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Brief Communication: An update of the article "Modelling flood damages under climate change conditions – a case study for Germany"

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Abstract. In our first study on possible flood damages under climate change in Germany, we reported that a considerable increase in flood-related losses can be expected in a future warmer climate. However, the general significance of the study was limited by the fact that outcome of only one global climate model (GCM) was used as a large-scale climate driver, while many studies report that GCMs are often the largest source of uncertainty in impact modelling. Here we show that a much broader set of global and regional climate model combinations as climate drivers show trends which are in line with the original results and even give a stronger increase of damages.

1 Introduction

Many studies have pointed out that an increase in temperature will amplify the hydrological cycle, and intense precipitation will increase (Kundzewicz and Schellnhuber, 2004). This is confirmed in a recent study by Lehmann et al. (2015), showing that there is indeed a trend to more intense precipitation worldwide which is in line, in general, with the Clausius–Clapeyron equation (relation of temperature to saturation vapour pressure, Pall et al., 2007). An increase in specific air humidity and intense precipitation, as well as in frequency of "wet" atmospheric circulation patterns, has also been reported for Germany (Hattermann et al., 2012).

This is why the German Insurance Association has commissioned a study with the aim to estimate what flood damage would occur in individual river reaches of Germany under a warmer climate (published in Hattermann et al., 2014), solely considering the pure climate change impact and keeping socio-economic drivers constant. Only a limited number of regional climate projections were available for the impact study, and these projections were all driven by a single global circulation model (GCM), while different recent studies show that GCMs are often the largest source of uncertainty in impact modelling (cf. Vetter et al., 2015).

In this short communication, we cross-check the robustness of the overall outcome of the first study, viz. that an increase in temperature will likely lead to an increase in flood hazard and flood-related losses in Germany, by applying a larger ensemble of climate change scenarios and scenario runs as a driver for the impact study.

The methodology to study the impacts of global climate change on flood hazard and damages in Germany used here is exactly as described in Hattermann et al. (2014). In short, 5473 river sections of the five largest river basins in Germany (the Rhine, the Danube, the Elbe, the Weser and the Ems) are considered. Most of these river sections (3766) are in Germany, but 1707 of them are in other countries that share international rivers with Germany. The changes in climate are transformed into changes in flood hazards on a daily time step using the ecohydrological model SWIM (Krysanova et al., 2015), and the related damages are calculated using river-section-specific damage functions as provided by the

German Insurance Association (GDV, Gesamtverband der Deutschen Versicherungswirtschaft) (see Hattermann et al., 2014). Human estates and small enterprises are taken into account in the damage functions.

The SWIM model has previously been implemented for the main German rivers by Hattermann et al. (2005) and Huang et al. (2010) and applied in various impact and adaptation studies (Hattermann et al., 2015; Huang et al., 2010). Investigation of climate change impacts on floods using the results of different RCMs as climate boundary conditions was carried out by Huang et al. (2013), Hattermann et al. (2011) and Falter et al. (2015).

2 The climate forcing data

While in the original study seven climate projections of two RCMs (REMO, Tomassini and Jacob, 2009 and CCLM, Böhm et al., 2006) driven by only one GCM (ECHAM5, Roeckner et al., 2003) were used, two newer climate data sets with a much broader combination of driving GCMs and RCMs are available now and are applied in this follow-up analysis to estimate the robustness of the outcome of the original study. The first one was developed in the ENSEMBLES project (Van der Linden and Mitchell, 2009), whereof 14 GCM/RCM combinations all for the SRES A1B emission scenario were taken as climate drivers for the impact estimation. The spatial resolution of these RCM data is approximately 25 km. For the HadCM3 GCM as well as the HadRM3 RCM, three realizations were included for “normal” climate sensitivity (Q0), “low” climate sensitivity (Q3) and “high” climate sensitivity (Q16) to the external forcing (e.g. greenhouse gas concentrations, by perturbing HadRM3 internal parameters; see Collins et al., 2006). The most recent set of climate scenario data are projections delivered by the CORDEX initiative (Coordinated Downscaling Experiments, Jacob et al., 2014), an internationally coordinated framework to produce improved regional climate change projections with a focus on climate change impact and adaptation studies. In CORDEX, a combination of GCMs and RCMs was applied for Europe, of which we selected 11 uncorrected and four bias-corrected runs for the RCP (Representative Concentration Pathway) scenario 8.5 (additional radiative forcing 8.5 W m^{-2} until the end of the century) and four bias-corrected runs for the RCP scenario 4.5 and with a time horizon until 2100. The bias correction was done using a quantile mapping method (cf. Wilcke et al., 2013; Gobiet et al., 2015). The combinations of GCMs and RCMs used in the study are listed in Appendix A.

