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ORIGINAL ARTICLE

Trend analysis for integrated regional climate change impact assessments in the Lusatian river catchments (north-eastern Germany)

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Abstract Trend analysis on observations and model-based climate change simulations are two commonly used methods for climate change detection and impact analysis. Here we propose an integrated assessment and interpretation of climate change impacts as a prerequisite for stakeholder outreach and planning of suitable climate change adaptation measures. The assessment includes (i) identifying trends in meteorological and hydrological observations and their nature, (ii) analysing the relation between the meteorological drivers and generated run-off as an integrated catchment response and (iii) analysing how hitherto changes agree with the simulations by regional climate models (RCMs). The Lusatian river catchments of Spree and Schwarze Elster, characterised by high anthropogenic impact (e.g. mining activities) and low natural water yield, serve as study areas. The results of this study suggest that increases in observed temperature and potential evapotranspiration are robust while observed precipitation remained nearly unchanged (1963–2006). The RCMs agree on simulating a temperature increase but simulate opposing trends for precipitation for both past (1963–2006) and future (2018–2060) periods, the latter inducing differences in the hydrological response (actual evapotranspiration and run-off). For stakeholder outreach, we communicated a range of potential future climates and identified the statistical RCMs (STAR, WettReg) as warm and dry scenarios, and the dynamical RCMs (REMO, CCLM) as wet scenarios. Ultimately, the combined analysis of trends in observations and simulation models can be beneficial for stakeholder outreach and may increase their willingness to plan and implement suitable climate change adaptation strategies which are urgently needed within the Lusatian river catchments.

Keywords Trends analysis · Change points · Regional climate models · Water management · Stakeholder outreach · Global dimming

Introduction

During recent years, many studies assessed the climate change impact on the hydrological cycle using scenario-based modelling (Faramarzi et al. 2013; Xu et al. 2005). The primary goal of these studies is to inform stakeholders about the potential impact of climate change on water

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resources for better environmental management, resource management, and decision making (Patt and Dessai 2005). In addition, scientists need to ensure that modelling results are accepted, trusted and understood (Aas et al. 2005; Boschetti et al. 2012). Model ensembles, consisting of a complex model chain of step-wise coupled models [Emission Scenario → Global Circulation Model (GCM) → Regional Climate Model (RCM) → Bias Correction → Impact Model (Hydrological Model)], are generally used for uncertainty estimation in climate change impact studies (Köplin et al. 2013; Rössler et al. 2012; Teutschbein et al. 2011). Using this approach, several representatives of each model chain member are included in the analysis potentially causing a large variability and even contradictory results (Gädeke et al. 2014; Hattermann et al. 2015; Teutschbein et al. 2011). The main advantage of ensemble-based climate change impact assessments is that the step causing the largest uncertainty can be identified. Yet, the meaningfulness of the final results is contingent on whether or not the chosen representatives of the model chain emulate an adequate sample of the entire population (Merz et al. 2012). Most studies agree that the largest source of uncertainty is the climate drivers (Graham et al. 2007; Kay et al. 2009; Vetter et al. 2016).

The detection of trends (or lack thereof) in observations of hydro-climatic variables can facilitate the communication of climate change uncertainties and risks to stakeholders. Consequently, trend analysis on observed meteorological and hydrological variables by statistical methods has also received increased attention along with the differentiation between gradual (monotonic) trends and abrupt changes (change points) (Guerreiro et al. 2014; McCabe and Wolock 2002; Villarini et al. 2011). A gradual trend may continue into the future and may therefore be interpreted as a harbinger of future change (Barkhordarian et al. 2011). Hence, gradual trends in observations should be used to validate the output from regional climate models (RCMs). Change points, on the other hand, indicate regime shifts related to non-stationary behaviour of hydro-climatic variables and must not necessarily be related to climate change. They are often difficult to predict unless their cause is known [e.g. changes in the measurement instrumentation, instrument location, field procedure, water resources and reservoir management (Clarke 2010)].

In catchments, such as the Lusatian river catchments in north-eastern Germany, where anthropogenic impact is high and natural water yield is low, the estimation of climate change impacts is especially challenging, but, at the same time, of high relevance for regional stakeholders for planning and developing of adaptation strategies to climate change. Therefore, several climate change impact assessments have been performed in this region (Al-Mukhtar et al. 2014; Conradt et al. 2012; Gädeke et al. 2014; Pohle et al. 2012, 2015). These assessments have, however, either relied on only one representative of regional climate and hydrological models or, when applying an ensemble-based modelling approach, focussed solely on the analyses of the uncertainties related to the model chain. Other studies have exclusively focussed on analysing trends in meteorological observations and run-off for change identification (Bormann 2010; Kundzewicz and Huang 2010; Stahl et al. 2010).

Here we propose an integrated analysis, assessment and interpretation of climate change impacts based on trend analysis and complex ensemble-based model chains (presented in Gädeke et al. (2014)) in order to attain a comprehensive overview of past and projected future hydro-climatic changes. The objective is threefold: (i) identification of trends and their nature in observed meteorological variables, (ii) analysis of the relation between the trends in the meteorological drivers and run-off as an integrated catchment response, (iii) assessment how simulations by RCMs agree with the observed trends in temperature, precipitation and run-off. Using this approach, we assess meteorological trends in both observations and RCMs and compare them to observed and simulated run-off trends (as the climate change impact), respectively. The results obtained present an opportunity for comparison with the results of a climate change impact assessment presented in Gädeke et al. (2014) and serve as a valuable approach for stakeholder outreach.

