

Projections of Precipitation in the Northern Foothills of the Tatra Mountains

Iwona Pinskwar, Adam Chorynski, Zbigniew W. Kundzewicz
and Virginia Ruiz-Villanueva

Abstract Floods are usually related to extreme and/or long-lasting intense precipitation events. In warmer climate, future precipitation extremes could be higher than nowadays. Assessment of these future changes and climate adaptation to future flood risk are very important issues. In this study, four regional climate models and seven global climate models for two climate scenarios A1B and A2 were used to get better description of the range of changes in annual as well as extreme precipitation events. With help of the delta-change method, projections were made based on responses from regional and global climate models, for 11 precipitation stations in the Tatra Mountains in Poland, for which observation data for 1961–1990 were available. Analyses were made of various indices, such as annual totals, maximum 24 h, 5-day; 10-day, monthly maximum sum of precipitation and also numbers of days with intense precipitation equal or above the thresholds of 30 and 50 mm. It was found that all RCM and GCM models under examination project an increase in mean annual precipitation totals as well as in heavy precipitation in two future time windows considered (2061–2090 and 2080–2100).

Keywords Extreme precipitation · Climate models · Projections · Delta-change method

I. Pinskwar (✉) · A. Chorynski · Z.W. Kundzewicz
Institute for Agricultural and Forest Environment, Polish Academy of Sciences,
Poznan, Poland
e-mail: iwona.pinskwar@isrl.poznan.pl

Z.W. Kundzewicz
Potsdam Institute for Climate Impact Research, Potsdam, Germany

V. Ruiz-Villanueva
Dendrolab.ch, Institute of Geological Sciences, University of Bern, Bern, Switzerland

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) stated that there is high confidence that recent climate changes have had discernible impacts on physical and biological systems (IPCC 2007). Many General Circulation Models (GCMs) predict increases in frequency and magnitude of extreme climate events and variability of precipitation (IPCC 2007, 2012). This is likely to influence terrestrial water resources (Srikanthan and McMahon 2001; Xu and Singh 2004). In addition, the costs of extreme meteorological events have exhibited a rapid upward trend in recent decades and have large impacts on society (IPCC 2012). Floods are the most destructive natural hazard in Poland and most of the flood damage in the country occurs in the basins of two large rivers: the Upper Vistula and the Upper Odra. Abundant rainfall in the Upper Vistula Basin, especially in its mountainous, right-hand, tributaries, such as the rivers: Dunajec, Raba, Wisloka and Skawa, leads to violent and highly erosive flood events. Destructive floods occurred most frequently in July (in 1903, 1934, 1960, 1970, 1997, 2001), but also in other months between May and September (e.g. May and June 2010).

The Tatra Mountains (in Polish: Tatry), located in southern Poland and northern Slovakia, are the highest range of the massive of the Carpathian Mountains. The northern foothills of the Tatra Mountains belong to the drainage basin of the largest Polish river—the Vistula. Precipitation recorded on the northern slopes of the Tatra Mountains is the highest in Poland and largely contributes to flood risk generation over a larger area (Niedziedz et al. 2015). Hence, assessment of future changes in intense precipitation in the northern foothills of the Tatra Mountains is very important. Every increase in magnitude, duration, and frequency of extreme precipitation may lead to an increase in climate-related flood risk. The mean annual precipitation at Kasprowy Wierch (1991 m a.s.l.) for the period 1951–2013 was 1752 mm, nevertheless, the record-high annual maximum precipitation at this station was 2599 mm in 2001 (with monthly maximum of 651 mm in July 2001). Even higher annual precipitation values were recorded in 2001 at two other stations: 2628 mm at Hala Gasienicowa and 2770 mm at Dolina Pieciu Stawow (Kundzewicz et al. 2014). Furthermore in the next year with large flood, i.e. in 2010 the highest value of the annual sum of precipitation (in available periods) occurred at five lower located stations, i.e. in Zakopane: 1646 mm, Poronin: 1562 mm, Witow: 1518 mm; Szaflary: 1150 mm and Jablonka: 964 mm. For other four stations it was one of the highest values: the 2-nd highest record for Hala Gasienicowa: 2359 mm; the 3-rd record for Morskie Oko: 2256 mm (in 1974: 2290 mm; in 2001: 2271 mm); the 7-th record for Bialka Tatrzańska: 1015 mm (in 1970: 1128 mm; in 2001: 1062 mm) and the 10-th record for Kasprowy Wierch: 2117 mm (see Chapter “Observed Changes in Air Temperature and Precipitation and Relationship between them, in the Upper Vistula Basin”).