In all climate projections, temperature shows a robust and statistically significant warming over Europe, with regional differences, in the range of 1–4.5° for RCP4.5 and of 2.5–5.5° for RCP8.5, the latter encompassing the warming range projected for the A1B scenario, with temperature increases between 3 and 4.5° (Jacob et al., 2014).

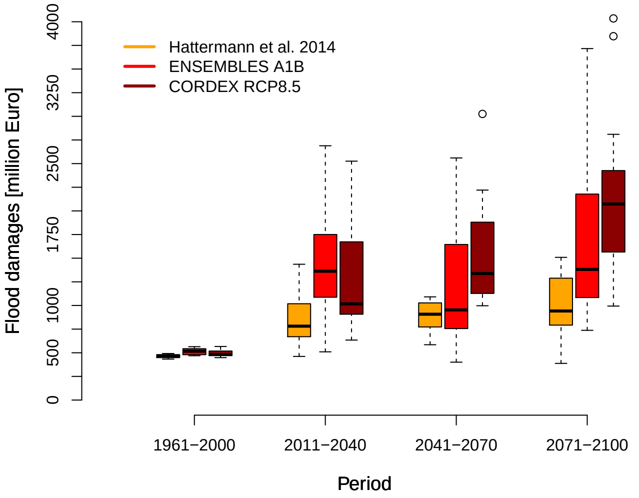

Figure 1. The annual losses per year in Germany simulated with different ensembles of climate projections as input. The bottom and top of the box give the first and third quartiles, the band inside the median and the whiskers give the upper and lower 1.5 interquartile range.

3 Results

Figure 1 illustrates the changes in flood-related damages under a warmer future when considering different sets of climate ensemble projections. The numbers show the total annual sum for Germany, considering human estates and small enterprises as affected assets. The results are compared for three future periods (2011–2040, 2041–2070 and 2071–2100) against the reference periods 1961–2000 (Hattermann et al., 2014, and ENSEMBLES project) and 1971–2010 (CORDEX, starting only in 1971). Table 1 summarizes the damages per period and ensemble projection, and Table A5 (Appendix A) reports all the statistics shown in Fig. 1. From the results it is visible that (a) the general outcome of the original study (an overall increase of flood-related damages in a warmer climate) is confirmed by the new results, (b) the ensemble expectations (medians and means) of the flood-related damages even increase when using the new climate data sets as drivers (Table 1), although (c) the simulated uncertainty is generally rising with an increasing number of scenario projections and from one scenario period to the next. The increase in damages until the end of the century is the strongest within the “high-end scenario”, RCP8.5, with more than a 300 % increase when comparing this increase to the reference period (long-term annual damage means and medians). The increase exceeds 200 % for the ENSEMBLES scenario, while it is only slightly above 100 % in Hattermann et al. (2014) (Table 1). However, when looking at the minimum and maximum increases until the end of the century, the range is from −11 to +207 % in Hattermann et al. (2014) and from +122 to +613 % in the scenario RCP8.5.

Table 1. Median (and mean) of damages per period and scenario projection (million EUR).