Study region

Our study focuses on the Lusatian river catchments of Spree (A ~ 10,000 km^2) and Schwarze Elster (A ~ 5700 km^2) located in north-eastern Germany (Fig. 1). The Lusatian river catchments have undergone dramatic alterations due to political, economic and societal changes after the German reunification in 1989. The closure of 12 of 17 lignite mines resulted in a significant decrease in mining drainage water discharged into the Spree and Schwarze Elster river catchments, while at the same time, the water requirements of the various users (e.g. lignite-based thermal power plants, numerous fish farms) remained constant. Parts of the abandoned open-pit mines have successively been converted to post-mining lakes which are estimated to cover an area of ~24,000 hectares, one-fourth of the lignite mining area utilised, after complete filling (Drebenstedt and Möckel 1998). Besides the disturbance of the natural precipitation run-off relation (Koch et al. 2012; Schoenheinz et al. 2011), significant water quality problems are arising in the post-mining landscape due to oxidised pyrite being leached out during groundwater rise after active lignite mining (Grünewald and Schoenheinz 2014; Schoenheinz et al. 2011).

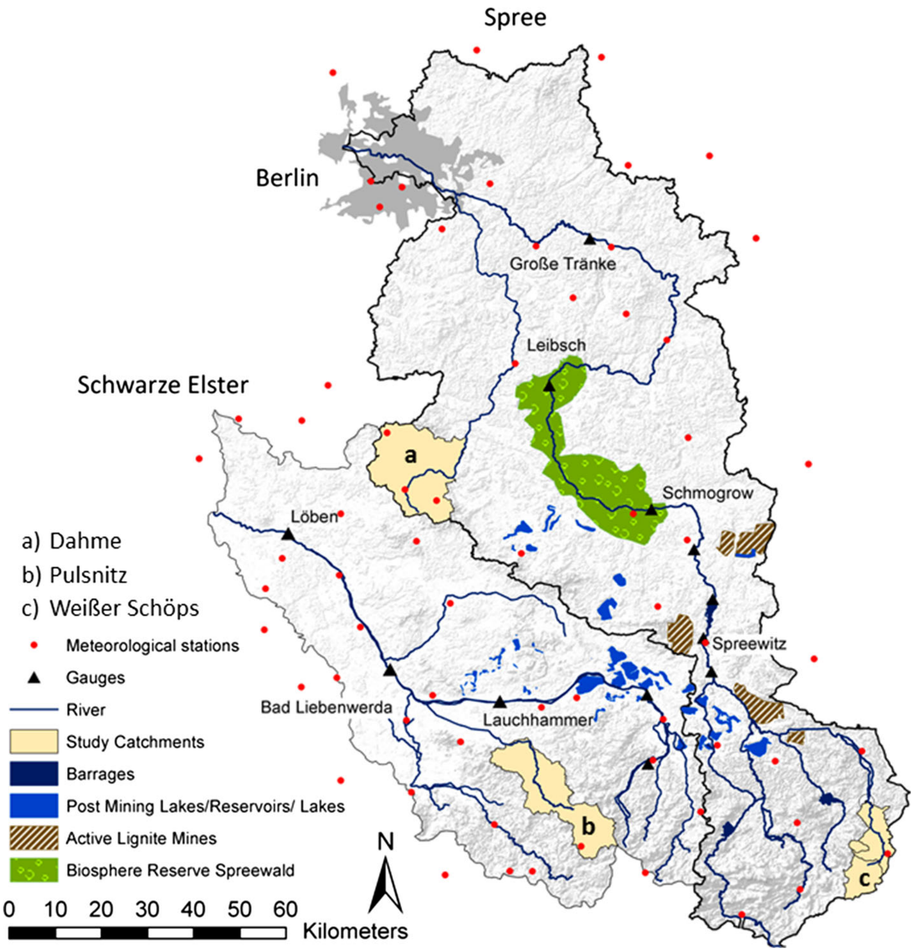

Fig. 1 Overview of the Lusatian river catchments Spree and Schwarze Elster

Potential changes in climate therefore pose a severe stress to the already limited water resources in the Lusatian river catchments (Pohle et al. 2016) and are of high trans-regional relevance as, e.g. the Spree River supplies freshwater resources for the German capital Berlin.

The Spree and Schwarze Elster river catchments are located in a transition zone between continental eastern and maritime western European climate. Long-term annual precipitation is moderate (corrected after Sevruk (1986) ~747 mm year^{-1}, 1963–2006) with the maximum occurring during summer. Long-term (1963–2006) average temperature amounts to 8.8 °C with a comparatively large difference between summer (July up to 18 °C) and winter (January down to −1.1 °C). Potential evapotranspiration reaches on average 685 mm year^{-1} with a maximum in July and a minimum in December. The long-term climatic water balance, precipitation minus potential evapotranspiration, is negative during the summer months (Schoenheinz et al. 2011). Thus, minimum run-off occurs during summer.

Three subcatchments with low anthropogenic impact were identified for analysing the impact of changes in meteorological drivers on run-off as the integral catchment response (Fig. 1). Dahme and Weißer Schöps catchments present tributaries to the Spree, while the Pulsnitz is a subcatchment to the Schwarze Elster river catchment. Based on their physiographic characteristics (land use, soil type), the subcatchments are representative for the Spree and Schwarze Elster catchments.

Data

The data basis [Table S1 (supplementary material)] can be subdivided into two main categories:

- Climatic data: measured (location of stations displayed in Fig. 1) and simulated (output from RCMs) air temperature (minimum, mean, maximum), global radiation, precipitation.
- Hydrological data: measured and simulated run-off.