Heavy precipitation plays a very important role as a flood generating factor. Therefore assessment of future changes of extreme precipitation events is necessary. This study presents projections of intensification of annual sum and precipitation

extremes in the future, for 11 meteorological stations located in the area of the northern foothills of the Tatra Mountains. A range of indices of heavy precipitation are examined. The calculation is based on application of a delta-change method to results of simulation by global and regional climate models. Particular attention was paid to the assessment of future changes (2061–2090 for RCMs and 2080–2100 for GCMs) in precipitation during the warm part of the year (April–September), especially for summer months, when floods occurred most often.

2 Data and Study Site

This study makes use of four regional climate model (RCM) simulations from the ENSEMBLES project (Van der Linden and Mitchell 2009) with the resolution of 0.22° (25 km), for two time horizons, 1961–1990 and 2061–2090. The projections correspond to A1B SRES greenhouse gas emission scenario (Nakicenovic et al. 2000), available for the area of the study. C4IRCA3 (Community Climate Change Consortium for Ireland, Rossby Centre Atmospheric model ver. 3; Norrköping, Sweden) is driven by global models (ECHAM5, HadCM3Q16), whose data are setting as boundary conditions for the regional model. The ETHZ CLM (Zurich, Switzerland) is driven by a global model HadCM3Q0; KNMIRACMO2 from the Royal National Meteorological Institute (de Bilt, the Netherlands) by ECHAM5, MIROC3.2-hires; and MPI-M-REMO from the Max Planck Institute (Hamburg, Germany) by ECHAM5. For the Hadley Centre Global Climate Model (HadCM3), multiple runs are represented by different climate sensitivities (Q0 = normal sensitivity, 3.50 K and Q16 = high sensitivity, 5.46 K).

To supplement results from this four-member RCM ensemble, seven additional GCM simulations (for A1B and A2 scenarios) were analysed, stemming from the KNMI Climate Explorer (<http://climexp.knmi.nl>). Projections of these models are available for the last two decades of the 21st century, i.e. 2081–2100. The global model BCCR BCM2 (Bergen Climate Model, BCM, version 2; Bjerknes Centre for Climate Research, BCCR, University of Bergen, Norway) has resolution 2.8° of latitude by 2.8° of longitude for time horizons: 1961–1990 and 2081–2099 (scenario A2). CCCMA CGCM3.1t63 is the third version of the Canadian Centre for Climate Modelling and Analysis (CCCma) Coupled Global Climate Model (CGCM3) and has resolution 2.8° by 2.8° (time horizons: 1961–1990 and 2081–2100; scenario A1B). GFDL's CM2 Global Coupled Climate Models were developed at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL). Two versions of the coupled model called CM2.0 (scenarios: A1B and A2) and CM2.1 (scenario A2) have resolution of 2° latitude by 2.5° longitude and time horizons: 1961–1990 and 2081–2100. MIROC3.2 hires global model (Center for Climate System Research/National Institute for Environmental/Frontier Research Center for Global Change, Japan) has resolution 1.13° by 1.13° (time horizons: 1961–1990 and 2081–2100, scenario A1B). HadCM3 (abbreviation for Hadley Centre Coupled Model, version 3) is a coupled Atmosphere-Ocean General Circulation model (AOGCM)

developed at the Hadley Centre in the United Kingdom. The resolution of this model is 2.5° by 3.75° (time horizons: 1961–1990 and 2080–2099, scenario A2).