Climate projection	Reference	2011–2040	2041–2070	2071–2100
Original	467.6 (464.7)	781.3 (854.6)	907.6 (886.5)	941.9 (992.7)
ENSEMBLES	516.5 (512.8)	1362.3 (1402.1)	953.3 (1288.9)	1381.3 (1717.2)
CORDEX RCP8.5	481.1 (494.5)	1017.4 (1287.7)	1337.5 (1561.2)	2073.2 (2145.7)

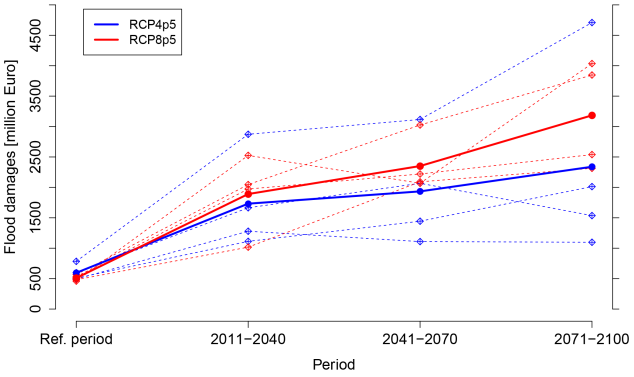

Figure 2. Comparison of impacts on monetary losses when using RCP4.5 or RCP8.5 scenarios as climate drivers. The dashed lines show the single runs; the solid lines represent the averages per period.

In Fig. 2, the damages are compared for the four bias-corrected RCP4.5 and RCP8.5 projections. It is visible that the average increase in damages is almost the same during the first period, in compliance with the very similar temperature increase in both scenarios. The differences increase in the second and third scenario period, with an approximately 36 % higher average in the RCP8.5 projections until 2100. In total, all projections generally show an increase in damages, but uncertainty is high and single runs may have a slight decrease in damages from one scenario period to another.

4 Conclusions

While the general significance of the original study was limited by a low number of GCM/RCM combinations, the new results with a much higher variety of climate projections as input for the damage estimation give a strong indication that flood-related damages will increase in Germany in a warmer climate unless counteracting adaptation measures are implemented. This is notwithstanding the fact that also the uncertainty is large: in almost all cases, the lower quartiles are higher than the upper quartiles of the reference and the median of the previous period, and of all 35 projections into the future, only one shows a slight decrease in average damages until the end of this century.

Appendix A: Tables of the climate model data used in the study

Tables A1–A4 give the different combinations of driving GCMs and nested RCMs, while Table A5 lists the statistics visualized in Fig. 1.

Table A1. Scenario data matrix used in Hattermann et al. (2014).

	Institute	DWD	MPI
	RCM	CCLM	REMO
	Resolution	0.18°	10 km
GCM MPI-ECHAM5		MPI-ECHAM5	MPI-ECHAM5
Scenario (no. runs)		A1b(2), B1(2)	A1b(1), A2(1), B1(1)
Period		1951–2100	1951–2100

Table A2. Fourteen selected GCM/RCM simulations (SRES A1B) from the ENSEMBLES project (Van der Linden and Mitchell, 2009).

	Institute	C4l	DMI	ETHZ	HC			ICTP	KNMI	MPI	SMHI
	RCM	RCA3	HIRHAM5	CLM3.21	HadRM3 Q0	HadRM3 Q3	HadRM3 Q16	REGCM3	RACMO2	M-REMO	RCA3
GCM	Resolution	25 km	25 km	25 km	25 km	25 km	25 km	25 km	25 km	25 km	25 km
HC HadCM3 Q0				1951–2100	1951–2100					1951–2100	
HC HadCM3 Q3						1951–2100					1951–2100
HC HadCM3 Q16		1951–2100					1951–2100				
MPI-MET ECHAM5 r3			1951–2100					1951–2100	1950–2100		1950–2100
CNRM Arpege			1951–2100								
UIB BCM			1961–2099								1961–2100

Table A3. CORDEX-EUR-11 simulation matrix for RCP8.5 used in the study.