Continuous daily meteorological data are available for the period 1963–2006 at 41 gauges in the Spree and 37 gauges in the Schwarze Elster river catchment (Fig. 1, including nearby stations). At the Potsdam Institute for Climate Impact Research (PIK), data gaps were filled, and temperature and global radiation, which are measured at 13 climate stations, were interpolated onto the more numerous precipitation stations.

The RCMs include two statistical [STAR (Orlowsky et al. 2008), WettReg (Spekat et al. 2010)] and two dynamical models [CCLM (Böhm et al. 2008), REMO (Jacob 2001)] which are frequently applied for climate change impact assessments within Europe (Gädeke et al. 2014; Hattermann et al. 2015; Pohle et al. 2012; Rössler et al. 2012). The spatial discretisation and resolution differs between the dynamical (uniform grid cells) and the statistical (meteorological stations) RCMs (Table S2). To be consistent and to reduce the bias a single RCM grid cell might introduce, the meteorological variables of four grid cells of the dynamical RCMs REMO and CCLM surrounding a meteorological station were interpolated onto the station using the inverse distance weighting method. Simulated temperature, precipitation and global radiation by the dynamical models were bias-corrected using a linear scaling approach (Lenderink et al. 2007). A comparison between bias-corrected output of the RCMs and observation is presented in Gädeke et al. (2014).

Methods

In this study, trends in precipitation, air temperature, global radiation and run-off were analysed in two steps: determination of trend magnitude and significance testing. For estimating trend magnitude, the slope of the linear regression was calculated. Trend significance was evaluated using the non-parametric, rank-based Pettitt test for change points (Pettitt 1979) and the non-parametric, rank-based Mann–Kendall test for gradual changes (Kendall 1975; Mann 1945). Due to the tests susceptibility to autocorrelation in the data (von Storch 1995), the trend free pre-whitening approach after Yue et al. (2002) was applied. Field significance was considered by a bootstrapping approach as proposed by Douglas et al. (2000). For all analyses, a significance level of 0.05 was chosen.

Potential evapotranspiration was calculated based on the Turc–Wendling Eq. (1):

$$\mathrm{PET} = (\mathrm{RG} + C) * \frac{T + 22}{150 * (T + 123)} \qquad (1)$$

where PET is potential evapotranspiration [mm day^{-1}], RG is global radiation [J cm^{-2} day^{-1}], C is a regional empirical parameter [according to Wendling et al. (1991) $C = 93$ in German low lands up to an elevation of 400 m] and T is the daily mean average temperature [°C]. The approach after Turc–Wendling has successfully been applied in previous studies in Germany (Haberlandt et al. 2011; Wendling et al. 1991).

On the scale of the Spree and Schwarze Elster river catchments, the analysis was conducted using annual spatially interpolated time series (by Thiessen polygons) to analyse the temporal development and to identify the type of potential change (gradual versus change points). In addition, a monthly station-wise analysis was carried out to detect intra-annual shifts for both gradual trends and change points as well as to identify spatial patterns of change. On the subcatchment scale, the analysis was expanded to include impacts of changes in the meteorological drivers on run-off and water balance due to the low anthropogenic influence. For all analyses, the period 1963–2006 was chosen.

The ability of the RCMs (Table S2) to reproduce observed mean temperature, precipitation, and run-off trends was assessed for the longest overlapping period between observation and simulation (1963–2006 for REMO, CCLM and WettReg). STAR does not have simulated data available for the past as it is based on a temporal analogue resampling technique. Trends in observed run-off time series were compared to run-off time series simulated by the process-based hydrological model WaSiM (Schulla 2015) driven by the meteorological output of the RCMs for one of the subcatchments of the River Spree, the Weißer Schöps river catchment. The hydrological model set up is described in Gädeke et al. (2014). In the scenario period 2018–2060, the mean temperature and precipitation trends of all RCMs were compared. Boxplots are chosen to represent the variability as an uncertainty measure of the RCM realisations.

Results

Trends in observations

Temperature

The trend analysis based on the interpolated annual temperature time series at the catchment scale revealed that there was an increase in mean (1.5 °C, Fig. 2, top), maximum (Spree: 1.4 °C, Schwarze Elster: 1.5 °C, Figure S1 top) and minimum (Spree: 1.1 °C, Schwarze Elster: 1.2 °C, Figure S1 bottom) annual temperature between 1963 and 2006. At the subcatchment scale, annual mean temperature also increased (Pulsnitz: 1.3 °C, Weißer Schöps: 1.4 °C, Dahme: 1.5 °C). The increasing temperature trends are significant for both the Mann–Kendall and the Pettit test with change points occurring in the year 1987 (Fig. 2). In agreement with the positive temperature trends on the annual scale, the monthly station-wise analysis shows that the number of positive mean temperature trends (Spree: 461, Schwarze Elster: 432, calculated as number of

