Spatio-temporal analysis of present and future precipitation responses over South Germany

Spyridon Paparrizos, Dirk Schindler, Simeon Potouridis and Andreas Matzarakis

ABSTRACT

Assessment of future precipitation responses is crucial for various sectors which include tourism, agriculture, and energy yield. The study is focused on South Germany and aims to analyse the future spatio-temporal responses of annual and seasonal precipitation. Future precipitation data were derived and analysed from a number of regional climate models (RCMs), while climate simulations were performed for the future periods 2021–2050 and 2071–2100, under the A1B and B1 Intergovernmental Panel on Climate Change (IPCC) emission scenarios. Spatial interpolation and distribution of precipitation was performed using the ordinary Kriging method within ArcGIS 10.2.1. The results indicated that precipitation in South Germany is expected to increase for both applied scenarios by 10–12%. Seasonal analysis indicated that with the exception of the summer season (JJA), where precipitation by the end of the century is expected to face an 8–16% reduction, in general it will show an increase in the upcoming years. Spatial analysis indicated that areas located on the highlands will face significant reductions that will reach up to 20%. Conversely, areas located in the lowlands will have increased precipitation. The increase in precipitation amount can have a direct positive impact on the sustainable development of tourism, agriculture, energy yield and water resources in South Germany.

Key words | climate change, IPCC emission scenarios, precipitation, South Germany, spatial interpolation

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INTRODUCTION

At continental, regional and ocean basin scales, numerous long-term changes in climate have been observed. These include widespread changes in precipitation amounts, wind patterns and aspects of extreme weather including droughts, heavy precipitation, etc. Significantly increased precipitation has been observed in eastern parts of north and south America, northern Europe and northern and central Asia. Drying has been observed in the Mediterranean, southern Africa and parts of southern Asia (Intergovernmental Panel on Climate Change (IPCC) 2007). Specifically for the European continent, the Intergovernmental Panel on Climate Change (IPCC) stated that the annual precipitation trend in the 20th century showed a clear general increase for northern Europe (IPCC 1996, 2001).

Climate change is a reality today, and some of the best evidence, such as melting glaciers, comes from mountainous areas. Mountains themselves play a major role in influencing regional and global climates and they can act as barriers for wind flow, which enhances precipitation on the windward side, and reduces precipitation and warmer temperatures on the leeward side (Kohler & Maselli 2009). Mountain ranges that mainly exist in South Germany are specifically vulnerable to climate change, particularly snow conditions (United Nations Environment Programme (UNEP) 2007). According to the Organisation for Economic

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Co-operation and Development (OECD 2007), the bottom snow line of natural snow will rise up to 1,200 m in Bavaria (Bayern) and 1,350 m in Swabia (Baden-Württemberg), respectively and Germany will be the country in the Alps experiencing the highest impact of climate change with a decrease in naturally snow-reliable ski regions of approximately 40%. Additionally, according to the results of Endler & & Matzarakis (2011) who performed an analysis of precipitation (amongst other variables) for the area of the Black Forest (Baden-Württemberg) the total amount of precipitation might increase by only 5% (A1B) to 10% (B1) especially in the autumn season.

Various studies regarding the future assessment of precipitation and especially extreme precipitation have also been performed for similar climates as well as for areas located in close proximity to the under-investigation study area. A recent study by Paparrizos *et al.* (2016b) was conducted for the Greek territory in areas that present various climate conditions and the results indicated that precipitation in Mediterranean climates will be significantly reduced. Moreover, climates with *Cfb* and *Dfb* Köppen-Geiger climate classification (mostly affected by Mediterranean climates though due to close proximity) were also examined in this study with the conclusion that precipitation will also be reduced. In general, regarding the European continent, according to various scholars (Nastos & Zerefos 2007, 2008, 2009; Hertig & Jacobeit 2008, 2015) as well as the IPCC assessment reports (IPCC 2014) precipitation will reduce in areas with lower latitude and increase in areas with higher latitude, with the exception of Finland. Moreover, Schönwiese *et al.* (1994) and Feidas *et al.* (2007) reported a prolonged significant trend towards a drier winter climate, while during summer, UNEP (2007) reported that the frequency of wet days has decreased over most of Europe except for northern Scandinavia and the Baltic Sea region.