RCM8.5	Institute	SMHI	MPI–CSC	KNMI		IPSL	DMI
	RCM	RCA4	REMO2009	RACMO22E	CLMcom-CCLM4-8-17	WRF331F	DMI-HIRHAM5
GCM	Resolution	0.11°	0.11°	0.11°	0.11°	0.11°	0.11°
MOHC-HadGEM2-ES		1971–2100					
ICHEC-EC-EARTH		1971–2100		1971–2100	1971–2100		1971–2100
MPI-M-ESM-LR		1971–2100	1971–2100		1971–2100		
CNRM-CERFACS-CNRM-CM5		1971–2100			1971–2100		
IPSL-CM5A-MR		1971–2100				1971–2100	

Table A4. Bias-corrected CORDEX-EUR-11 simulations for RCP4.5 and RCP8.5 used in the study (Wilcke et al., 2013; Gobiet et al., 2015).

	Institute	SMHI	MPI–CSC	KNMI
	RCM	RCA4	REMO2009	RACMO22E
GCM	Resolution	25 km	25 km	25 km
MOHC-HadGEM2-ES		1971–2100		
ICHEC-EC-EARTH		1971–2100		1971–2100
MPI-M-ESM-LR			1971–2100	

Table A5. Summary of the damage statistics visualized in Fig. 1.

	Hattermann et al. (2014)			
	1961–2000	2011–2040	2041–2070	2071–2100
Min.	433.2	461.2	585.0	387.6
1st qu.	456.8	670.9	825.7	826.2
Median	467.6	781.3	907.6	941.9
Mean	464.7	854.6	886.5	992.7
3rd qu.	473.7	936.6	1015.0	1282.3
Max.	492.0	1435.8	1091.2	1508.8
	ENSEMBLES A1B			
	1961–2000	2011–2040	2041–2070	2071–2100
Min.	468.7	510.0	400.5	737.2
1st qu.	479.7	1087.2	756.1	1083.7
Median	516.4	1362.3	953.3	1381.3
Mean	512.8	1402.1	1288.9	1717.2
3rd qu.	542.9	1750.5	1645.0	2177.8
Max.	564.4	2688.7	2559.9	3716.2
	CORDEX RCP8.5			
	1971–2010	2011–2040	2041–2070	2071–2100
Min.	448.6	634.1	997.2	993.6
1st qu.	470.6	907.5	1127.5	1565.5
Median	481.1	1017.4	1337.5	2073.2
Mean	494.5	1287.7	1561.2	2145.7
3rd qu.	518.4	1672.9	1880.8	2426.4
Max.	566.4	2525.8	3025.4	4035.3

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References

Böhm, U., Kücken, M., Ahrens, W., Block, A., Hauffe, D., Keuler, K., Rockel, B., and Will, A.: CLM-the climate version of LM: Brief description and long-term applications, COSMO Newsletter, 6, 225–235, 2006.

Collins, M., Booth, B. B., Harris, G. R., Murphy, J. M., Sexton, D. M., and Webb, M. J.: Towards quantifying uncertainty in transient climate change, Clima. Dynam., 27, 127–147, 2006.

Falter, D., Schröter, K., Dung, N. V., Vorogushyn, S., Kreibich, H., Hundecha, Y., Apel, H., and Merz, B.: Spatially coherent flood risk assessment based on long-term continuous simulation with a coupled model chain, J. Hydrol., 524, 182–193, doi:10.1016/j.jhydrol.2015.02.021, 2015.

Gobiet, A., Suklitsch, M., and Heinrich, G.: The effect of empirical-statistical correction of intensity-dependent model errors on the temperature climate change signal, Hydrol. Earth Syst. Sci., 19, 4055–4066, doi:10.5194/hess-19-4055-2015, 2015.

Hattermann, F. F., Wattenbach, M., Krysanova, V., and Wechsung, F.: Runoff simulations on the macroscale with the eco-hydrological model SWIM in the Elbe catchment-validation and uncertainty analysis, Hydrol. Process., 19, 693–714, doi:10.1002/hyp.5625, 2005.

Hattermann, F. F., Weiland, M., Huang, S., Krysanova, V., and Kundzewicz, Z. W.: Model-supported impact assessment for the water sector in Central Germany under climate change – a case study, Water Resour. Manag., 25, 3113–3134, 2011.