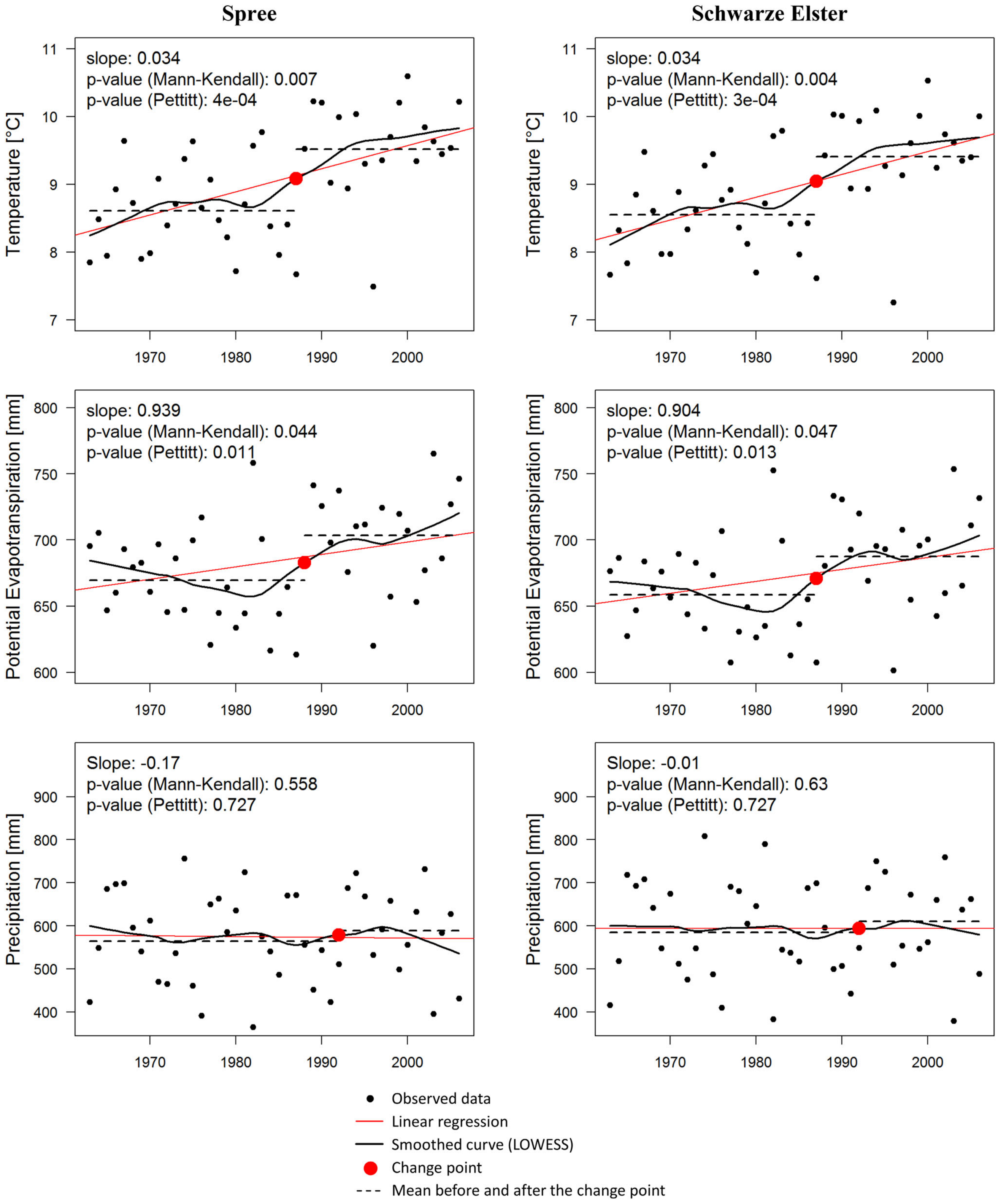

Fig. 2 Trend interpretation for mean temperature (*top*), potential evapotranspiration (*centre*) and precipitation (*bottom*) in the Spree and Schwarze Elster river catchments (interpolated annual values, 1963–2006)

months * number of stations) significantly outweighs the number of negative trends (Spree: 31, Schwarze Elster: 12) (Figure S1, top). Out of the positive trends, 27 and 29% are significant for the Mann–Kendall test and 34 and 25% for the Pettitt test in the Spree and Schwarze Elster river catchments, respectively. A few negative trends can be identified in the months of June, September (only maximum temperature), November (all except mean temperature in Schwarze Elster river catchment) and December (mean temperature in the Schwarze Elster river catchment) [maximum (Figure S2) and minimum temperature (Figure S3)]. During all other months, mean temperature trends are positive at all stations. Field significant positive trends are identified in spring (April, May) and summer (August). Positive change points are also field significant in April, May and August (Fig. 3, top).

The magnitude of the detected field significant minimum, mean and maximum temperature trends is strongest in January (except for mean temperature in the Schwarze Elster river catchment, Table S3) when mean temperature increase amounts to 2.8 °C in the Spree on average over all stations, ranging from 2.4 °C in Bischofswerda to 3.4 °C in Haselberg (south–north gradient). In the Schwarze Elster river catchment, significant temperature increase is strongest in May (1.5 °C, ranging from 2.0 °C in Oppach to 1.3 °C in Zahna).

Potential evapotranspiration

Potential evapotranspiration increased by 6% in the Spree and Schwarze Elster river catchments (Fig. 2, centre), by 4% in the Pulsnitz, 7% in the Weißer Schöps and 5% in the