The increased concentrations of greenhouse gases in the atmosphere constitute one of the main factors that affect precipitation as well as various aspects of the global climate (Houghton *et al.* 2001; Thorpe & Andrews 2014). Furthermore, topography has a very significant role in the spatial distribution of precipitation (Paparrizos 2016).

Assessment of future precipitation responses is crucial for several factors of the economy as well as the environment. Germany is the seventh most visited country in the world with more than 35 million foreign visitors (United Nations World Tourism Organisation (UNWTO) 2011). Regarding tourism activities, South Germany is a popular place especially during the winter, due to the existence of multiple ski resorts as well as mountain ranges. On the other hand, summer tourism areas in South Germany may also be affected by regional warming, but in a positive way (Endler *et al.* 2010). The agriculture sector relies very strongly on the variations in precipitation (Paparrizos & Matzarakis 2016), and although in Germany it contributes only 1% of the total gross domestic product, it has achieved a massive increase in productivity in recent decades and occupies an area of approximately 170,000 km^2 which is more than half of the German territory employing more than 1.3 million people (Bundesministerium für Ernährung und Landwirtschaft (BMEL) 2010). Additionally, Germany is the world's 6th largest energy consumer (Bundesministerium für Wirtschaft und Energie (BMWI) 2010), while sustainable and renewable energy sources provide almost 34% of the energy yield supply (Burger 2016). Agriculture, summer and winter tourism (along with health-tourism) and energy yield constitute only some of the sectors where the assessment of climate conditions, and specifically of precipitation responses, is crucial as it can directly affect human beings, and thus stakeholders need to be reliably informed and educated (Matzarakis 2006).

The current study is focused on the integrated analysis and mapping of present and future inter-annual and seasonal responses of precipitation. The selected future periods are the years 2021–2050 (1st period) and 2071–2100 (2nd period) under the A1B and B1 scenarios that were developed by the IPCC 4th Assessment Report (AR4) (IPCC 2007). Future output simulations of precipitation were obtained and analysed from six regional climate models (RCMs). Spatial interpolation was performed used a developed downscaling technique and ArcGIS 10.2.1.

STUDY AREAS AND METHODOLOGY

Study area

The examined study areas are the federal states of Baden-Württemberg (35,752 km^2) and Bayern (70,550 km^2) that are located in South Germany. These two federal states share common borders with the Czech Republic, Austria, Switzerland and France (Jung & Schindler 2015; Schindler *et al.* 2016). According to Köppen-Geiger climate classification (Peel *et al.* 2007), the federal state of Baden-Württemberg faces mostly oceanic climate (*Cfb*), while Bayern faces humid continental conditions (*Dfb*) and in some cases in the borders between Austria, Alpine climate conditions exist. The elevation varies between 24–2,962 m (Zugspitze – Germany's highest peak). Figure 1 depicts the location and topography of the federal states in relation to Germany and Europe.

Climate data

Daily precipitation values measured at 85 ground meteorological stations of the German Meteorological Service (DWD) located over wide areas of Baden-Württemberg and Bayern for the common years 1975–2002 were used in the current study as reference period data and can be seen in the appendix (Table A1, available with the online version of this paper).

Future output simulations of precipitation derived from six RCMs were carried out through the ENSEMBLES European Project (http://ensemblesrt3.dmi.dk/). The daily precipitation values were used from the following RCMs: METNO_HIRAM, CNRM-RM4.5, HIRHAM5, HADCM3C, HADGEM2, and ETHZ-CLM. The simulations concerned the future periods 2021–2050 and 2071–2100, under the IPCC Emission Scenarios A1B and B1, respectively. Detailed information concerning the characteristics of the RCMs, driving general circulation models as well as the IPCC scenarios can be found in Paparrizos (2016). Following the extraction, the output simulations were validated with the ground truth using the coefficient of efficiency (EF), a step that constitutes a key point in studies related with future climate assessment (Nastos *et al.* 2013).