Hattermann, F. F., Kundzewicz, Z. W., Huang, S., Vetter, T., Kron, W., Burghoff, O., Merz, B., Bronstert, A., Krysanova, V., and Gerstengabe, F.-W.: Flood risk in holistic perspective - observed changes in Germany, in: Changes in Flood Risk in Europe, edited by Kundzewicz, Z. W., IAHS Press, Wallingford, Oxfordshire, UK, 212–237, 2012.

Hattermann, F. F., Huang, S., Burghoff, O., Willems, W., Österle, H., Büchner, M., and Kundzewicz, Z.: Modelling flood damages under climate change conditions – a case study for Germany, Nat. Hazards Earth Syst. Sci., 14, 3151–3168, doi:10.5194/nhess-14-3151-2014, 2014.

Hattermann, F. F., Huang, S., and Koch, H.: Climate change impacts on hydrology and water resources, Meteorol. Z., 24, 201–211, doi:10.1127/metz/2014/0575, 2015.

Huang, S., Krysanova, V., Oesterle, H., and Hattermann, F. F.: Simulation of spatiotemporal dynamics of water fluxes in Germany under climate change, Hydrol. Process., 24, 3289–3306, doi:10.1002/hyp.7753, 2010.

Huang, S., Hattermann, F. F., Krysanova, V., and Bronstert, A.: Projections of climate change impacts on river flood conditions in Germany by combining three different RCMs with a regional eco-hydrological model, Climatic Change, 116, 631–663, 2013.

Jacob, D., Petersen, J., Eggert, B., et al.: EURO-CORDEX: new high-resolution climate change projections for European impact research, Reg. Environ. Change, 14, 563–578, doi:10.1007/s10113-013-0499-2, 2014.

Krysanova, V., Hattermann, F., Huang, S., Hesse, C., Vetter, T., Liersch, S., Koch, H., and Kundzewicz, Z. W.: Modelling climate and land-use change impacts with SWIM: lessons learnt from multiple applications, Hydrolog. Sci. J., 60, 606–635, doi:10.1080/02626667.2014.925560, 2015.

Kundzewicz, Z. and Schellnhuber, H.: Floods in the IPCC TAR perspective, Nat. Hazards, 31, 111–128, 2004.

Lehmann, J., Coumou, D., and Frieler, K.: Increased record-breaking precipitation events under global warming, Climatic Change, 132, 501–515, doi:10.1007/s10584-015-1434-y, 2015.

Pall, P., Allen, M., and Stone, D.: Testing the Clausius–Clapeyron constraint on changes in extreme precipitation under CO_2 warming, Clim. Dynam., 28, 351–363, doi:10.1007/s00382-006-0180-2, 2007.

Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Manzini, L., Rhodin, A., Schlese, U., Schulzweida, U., and Tompkins, A.: The Atmospheric General Circulation Model ECHAM5: Part 1: Model Description, Max-Planck-Institute for Meteorology, Hamburg, Germany, Report No. 349, 140 pp., 2003.

Tomassini, L. and Jacob, D.: Spatial analysis of trends in extreme precipitation events in high-resolution climate model results and observations for Germany, J. Geophys. Res., 114, D12113, doi:10.1029/2008JD010652, 2009.

Van der Linden, P. and Mitchell, J. F. B. (Eds.): ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project, Met Office Hadley Centre, Exeter, UK, 160 pp., 2009.

Vetter, T., Huang, S., Aich, V., Yang, T., Wang, X., Krysanova, V., and Hattermann, F.: Multi-model climate impact assessment and intercomparison for three large-scale river basins on three continents, Earth Syst. Dynam., 6, 17–43, doi:10.5194/esd-6-17-2015, 2015.

Wilcke, R., Mendlik, T., and Gobiet, A.: Multi-variable error correction of regional climate models, Climatic Change, 120, 871–887, doi:10.1007/s10584-013-0845-x, 2013.