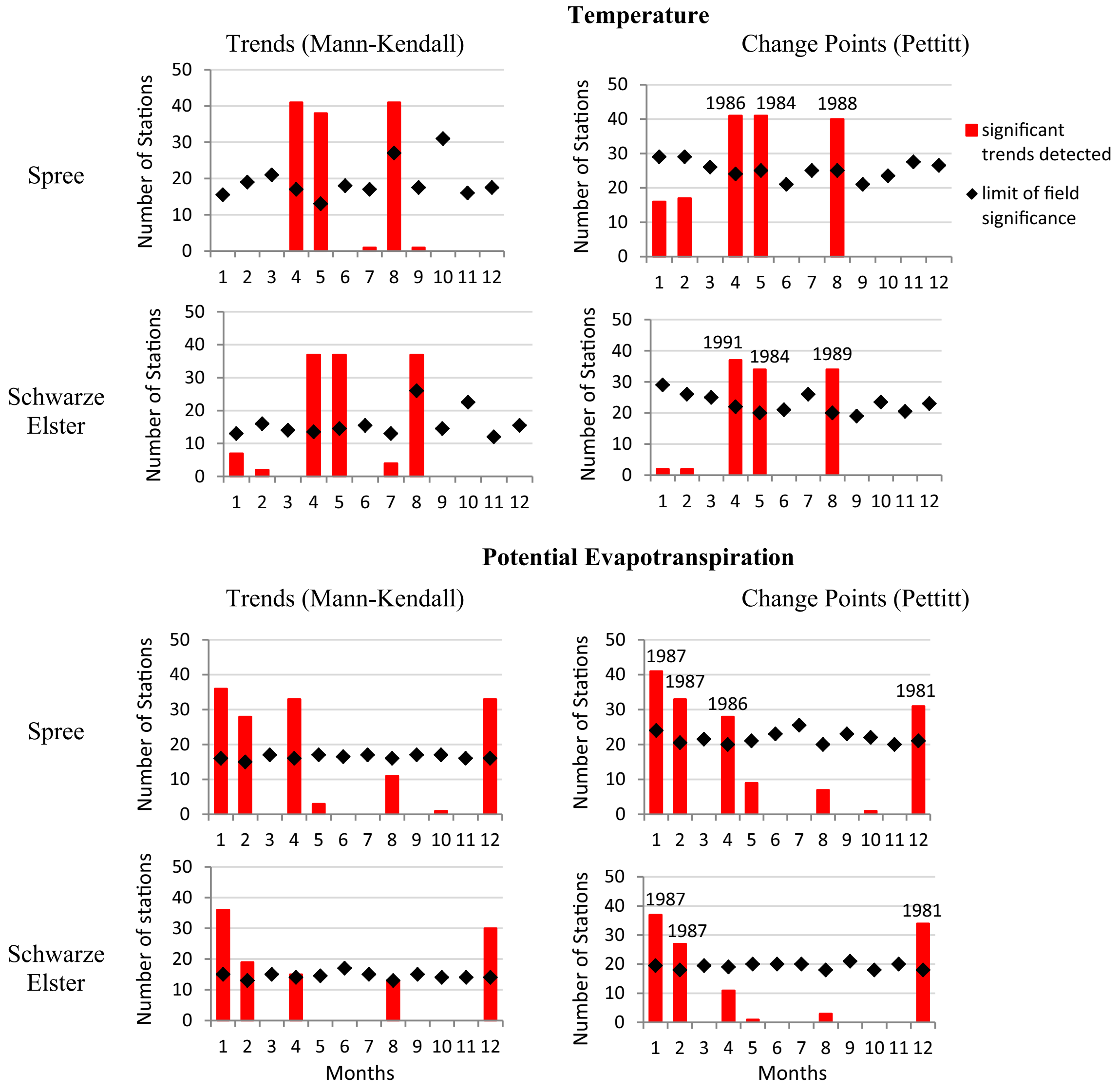

Fig. 3 Mean temperature (*top*) and potential evapotranspiration (*bottom*) (1963–2006): number of stations with significant positive changes and the limit of field significance. For field significant change points, the year of change is displayed

Dahme river catchments between 1963 and 2006. The gradual increase is significant in the Spree, Schwarze Elster and Weißer Schöps river catchments based on the Mann–Kendall test. The detected change points in 1988 (Spree, Weißer Schöps) and 1987 (Schwarze Elster, Dahme) are significant because of the shift from a negative to positive trend around the 1980s. In fact, potential evapotranspiration decreased until the 1980s by ~4% after which it increased by ~7% in the Spree and Schwarze Elster river catchments. The monthly spatially explicit analysis shows that the number of positive trends (Spree: 412, Schwarze Elster: 304) outweighs the number of negative trends (Spree: 80, Schwarze Elster: 69) (Figure S1, centre). Out of the positive trends, 35 and 37% are significant for the Mann–Kendall test and 36 and 37% for the Pettitt test in the Spree and Schwarze Elster river catchments, respectively. The positive potential evapotranspiration trends during the winter months are mainly driven by an increase in global radiation (Figure S5) while the positive trends during the summer months are a result of an increase in temperature (Figure S1, top). Significant positive potential evapotranspiration trends are field significant in January, February, April, August (only Schwarze Elster) and December (Fig. 3, bottom left). Positive change points are field significant in January, February, April (Spree) and December (Fig. 3, bottom right). The detected negative trends in June and July are not significant (Figure S1, centre and Fig. 3, bottom). Increase in potential evapotranspiration is on average largest in April while decrease is largest in June in both river catchments.

Precipitation

Change in precipitation is minor in the study area since 1963 (Spree: −1%, Schwarze Elster: −0.1%, Dahme: +0.5%, Weißer Schöps: +6%, Pulsnitz: +11%). Consequently, the trends are not significant in all catchments (Fig. 2, bottom for Spree and Schwarze Elster). The monthly station-wise analysis shows that the number of stations with positive trends (Spree: 254, Schwarze Elster: 251) slightly exceeds the number of stations with negative trends (Spree: 238, Schwarze Elster: 193) (Figure S1, bottom). The analysis further suggests a tendency towards decreasing summer and increasing winter precipitation. On average, trend magnitude is lowest in April (negative) and highest in July (positive). On the monthly basis, significant change points as well as gradual trends are below field significance except for June in the Schwarze Elster river catchment.