Analysing simulations from an ensemble of various models allows to account for the uncertainty. The list of regional and Global Climate Models whose simulations were used in this study with references is given in Table 1.

Hence, the results from climate models are used to produce future projections of precipitation indices, by modification of observed precipitation data in the control period (1961–1990), from 11 meteorological stations in the Upper Vistula River Basin—situated on the northern foothills of the Tatra Mountains in basins of the rivers: Czarny Dunajec, Biały Dunajec, and Bialka. For one station, Hala Ornak, data extend from 1970 to 1990; but even if the period is shorter, this station is very important from the point of view of the impact of precipitation on the formation of floods, so that it is retained. The Czarny Dunajec is considered as headwater of the Czarny Dunajec, one of the largest rivers of the Polish Carpathians. Czarny Dunajec rises at 1540 m a.s.l. in the Western Tatra massif as the Stream Chocholowski. The Stream Chocholowski collects water from Jarzabczy Wierch (2137 m a.s.l.), Wolowiec (2064 m. a.s.l.) and Rakon (1879 m. a.s.l.) (Czarnecka 1983). The Czarny Dunajec joins with the Biały Dunajec in the town of Nowy Targ at the altitude of 578 m (Wyzga and Zawiejska 2010). The Malolacki stream (lower Cicha Woda and Zakopianka rivers) is headwater of the Biały Dunajec. It rises at about 2000 m a.s.l. from the peaks of the Czerwone Wierchy massif. The Stream Biala Woda gives rise of the River Bialka whose source areas are situated in granite parts of the High Tatra massif (Czarnecka 1983). Jablonka station is located in Czarna Orawa Basin (The Danube Basin). Data from this station were used due to the limited availability of data in this area. Location of this station is close to the Dunajec River Basin and it enriches our knowledge of distribution of precipitation (Fig. 1; Table 2). According to Starkel (1991) this region is characterised by high values of excess water and accelerated outflow. In the north of this area, mountainous valleys are situated where a periodic retention takes place. The stations read: Kasprowy Wierch, Hala Gasienicowa, Morskie Oko, Hala Ornak (with shorter available period of records: 1970–1990), Kuznice, Zakopane, Witow, Poronin, Bialka Tatrzanska, Szaflary and Jablonka (in The Danube Basin). Locations of these stations are shown in Fig. 1.

3 Methods

3.1 Introduction to Downscaling

Global general circulation models (GCMs) are powerful tools for constructing future climate projections. However, such models currently operate at coarse spatial resolutions, hence are unable to resolve significant subgrid-scale features, including topography and land use. In brief, climate models are restricted in their usefulness

Table 1 RCM and GCM simulations used in this study

	Model output	Scenario	Projection	References
RCMs	C4IRCA3	A1B	2061–2090	Kjellström et al. (2005)
	ETHZ CLM	A1B	2061–2090	Böhm et al. (2006)
	KNMI RACMO2	A1B	2061–2090	Van Meijgaard et al. (2008)
	MPI-M-REMO	A1B	2061–2090	Jacob (2001), Jacob et al. (2001)
GCMs	BCCR BCM2	A2	2081–2099	Ottera et al. (2009)
	CCCMA CGCM3.1t63	A1B	2081–2100	http://www.ec.gc.ca/ccmac-ccma/default.asp?lang=En&n=1299529F-1
	GFDL-CM2.0	A1B	2081–2100	Delworth et al. (2006)
	GFDL-CM2.0	A2	2081–2100	
	GFDL-CM2.1	A2	2081–2100	
	MIROC3.2 hires	A1B	2081–2100	Hasumi and Emori (2004)
	UKMO HADCM3	A2	2080–2099	Collins et al. (2001)