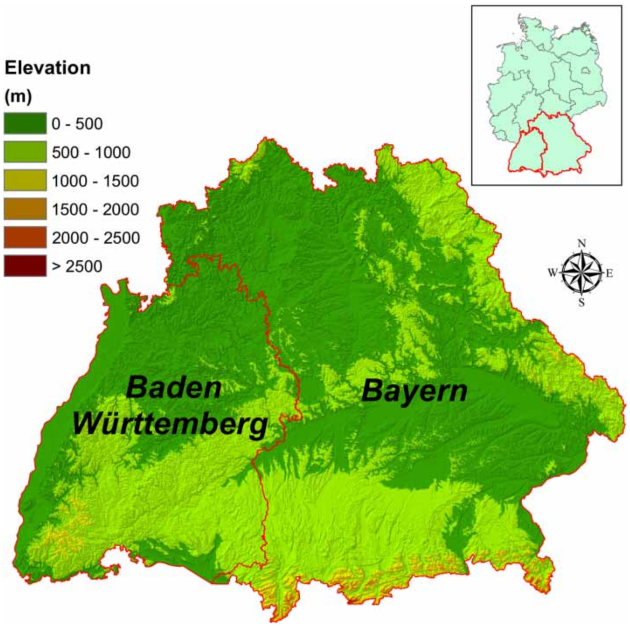

Figure 1 | Location of the study areas in Germany and Europe.

Downscaling and spatial interpolation techniques

The technique that was adopted in the current study involves a combination of statistical and dynamic downscaling that uses several topographic and physiological parameters in its application.

The statistical approach includes the development of statistical relationships that were derived by performing various multi-linear regressions (MLR) for each scenario and examined future periods (including the reference period) using the elements of all the existing ground meteorological stations that were adopted in the current study.

Initially, precipitation data from the point stations that are mentioned in Table A1 were used as the dependent variable, while various factors that affect the physical and environmental composition of precipitation were used as independent or explanatory variables. In the current study, the examined independent variables that affect precipitation and were chosen to be implemented are: elevation (m), slope (%), longitude (X) and latitude (Y) (°), and distance from a body of water (km). Following this, various multiple regression analyses were performed for each reference period and scenario. Moreover, various regression techniques were tested (simple linear, polynomial, and stepwise) and the models fit results were cross-validated each time in order to identify the most appropriate equation to simulate the precipitation amount. Through this procedure, Equation (1) was created and has the following form:

$$PREC_{value} = b_0 + b_1{}^{*}\mathrm{elev} + \mathrm{b}_2{}^{*}\mathrm{slp} + \mathrm{b}_3{}^{*}\mathrm{X} + \mathrm{b}_4{}^{*}\mathrm{Y} + \mathrm{b}_5{}^{*}\mathrm{WD} \quad (1)$$

where $PREC_{value}$ constitutes the value of precipitation in mm of the dependent variable at a certain point; b_0 to b_5 represent the coefficient parameters obtained for each independent variable from the MLR; *elev* represents the elevation (m); *slp* is the slope (%); *X* is longitude (°); *Y* is latitude (°); and *WD* is the distance between the examined point and a body of water (e.g. lake or sea, in km).

During the MLR and in order to preserve the statistical significance of the examined explanatory variables that were included in the MLR, the output *P*-value was implemented, which was used to determine the variable(s) that will be used in the MLR in order to eliminate deficiencies. The preconditions that the *P*-value should meet are as follows:

- The output *P*-value should belong each time within the significance level ($P \leq 0.05$), in order for a strong presumption to exist against the null hypothesis.
- In cases where the significance level of the examined factor is less than 95% during the multi-linear regression analysis, this factor should be eliminated from the procedure and the multi-linear regression should be re-performed.

A point that is worth mentioning regarding the above statement of *P*-value significance level is the growing concern over the credibility of claims of new discoveries based on 'statistically significant' findings. Moreover, Benjamin *et al.* (2017) proposed a change for new discoveries from $P < 0.05$ to $P < 0.005$ in order to improve the reproducibility of scientific research in many fields and results that would currently be called 'significant' but do not meet the new threshold should instead be called 'suggestive'.

