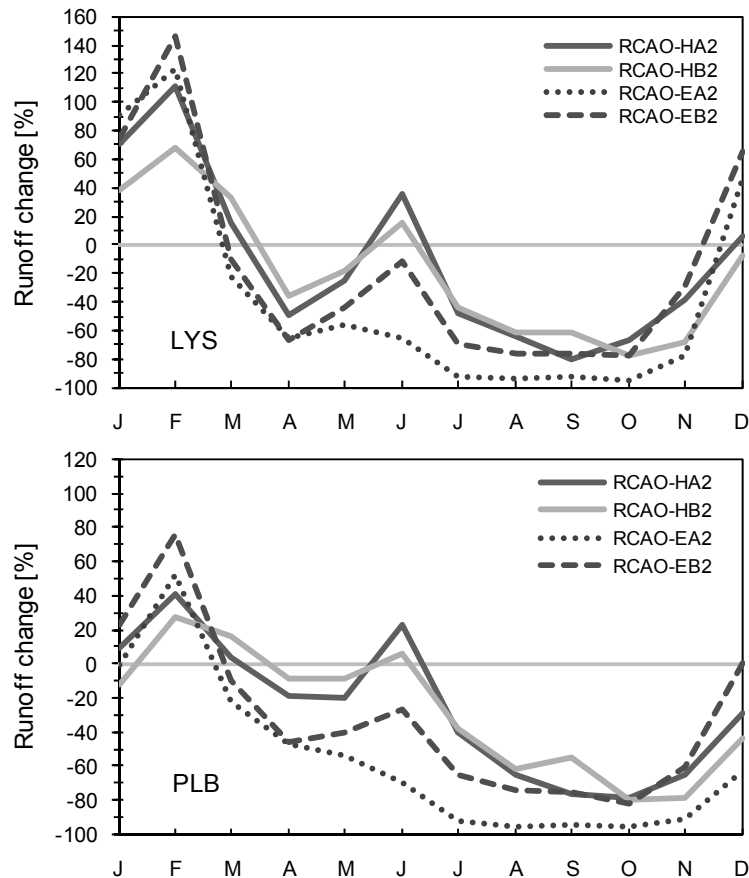
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**Fig. 7.** Mean annual cycle of runoff changes for **(a)** Lysina and **(b)** Pluhův Bor. Changes between runoff were calculated using observed data for the control period (1967–1990) and future runoff in 2071–2100 was simulated based on bias-corrected RCAO outputs (using the HadAM3H and ECHAM4/OPYC3 with SRES A2, B2 scenarios).

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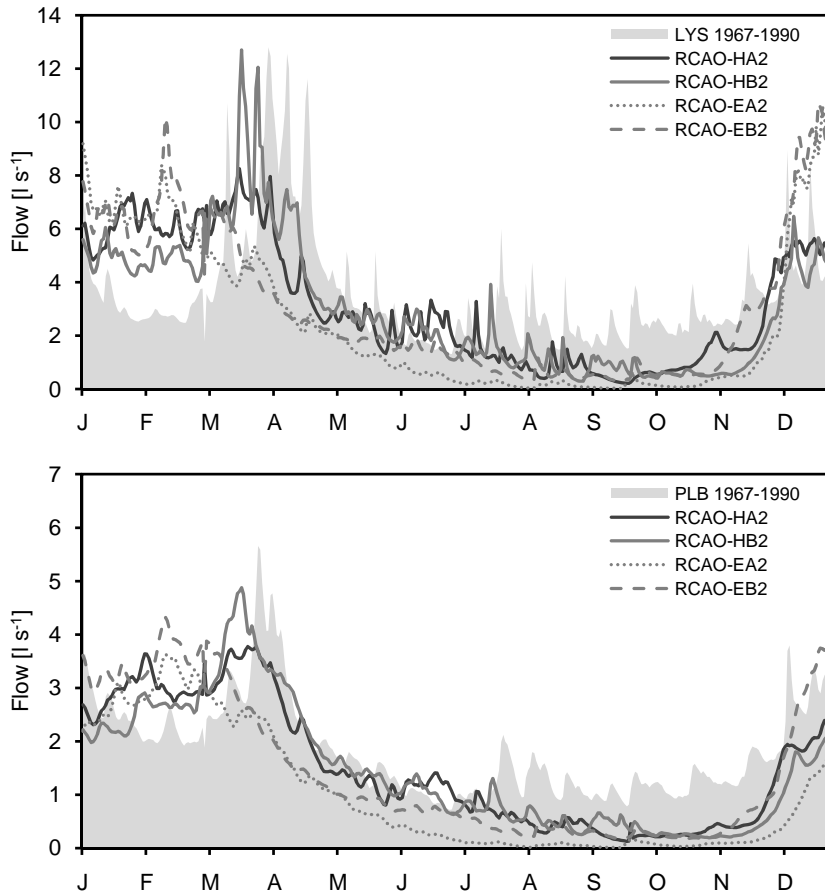
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**Fig. 8.** Comparison of simulated daily mean flow based on observed data in the control period (1967–1990) and simulations based on bias-corrected RCAO outputs (using HadAM3 and ECHAM4/OPYC3, SRES A2, B2 scenarios for 2071–2100) at the **(a)** Lysina and **(b)** Pluhův Bor catchment.

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