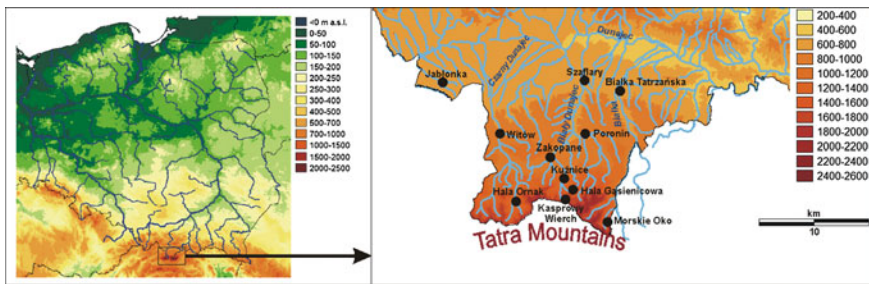


Fig. 1 Location of the studied area in Poland and location of the meteorological stations in the area of the northern foothills of the Tatra Mountains

for many subgrid-scale applications, such as hydrological modelling and impact assessment, essential for designing flood risk reduction and climate change adaptation policies (Wilby and Wigley 1997).

Hence, it is of utmost importance to solve the mismatch of scales, between low-resolution GCMs and high-resolution practical needs, by development of methodologies to infer small-scale (local or regional) information from large-scale information. All these methodologies are collectively called “downscaling techniques”.

Increasing the resolution of climate models could improve the estimates of regional-scale phenomena but downscaling outputs from GCMs is the primary approach for addressing the inadequacies of large-scale models (Wilby and Wigley 1997). Climate variables simulated by individual GCMs often do not agree with observed time series. This poses a problem for using these simulations as input data

Table 2 Altitude of 11 meteorological stations and their location in the river basin

Station	Hs (m a.s.l.)	River basin		
		Name of the river	Area (km ²)	
Hala Ornak	1109	Czarny Dunajec	456.1	Dunajec Basin to the Bialka River tributary 1037.4 km ²
Witow	835	Czarny Dunajec		
Kasprowy Wierch	1991	Bialy Dunajec	224.0	
Hala Gasienicowa	1520	Bialy Dunajec		
Kuznice	1024	Bialy Dunajec		
Zakopane	857	Bialy Dunajec		
Poronin	773	Bialy Dunajec		
Szaflary	655	Bialy Dunajec		
Morskie Oko	1408	Bialka	229.9	
Bialka Tatrzańska	700	Bialka		
Jablonka	615	Czarna Orawa	135.4 to the Jablonka gauge	

for hydrological impact studies. The correction procedures usually identify possible differences between observed and simulated climate variables (Hagemann et al. 2011), which provide the basis for correcting both control and scenario GCM runs with a transformation algorithm.

3.2 Dynamical and Statistical Downscaling

Many downscaling techniques have been proposed (Wilby and Wigley 1997), which can be grouped into two fundamental approaches: dynamic downscaling (DD) and statistical downscaling (SD) methods. Dynamic downscaling, nesting a fine-scale regional climate model (RCM) in a coarse scale model, produces spatially complete fields of climate variables, thus preserving spatial correlation as well as physically plausible relationships between variables. In the statistical downscaling, high-resolution (small-scale) predictands are obtained by identifying relationships in the observed climate between these predictands and large-scale predictors.

The relationships obtained in SD can be applied to GCM output for the future conditions, to produce projections.

Both approaches, dynamic downscaling and statistical downscaling have advantages and disadvantages, and both necessitate assumptions that indeed cannot be credibly verified for the climate change context (Wilby and Wigley 1997). The advantage of dynamic downscaling is simulating fine-scale physical processes, based on rigorous and universal laws. However, dynamic downscaling is very computationally intensive, restricting its use in impact studies and essentially impossible for multi-decade simulations with different global climate models and/or multiple greenhouse gas emission scenarios.

The main advantages of the statistical downscaling (Wilby et al. 1998) are:

- (i) computational efficiency (empirical relationships between the coarse-resolution GCM and high-resolution local climate variables are used, hence calculations can be easily made for several variants: time horizons, climate models, and greenhouse gas emission scenarios);
- (ii) specific information is provided for small areas or even point locations where observations are available.