Several statistical tests took place to ensure the validity of the adopted model, to avoid multi-collinearity, spatial dependence and model over-fitting.

With the use of the new equations and in order to transform the 'point information' into 'area information' the dynamic approach was implemented which included the incorporation of ArcGIS and the creation of a 5×5 km grid of sample points. Following that and through the MLR equations, each grid point received a precipitation value and the spatial distribution was conducted. A detailed description of the combined downscaling technique can be found in Paparrizos *et al.* (2016a). The same technique has been used by Paparrizos *et al.* (2016b, 2016c) and Paparrizos & Matzarakis (2016).

RESULTS AND DISCUSSION

Prior to future precipitation assessment, multiple statistical tests and checks initially took place to ensure the validity of the model and the data, and justify the technique that was adopted in the current study. Briefly, in order to avoid co-variance between the explanatory variables, the Pearson's correlation coefficient was tested which was found to be very low, while multi-collinearity was checked using the variance inflation factor which was also significantly low. Additionally, cross-validation was performed to avoid model over-fitting.

Following that, the validation of the future simulations in relation to the reference periods' data was performed, the results of which are depicted in Table 1. Table 2 depicts the output *P*-values that were derived through the multi-linear regression (and thus the explanatory variables that were used during the multi-linear regression) and were taken into account during the spatial interpolation. Figure 2 presents the multi-linear regression graphs of precipitation averages for the meteorological stations that were used in the current study. Tables 3 and 4 present the results of the inter-annual and seasonal analysis of precipitation, while Figures 3 and 4 illustrate the future responses of precipitation in mm and in terms of percentage, respectively.

Through the assessment of the *P*-values of the examined predictor variables it is obvious that in the future and under various scenarios, different explanatory variables would be responsible for explaining precipitation changes. Characteristically, according to Table 2 the parameters of elevation

Table 1 | Reference (observed) and future (RCMs) simulations data validation

South Germany

	A1B	B1
EF	*0.74*	*0.65*
std (reference period)	20.9	
std (2001–2100)	44.1	47.5
Difference	23.2	26.6

Table 2 | Output *P*-values – multi-linear regression

South Germany

Reference period		**A1B - 2021–2050**		**B1 - 2021–2050**		**A1B - 2071–2100**		**B1 - 2071–2100**	
Regression – Statistics		***Regression – Statistics***		***Regression – Statistics***		***Regression – Statistics***		***Regression – Statistics***	
Adjusted coefficient	0.70	Adjusted coefficient	0.67	Adjusted coefficient	0.68	Adjusted coefficient	0.65	Adjusted coefficient	0.65
P – values		***P – values***		***P – values***		***P – values***		***P – values***	
Intersection	**0.000**	**Intersection**	**0.000**	**Intersection**	**0.000**	**Intersection**	**0.000**	**Intersection**	**0.000**
Elevation (h)	**0.000**	**Elevation (h)**	**0.043**	**Elevation (h)**	**0.038**	**Elevation (h)**	**0.010**	**Elevation (h)**	**0.046**
Slope (%)	0.616	Slope (%)	0.321	Slope (%)	0.344	Slope (%)	0.369	Slope (%)	0.378
X	**0.001**	**X**	**0.001**	**X**	**0.001**	**X**	**0.002**	**X**	**0.002**
Y	0.580	**Y**	**0.028**	**Y**	**0.012**	Y	0.062	**Y**	**0.038**
Distance from water (km)	0.171	Distance from water (km)	0.206	Distance from water (km)	0.236	Distance from water (km)	0.177	Distance from water (km)	0.202

P-values (*P*): $P \leq 0.01$ indicates very strong presumption against null hypothesis; $0.01 \leq P \leq 0.05$ indicates strong presumption against null hypothesis; $0.05 \leq P \leq 0.1$ indicates low presumption against null hypothesis.
Coefficients in bold were included in the final multi-linear regression analysis since they have (very) strong presumption against the null hypothesis.