Water balance and run-off

The analysis of the water balance components reveals that, despite increasing precipitation, run-off decreases in all subcatchments due to increasing evapotranspiration (Table 1). Precipitation increase is larger in the southern compared to the northern part of the Lusatian river catchments. The increase in long-term average potential evapotranspiration is highest in the Weißer Schöps and lowest in the Pulsnitz river catchment (despite having the highest absolute long-term average potential evapotranspiration). Actual evapotranspiration is highest in the Dahme, followed by the Pulsnitz and Weißer Schöps river catchments. In absolute terms, run-off decrease is largest in the Pulsnitz (−92 mm), followed by the Weißer Schöps (−38 mm) and Dahme (−33 mm) river. In relative terms, measured run-off decreased by −30, −20 and −46% between 1963 and 2006 in the Pulsnitz, Weißer Schöps and Dahme river catchments, respectively (Fig. 4). Except in the Dahme river catchment, run-off decrease is not significant on an annual basis (Fig. 4). In the Pulsnitz river catchment, an increase in run-off up to the middle of the 1980s and a decrease thereafter, with a significant change point in the year 1988 is identified. The analysis suggests that the detected change point in the Pulsnitz river catchment as well as the significant decrease in run-off in the Dahme river catchment is of anthropogenic origin. In the Dahme river catchment, no significant change in precipitation is observed, but since the 1980s the run-off coefficient, defined as the ratio between annual run-off and annual precipitation, has strongly decreased (Gädeke 2014).

Comparison of trends in observations with simulations by climate downscaling approaches

Concerning mean annual temperature, all RCMs underestimate (averages: REMO: 0.05 °C, CCLM: 0.61 °C, WettReg: 0.10 °C) the trend magnitude detected in the observed time series in the Spree and Schwarze Elster (Fig. 5, top left) and their subcatchments during the period 1963–2006. The RCMs and the observations agree on a positive temperature trend in summer, autumn (all RCMs) and spring (REMO). Yet, the large observed temperature increase in winter is not captured by the RCMs. CCLM overestimates temperature trend magnitude in summer and fall (on average). For the period 2018–2060 (Fig. 5, bottom left), all RCMs simulate positive temperature trends in all study catchments annually and seasonally. Simulated increase in temperature is highest during winter (on average 0.05 °C year^{-1}) and lowest (on average 0.03 °C year^{-1}) during autumn. WettReg computes, on average, the strongest increase in temperature (0.05 °C year^{-1}).

Observed precipitation decreased in the Spree (−8 mm year^{-1}) and Schwarze Elster (−0.4 mm year^{-1}) river catchments during the period 1963–2006 (Fig. 5, top

Table 1 Overview of long-term water balance trends (precipitation (*P* [mm]), run-off (*R* [mm]), potential evapotranspiration (ETP [mm]), actual evapotranspiration (ETA [mm]). ETA is calculated based on the water balance (ETA = *P*–*R*). Trends are shown in brackets and represent the absolute change between 1963 and 2006)

	P	ETP	ETA	*R*
Spree	574 (−7 mm)	684 (+40 mm)	–	–
Schwarze Elster	595 (−0.5 mm)	673 (+39 mm)	–	–
Pulsnitz	770 (+62 mm)	708 (+25 mm)	492	276 (−92 mm)
Weißer Schöps	656 (+39 mm)	696 (+48 mm)	470	186 (−38 mm)
Dahme	561 (+3 mm)	673 (+34 mm)	504	57 (−33 mm)

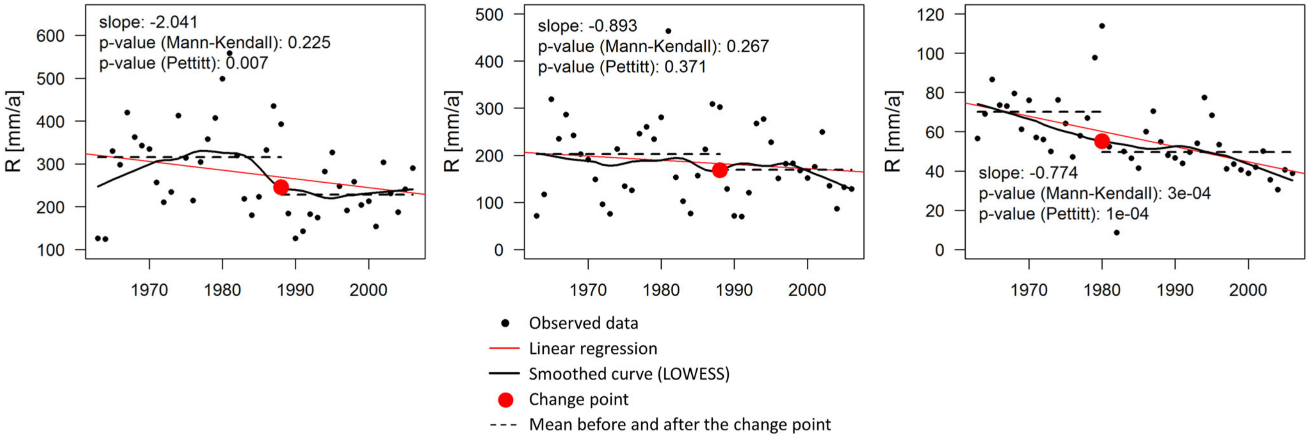

Fig. 4 Run-off (*R*) in the Pulsnitz (*left*, Königsbrück), Weißer Schöps (*centre*, Särichen) and Dahme (*right*, Prierow) and trend interpretation (1963–2006)