The disadvantages of statistical downscaling, as compared to dynamic downscaling are:

- (i) adequate historical observations of the studied variables (covering a sufficient time span and being of sufficient quality) are needed;
- (ii) assumption of stationarity in the relationships between predictors and predictands is necessary, while it is well recognized that stationarity is dead (Milly et al. 2008, 2015).

The local detail available via statistical downscaling is assumed to be relevant also in the future and this assumption seems plausible. It is likely that in future as well as in the period for which observations are available, the system characteristics as well as variables of concern can be quite different for points which are located not long apart. In contrast, dynamic downscaling approaches typically provide spatial resolutions of the order of, say, 20 km, which can still be insufficient to resolve topography with enough detail and to show differences in the projected changes for points located close together.

Statistical downscaling methods cover such approaches as regression-type models (both linear and nonlinear), neural networks, weather generators for generating synthetic sequences of local variables, and techniques based on weather classification that draw on the attributes of models to simulate circulation patterns. The approach also includes analogue methods that seek similar states and perform a multiple regression analysis for the most analogous days or using the probability distribution of analogous days. Evaluation of SD is done most commonly through cross-validation with observational data.

3.3 *Delta-Change Method*

A delta-change method can be used to transform observations into a time series that is representative of future conditions consistent with the GCM climate change signal (Van Pelt et al. 2012). The delta method makes use of “change factors”. The simplest form of the delta method (sometimes referred to as the “classical delta method”) only considers changes in the mean that may vary seasonally or spatially. The assumption that one has to make is that changes at the (large) scale of the climate model (GCM) can be directly applied to the (local/point) scale of the time series. An “advanced delta method” (Van Pelt et al. 2012) does not only take changes in the mean into account but also the changes in the extremes. Then, rather than a proportional adjustment of observed values, a non-linear transformation is applied to the data.

We used the statistical delta-change approach, thus applying differences between the control and future RCM/GCM simulations to baseline observations by adding or scaling the mean precipitation change to each day. We obtain meteorological time series with the same resolution, characteristics and variance as in the past. The procedure can be described as follows cf. Van Pelt et al. (2012):

First, non-overlapping five-day precipitation sums are the starting point for the transformation. The observed five-day precipitation amounts P are transformed using:

- for the sum of precipitation below 90 quantile:

$$P^* = aP^b \quad (1)$$

- for the sum of precipitation above 90 quantile:

$$P^* = \frac{\overline{E^F}}{\overline{E^C}} (P - P_{90}^O) + a(P_{90}^O)^b \quad (2)$$

where P is a historical five-day sum, P^* the transformed (future) five-day sum, and a and b the transformation coefficients (parameters), P^O and P^* represent the observed and transformed future precipitation data, C and F are representative for the control and future climates, and E^C and E^F represent the excess variable of the control and future period of the RCMs/GCMs. The amount E above the 90 % quantile is the excess:

$$E = P - P_{90} \quad (3)$$

To get the daily observation data the change factor R was applied for each 5-day sum period:

$$R = P^*/P \quad (4)$$

We performed this procedure for precipitation data recorded at 11 stations spatially distributed over the entire analysed region.

In this study, projections of annual and extreme precipitation in the northern foothills of the Tatra Mountains were calculated. To obtain insight into possible future changes, several precipitation indices were examined:

- annual sum of precipitation;
- 24 h maximum sum of precipitation;
- maximum sum of 5-day precipitation for warm season (April–September);
- maximum sum of 10-day precipitation for warm season (April–September);
- maximum monthly sum of precipitation for warm season (April–September);
- number of days with intense precipitation greater than or equal to 30 and 50 mm during warm season (April–September).

The 24 h maximum sum of precipitation and maximum sum of 5-day precipitation are especially important due to the possibility of causing violent floods and landslides in small catchments. The long-lasting and very intensive precipitation such as 10-day or monthly values can generate floods on larger area.