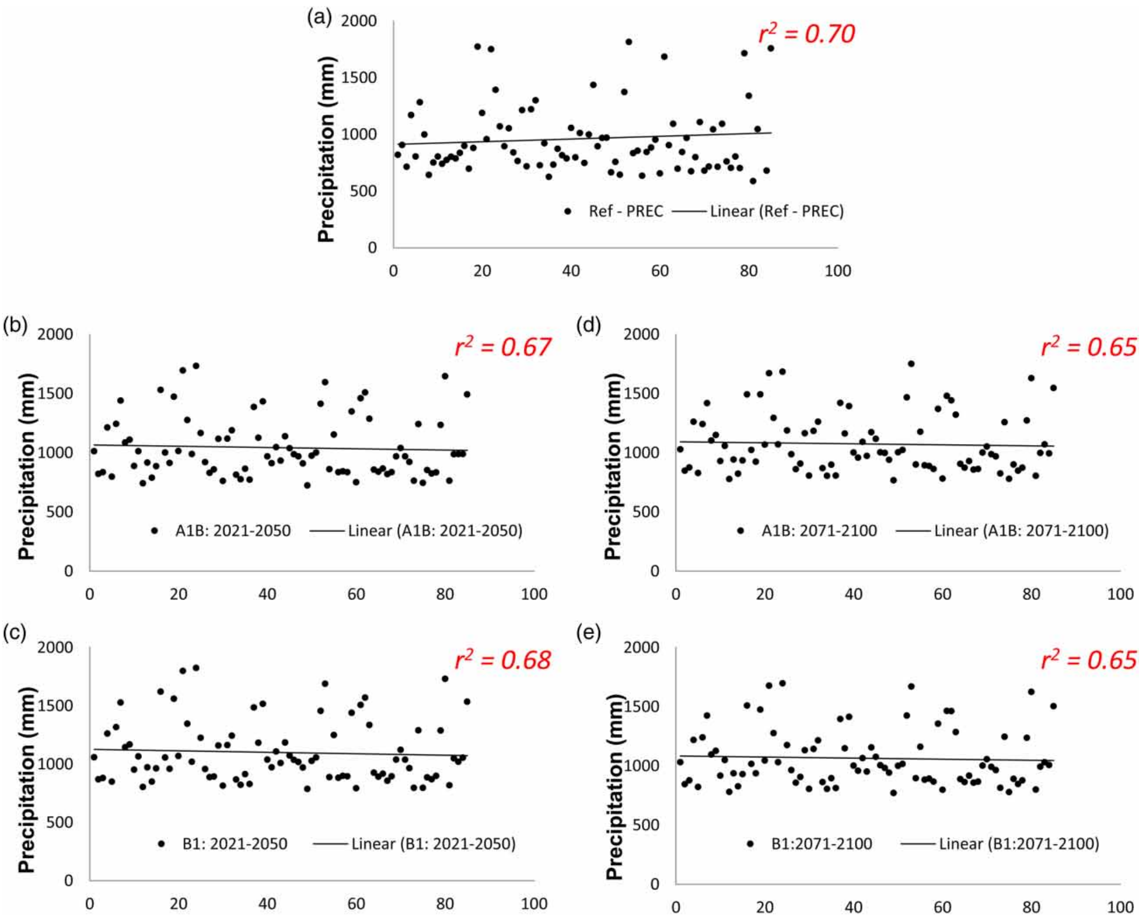

Figure 2 | Multi-linear regression graphs of precipitation averages for the meteorological stations of South Germany: (a) for the reference period (1975–2002), (b) A1B scenario (2021–2050), (c) for B1 scenario (2021–2050), (d) A1B scenario (2071–2100), and (e) B1 scenario (2071–2100).

Table 3 | Inter-annual precipitation analysis results – South Germany (green marked percentages indicate an increase in terms of percentage)

South Germany – Precipitation (mm)

Scenario/Period	A1B	B1	A1B	B1
Current		1009.6		
2021–2050	1,093	1151.7	8.3%	14.1%
2071–2100	1125.1	1114.7	11.4%	10.4%

Please refer to the online version of this paper to see this table in colour: http://dx/doi:10.2166/wcc.2017.009.