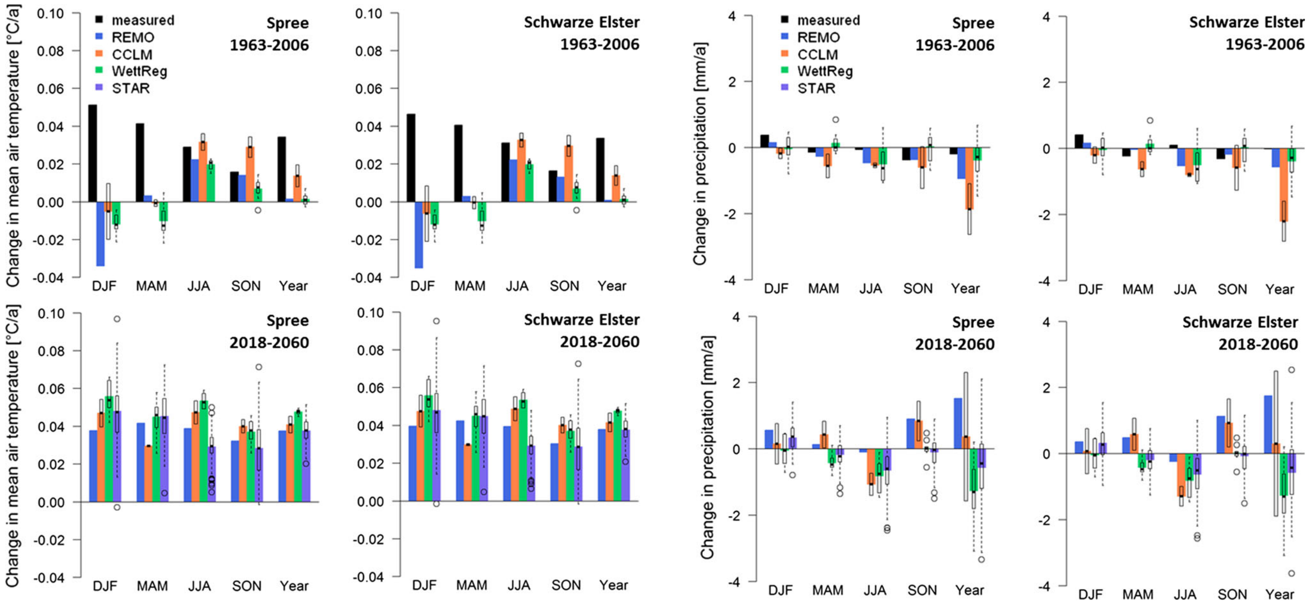

Fig. 5 Comparison of trend magnitude between measured and simulated temperature (*left*) and precipitation (*right*) for the period 1963–2006 (*top*) and between simulations for the period 2018–2060 (*bottom*) in the Spree and Schwarze Elster river catchments [DJF (December, January, February), MAM (March, April, May), JJA (June, July, August), SON (September, October, November)]

right). On the annual basis, the RCMs agree on simulating on average decreasing precipitation but differ in magnitude in all study catchments. Contrary to the observations, the RCMs do not simulate the redistribution from summer to winter. Except CCLM in the Spree river catchment, none of the RCMs consistently agrees with the direction of the observed trends. For the period 2018–2060, REMO and CCLM compute a positive trend and the statistical RCMs simulate on average a strong decrease in precipitation on the annual basis (Fig. 5, bottom right). Seasonally the dynamical RCMs simulate positive trends, except during summer, while the statistical RCMs simulate negative precipitation trends in all seasons except WettReg in autumn and STAR in winter.

Measured and simulated discharge [using the process-based hydrological model WaSiM (Schulla 2015)] were compared for the reference period in the Weißer Schöps river catchment. Within the study region, we found that the hydrological behaviour of the Weißer Schöps river subcatchment is least impacted by anthropogenic influences The comparison shows that on the annual basis the RCMs agree with the observations on a negative trend (Figure S6). Measured discharge decreases by 0.16 m^3 s^{-1} $year^{-1}$. REMO (0.13 m^3 s^{-1} $year^{-1}$, 22%) and the average of the WettReg simulations (0.09 m^3 s^{-1} $year^{-1}$, 83%) underestimate while CCLM (0.25 m^3 s^{-1} $year^{-1}$, −35%) overestimates the absolute observed negative discharge trend between 1963 and 2006. Seasonally, the RCMs agree with the direction of observed changes in winter, summer and fall (Figure S6). The average of the WettReg simulations agrees best with the observations followed by REMO and CCLM. In spring, the RCMs simulate an increase (REMO 0.37 m^3 s^{-1} $month^{-1}$, CCLM 0.03 m^3 s^{-1} $month^{-1}$, WettReg 0.07 m^3 s^{-1} $month^{-1}$ in discharge while observed discharge has decreased (−0.2 m^3 s^{-1} $month^{-1}$). The future projections, presented in Gädeke et al. (2014), show opposing trends for discharge based on choosing a dynamical (slight increase in simulated discharge) and statistical (strong decrease in simulate discharge) RCM in the Weißer Schöps river catchment.

Discussion

This study presents a thorough trend analysis using both observations and model simulations for the Lusatian river catchments (north-eastern Germany). More specifically, the trends in meteorological drivers (temperature, precipitation and potential evapotranspiration) and the catchment integrated run-off signal were used to validate and assess the suitability of two statistical and two dynamical RCMs for planning adaptation measures to climate change. The results obtained facilitated, together with the model-based climate change impact assessment (Gädeke et al. 2014), the communication of climate change uncertainties and risks to stakeholders.