4 Results

Climatological models have greater difficulty in simulating precipitation as opposed to temperature because of complexity phenomenon involving the sub-grid scale features such as topography or land use that are often inadequate for assessing the correct location and intensity of precipitation. Especially this is noticeable for such complex and difficult area as northern foothills of the Tatra Mountains. Although there is some disagreement as to the range of changes, almost all the RCMs and GCMs model agree on the signs of change; i.e. increase in mean and extreme precipitation.

Figure 2 presents comparison of relative changes for three indices: (1) mean 10-day maximum precipitation; (2) mean monthly maximum precipitation; and (3) mean annual sum of precipitation (future versus control period). They were derived from raw RCM and GCM model output (the ratio between future and control period P_{fmean}/P_{cmean}) in comparison with relative change obtained from the transformation procedure (the ratio between transformed observation and observation P^*_{mean}/P_{mean}). The correction leads to an acceptable correspondence in the case of all indices (R^2 about 0.6).

Changes in mean values are often lower than changes in extreme events: for example the range of relative changes in mean annual sum of precipitation is between 1.2 and 1.4 while the range for relative changes for mean 10-day maximum precipitation and mean monthly maximum precipitation is up to 1.7 (Fig. 2).

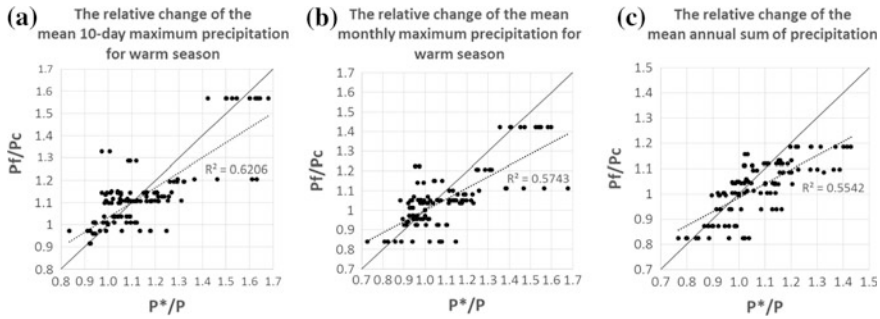


Fig. 2 The relative changes from RCMs and GCMs output versus the relative changes from transformed observations for 10 meteorological stations (without Hala Ornak) for three indices: **a** mean 10-day maximum precipitation for warm season (*left chart*); **b** mean monthly maximum precipitation for warm season (*middle chart*); and **c** mean annual sum of precipitation (*right chart*). Grey line represents the perfect correspondence (i.e. the 1:1 line)

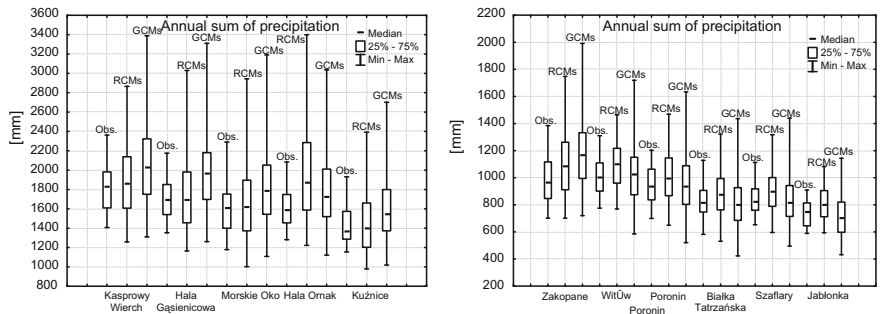


Fig. 3 Observed annual sum of precipitation for the control interval 1961–1990 and projected annual sum of precipitation for RCMs (2061–2090) and GCMs (2081–2100) for stations located at elevation above 1000 m a.s.l. (*left*) and stations situated below 1000 m a.s.l. (*right*)

In general, the analysed RCM and GCM models project an increase in the annual sum of precipitation for the studied area. The future median value may not change considerably for stations located above 1000 m a.s.l. for RCMs and is likely to be higher for these stations for GCMs. For stations at lower elevations, RCMs project an increase in the median value of the annual sum of precipitation while GCMs project a smaller increase or even decrease for stations: Białka Tatrzańska, Szafłary and Jablonka. However, the future level of the 75 percentile and the maximum value of annual precipitation are projected to be higher than those observed in 1961–1990, in every case. Figure 3 shows box plots with observed annual sum of precipitation for the interval 1961–1990 and projected annual sum of precipitation for RCMs and GCMs for listed stations.