Table 4 | Seasonal precipitation analysis results – South Germany (red marked percentages indicate decrease, while green marked percentages indicate an increase in terms of percentage)

South Germany – Precipitation (mm)

Current	Winter	231.7			
	Spring	230.7			
	Summer	295.2			
	Autumn	220.7			
	Scenario/Period	**A1B**	**B1**	**A1B**	**B1**
		mm		**%**	
2021–2050	Winter	209.2	238.5	−10.7%	2.8%
	Spring	241.0	231.4	4.3%	0.3%
	Summer	325.2	367.8	9.2%	19.7%
	Autumn	282.1	281.0	21.8%	21.4%
2071–2100	Winter	286.8	242.8	19.2%	4.6%
	Spring	267.3	262.2	13.7%	12.0%
	Summer	254.0	273.5	−16.2%	−7.9%
	Autumn	266.7	285.9	17.3%	22.8%

Please refer to the online version of this paper to see this table in colour: http://dx/doi:10.2166/wcc.2017.009.

and longitude are influencing the multi-linear regression (and thus the spatial distribution of precipitation) the most, while the parameters of slope and distance from a water body are not influencing the results at all (and they were not used during precipitation distribution in the cases where $P > 0.05$). Especially for the variable of longitude, the *P*-values are significant for every applied scenario and in many cases they show a stronger effect than elevation.

Prior to precipitation analysis an estimation of the coefficient of efficiency was conducted in order to validate the output simulations in relation to the ground truth. The results indicated that the EF was rather satisfactory (EF A1B: 0.74 – EF B1: 0.65). The adjusted coefficient that was estimated through the ground network of meteorological stations and can be seen in Figure 2 also delivered significantly important results (R^2 *reference*: 0.70, R^2 *A1B_21-50*: 0.67, R^2 *B1_21-50:* 0.68, R^2 A1B_71-00: 0.65, R^2 *B1_71-00:* 0.65).

According to the results of the future analysis, precipitation is expected to increase by 8–15% under the A1B scenario. On the other hand, the B1 scenario results indicated that precipitation is expected to initially increase by 14% during the 1st examined future period, while by the end of the century the increase might be smaller, and it could reach up to 10%. A noteworthy issue is that by the end of the century according to the A1B scenario the increase in terms of percentage is higher than B1, although A1B is considered a relatively pessimistic scenario (IPCC 2007). In terms of precipitation amount (mm), according to the results the study area could present a mean increase of almost 110 mm.

Seasonal analysis which is presented in Table 3 showed that summer (JJA) during the 2nd examined period constitutes the only period where precipitation could be reduced by 8–16%. In addition to the 2nd period's reduction, summer precipitation during the 1st examined period might face only minor increases. Winter season (DJF) during the 1st period of the A1B scenario is also expected to face minor decreases. Conversely, autumn season (SON) is expected to face the greatest increases that might reach up to 17–23% by the end of the 21st century. Moreover, according to Table 3, autumn season could face the most significant increases for both periods and applied scenarios, while a significant decrease could be expected by the end of the century, and especially according to the results of the A1B scenario. Contrarily, the results indicated that spring precipitation might face negligible changes during 2021–2050 that could become important by 2071–2100.

The spatial interpretation of precipitation indicated that areas located on the highlands are expecting to face a negative trend, while areas in the lowlands could experience an increase. Additionally, the results indicated that in the upcoming years the significant variations that existed in the reference period analysis (665–2,143 mm) are expected to be moderated and precipitation distribution is expected to become more homogeneous.