Air temperature and potential evapotranspiration (a function of air temperature and global radiation in the empirical Turc–Wendling approach) have consistently increased in the study catchments of Spree and Schwarze Elster since the 1960s. The intra-annual analysis showed that the temperature increase is significant especially during spring and summer. Precipitation trends are not statistically significant, but show a tendency to increase in winter and decrease in summer (1963–2006). Increasing temperature and evapotranspiration along with decreasing precipitation have negatively impacted agriculture (due to primarily sandy soils with low available water capacity) (Bloch et al. 2014; Wagner et al. 2016) and led to more frequent low flows during summer (Reyer et al. 2011). Climate change may therefore intensify water user conflicts in the Lusatian river catchments, especially during hot dry summer months.

The simultaneous analysis of gradual trends and change points facilitated the identification of regime shifts and a differentiation between stationary versus non-stationary system behaviour. Change points for both temperature and potential evapotranspiration occurred mostly in the years 1987 and 1988, indicating a regime shift. Furthermore, before 1980 potential evapotranspiration show a negative trend, after 1980 a positive trend. The decrease in potential evapotranspiration before the 1980s can potentially be attributed to decreasing global radiation (Figure S5) which may be an indication of the effect of increased industrial pollution during the times of the German Democratic Republic in Eastern Germany referred to as the global dimming (Calanca et al. 2006; Telisca 2013; Wild 2009). An investigation thereof could be a future extension of the research.

The RCMs reproduce the temperature increase in the observation even though differences in magnitude exist. For precipitation, on the other hand, uncertainties are larger and opposing trends are simulated for the future (2018–2060). This result is supported by Blöschl and Montanari (2010) who pointed out that scenarios concerning future temperature are more robust compared to precipitation for Central Europe. Trends in simulated runoff (hydrological model WaSiM driven by RCMs) show an overall good agreement with the observations. Considering the fact that precipitation has not changed considerably during the last decades, the strong decrease in precipitation simulated by the statistical RCMs should be interpreted by considering the nature of the statistical downscaling algorithms which are based on a temporal analogue resampling technique (Orlowsky et al. 2008). Wechsung and

Wechsung (2015) present a thorough analysis on the shortcoming of the statistical RCM STAR.

Our assumption that gradual trends will continue (at least for a certain period) into the future is certainly questionable. However, our analyses identified the statistical RCMs as dry and the dynamical RCMs, without bias correction, as wet scenarios. This outcome is supported by the ensemble modelling study presented in Gädeke et al. (2014) where opposing trends (wet vs. dry) in precipitation, evapotranspiration and run-off were simulated based on whether a dynamical or statistical RCM was chosen. Consequently, only relying on the results of the model ensemble is, by itself, not beneficial for the planning of suitable adaptation strategies.

Our integrated assessment underpins that regional stakeholders can only be advised with confidence that the future will most likely be warmer while changes in precipitation remain highly uncertain. The approach of investigating how projected climate change scenarios agree with the changes observed in climate and water balance components raised stakeholder's attention, facilitated communication and outreach. In fact, stakeholders seemed more likely to trust modelling results when it has been demonstrated that trends in observations and simulation outcomes agree. The integrated approach based on trend analysis and complex ensemble-based model chains is therefore regarded beneficial for the process of identifying, planning and implementing adaptation strategies to climate change. Since both climate and land use changes of trans-regional relevance are occurring in the Lusatian river catchments simultaneously, an effective integrated river basin planning and management, which focuses on robustness to a yet unpredictable future, is essential.

In general, scientists need to ensure that climate change related information is easily accessible and presented in a useful and understandable way. From an early stage on, a close and regular cooperation between researchers and regional stakeholders from industries, governmental and non-governmental agencies is necessary in order to ensure that climate change related implications are accepted. Climate and land use change scenarios should be regarded as communication tools which allow stakeholders to gain enough knowledge to make informed decisions/choices regarding adaptation strategies and measures on their own (Patt and Weber 2014).

Ultimately, we also urge for the need to continue monitoring programmes both in terms of quantity (time series length, temporal and spatial resolution) and quality. Replacing funding to support only mechanistic science and predictive modelling is not recommended (Lovett et al. 2007; Schindler and Hilborn 2015), because observations can identify both gradual changes and also regime shifts which are yet difficult to model but may be of high relevance for assessing and planning adaptation strategies to climate change.

Conclusion and outlook

We proposed an integrated assessment and interpretation of climate change impacts as a prerequisite for stakeholder outreach and planning of suitable climate change adaptation measures in the heavily anthropogenically impacted Lusatian River catchments (north-eastern Germany). The results of the analysis suggest that the increase in temperature and potential evapotranspiration is robust, while precipitation remained nearly unchanged. The RCMs agree on simulating a temperature increase but simulate opposing trends for precipitation. We identified the statistical RCMs (STAR, WettReg) to generate warm and dry scenarios, while the dynamical RCMs (REMO, CCLM) represent wet scenarios. Ultimately, the combined analysis of trends in observations and simulation models (RCMs and hydrological models) is beneficial for stakeholder communication and outreach and may increase their willingness to plan and implement suitable adaptation strategies to climate change which are urgently needed within the Lusatian river catchments.

Future research should be directed towards focusing on trend attribution in the Lusatian river catchments. The role of global dimming as well as the impact of the large-scale land use changes, especially the influence of the number and extend of post-mining lakes, on the regional water and energy balance should be investigated. In addition, the integrated assessment and management of water quality which is of big concern in the former lignite mining district and quantity needs to be further refined. The analysis should also be regularly updated both with more recent observations and RCM results as new global as well as regional climate models are further developed and forced by different emission scenarios or Representative Concentration Pathways. A spatial explicit analysis of the ability of the RCMs to reproduce observations could further increase the results credibility.

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