Summarizing, the outputs of the current study indicated that precipitation in expected to increase in the upcoming

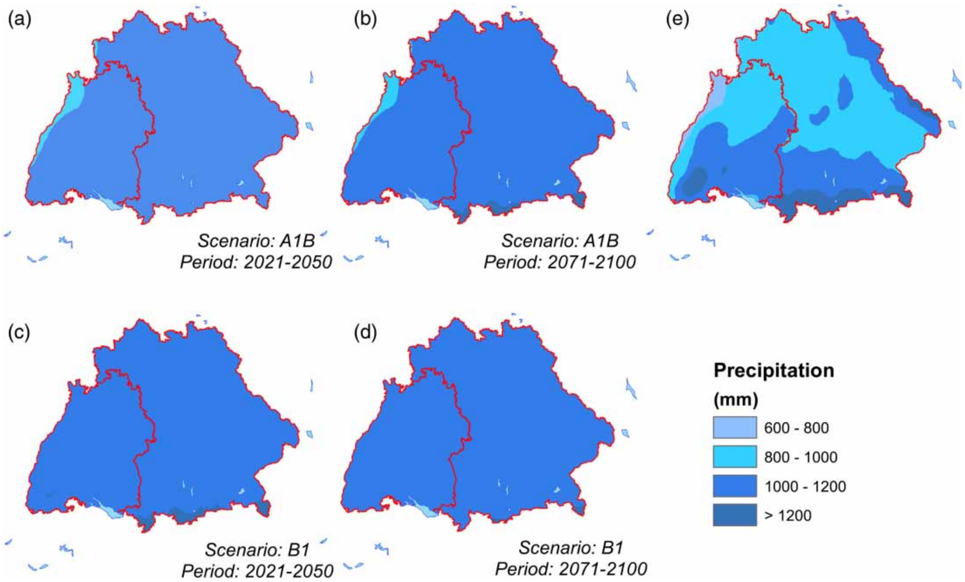

Figure 3 | Future precipitation responses (mm) – South Germany: (a) A1B scenario (2021–2050), (b) A1B scenario (2071–2100), (c) B1 scenario (2021–2050), (d) B1 scenario (2071–2100) against the (e) reference period (1975–2002).

years. This could have a direct impact in various sectors as the results suggest that more precipitated water could be available for hydroelectric use. A recent study by Burger (2016) indicated that hydro-power meets 3.5% of the electricity demand in Germany and between the years 2015–2016 it was increased by 9.1%. Furthermore, Germany achieved a surplus in power generation for 2016 and exported power into its neighbouring countries with benefits of more than 1.5 billion (10^9) €.

It is also worth mentioning that the Rhine River is located in the west part of the study area and a considerable part of it is 'fed' by the precipitated water within the

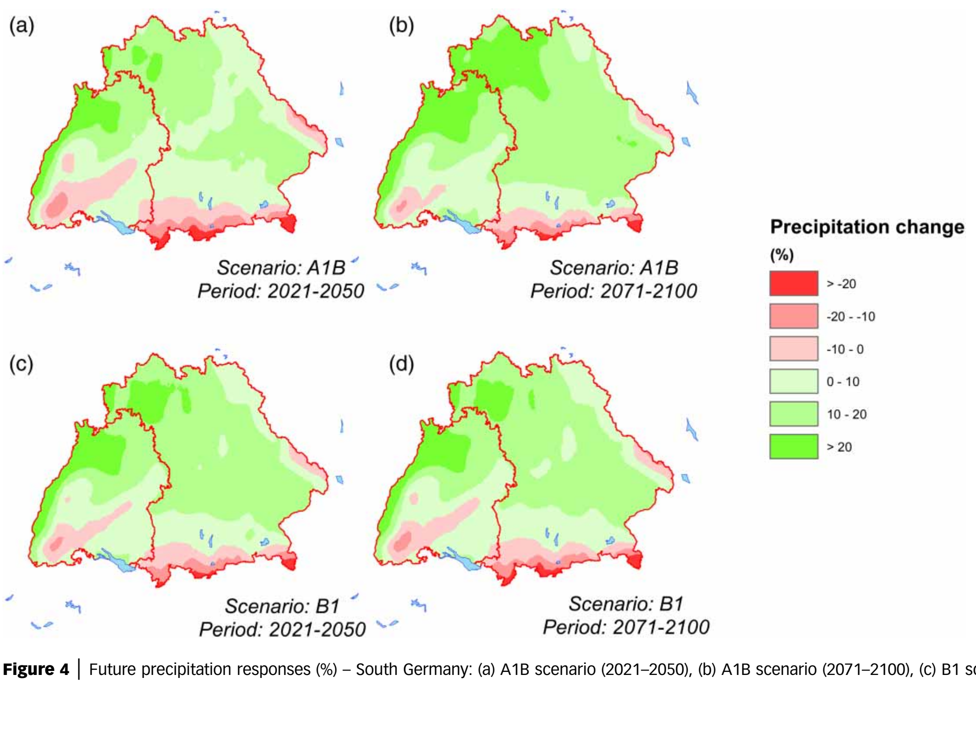

Figure 4 | Future precipitation responses (%) – South Germany: (a) A1B scenario (2021–2050), (b) A1B scenario (2071–2100), (c) B1 scenario (2021–2050), (d) B1 scenario (2071–2100).

examined area. The Rhine River, a natural border between Germany and France, can provide freshwater to most of the agricultural production that takes place on the west side on Germany and help the sustainable development of cultivations such as vineyards (Neumann & Matzarakis 2011), etc. Additionally, it can also be beneficial for all the agricultural activities that take place in the northwest part of Switzerland (Upper Rhine), the Ruhr valley (Middle and Lower Rhine) within the German territory, and for the neighbouring countries such as France and the Netherlands as well.

On the other hand, in the last couple of decades Europe and especially the Rhine valley has witnessed a growth in the scale and frequency of extreme natural disasters due to flooding phenomena (te Linde *et al.* 2011). The flooding events of 1993 and 1995 caused severe damage of 1.4 and 2.6 billion (10^9) €, respectively (Engel 1997; Glaser & Stangl 2003). Furthermore, the impact of the flood events is likely to have more severe socio-economic consequences in the upcoming years due to the increase of annual maximum peak discharges (Middelkoop *et al.* 2001), as well as the growing number of people living in areas with high flood exposure level (Bouwer *et al.* 2007; Pielke *et al.* 2008).

Future decrease of precipitation in areas characterized by higher altitudes might be a problem for winter recreation activities associated with snowfall, and for this reason new and equally profitable activities should be implemented such as hiking, climbing, etc., as in the upcoming years the inevitable increase of air temperature will ensure that precipitation will occur as rainfall, and not snowfall. In any case, the winter tourism industry needs to become more flexible in the upcoming years, in order to prosper.

CONCLUSIONS

The current study dealt with the integrated analysis of present and future responses and spatial interpolation of precipitation over the federal states of Baden-Württemberg and Bayern located in South Germany. Output simulations from the ENSEMBLES European Project were obtained and analysed and ArcGIS 10.2 was employed in order to interpret the results in terms of precipitation amount (mm) and percentage (%).

Precipitation is expected to increase in the upcoming years; yet according to the spatial analysis, areas located in higher altitudes are anticipated to face relatively significant decreases in excess of −20%. Nevertheless, decrease in precipitation according to Figures 3 and 4 may only occur in areas that exceed 900–1,000 m altitude, while in the lowlands precipitation is expected to increase and could result an overall positive balance of 8–14%. Seasonal analysis indicated that the precipitation amount will increase for winter (DJF), spring (MAM) and autumn (SON) seasons, but decrease during the summer (JJA). When working with future data, various uncertainties exist; and although there has been a significant improvement in the simulation of precipitation patterns since the AR4, there is still a great deal of work to be done. The Representative Concentration Pathways that have been employed recently in order to assess the future responses of precipitation were not adopted in the current study as they do not represent fully integrated scenarios (they are not a complete package of socio-economic emissions and climate projections). Additionally, according to the IPCC AR5, experience shows that their full integration process may take up to 10 years.

In any case, the increase of precipitation suggested from the analysis could prove very useful in several sectors of the economy supposing that issues associated with the uprising flooding phenomena could be addressed. Energy yield and agriculture can benefit and, in addition, the increased precipitation can feed the torrential streams with excess water which can be beneficial in an era of climate change.

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