Figure 4 shows the return period plots (Gumbel distribution) of the maximum daily precipitation for the future projections obtained from the RCMs and GCMs used in this study for 11 meteorological stations and comparison with observed data. It is

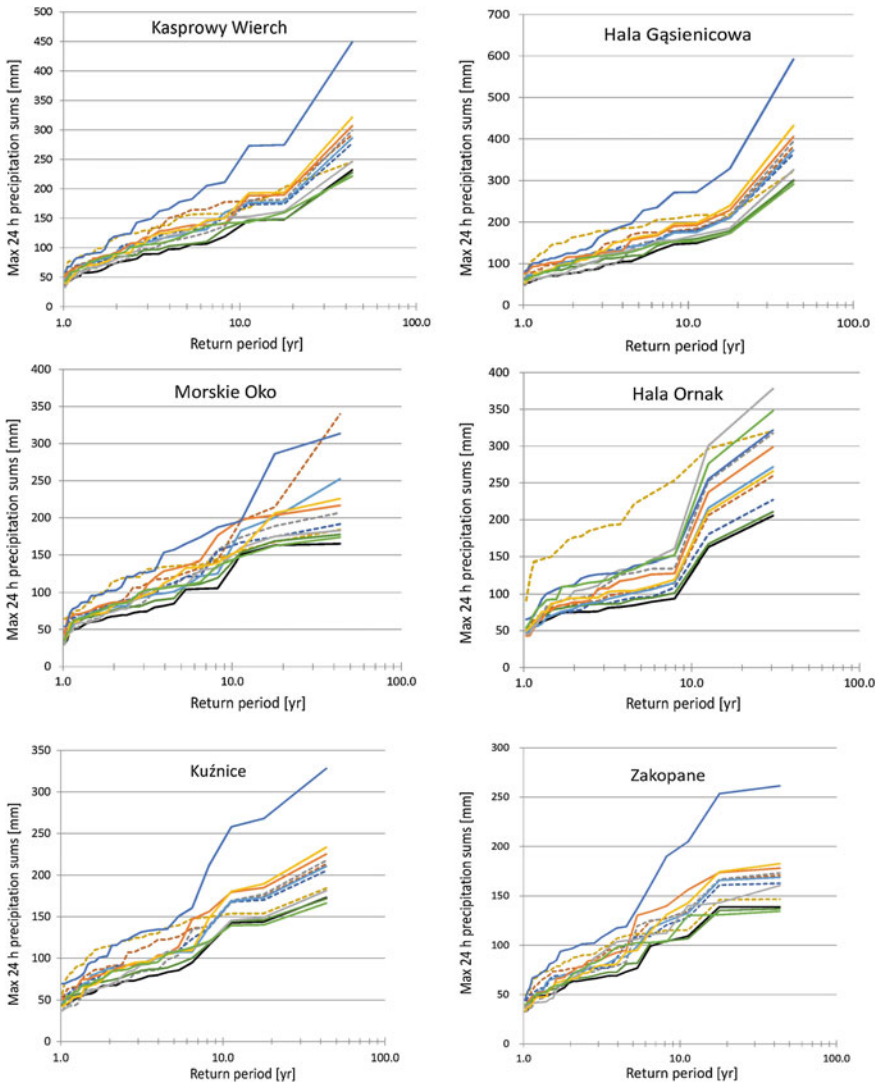


Fig. 4 The return period plots (Gumbel distribution) calculated for 30-year time series (21 for Hala Ornak) of the maximum daily precipitation for observed data (1961–1990) and the RCMs (2061–2090) and GCMs (2081–2100) for 11 meteorological stations situated on the northern foothills of the Tatra Mountains

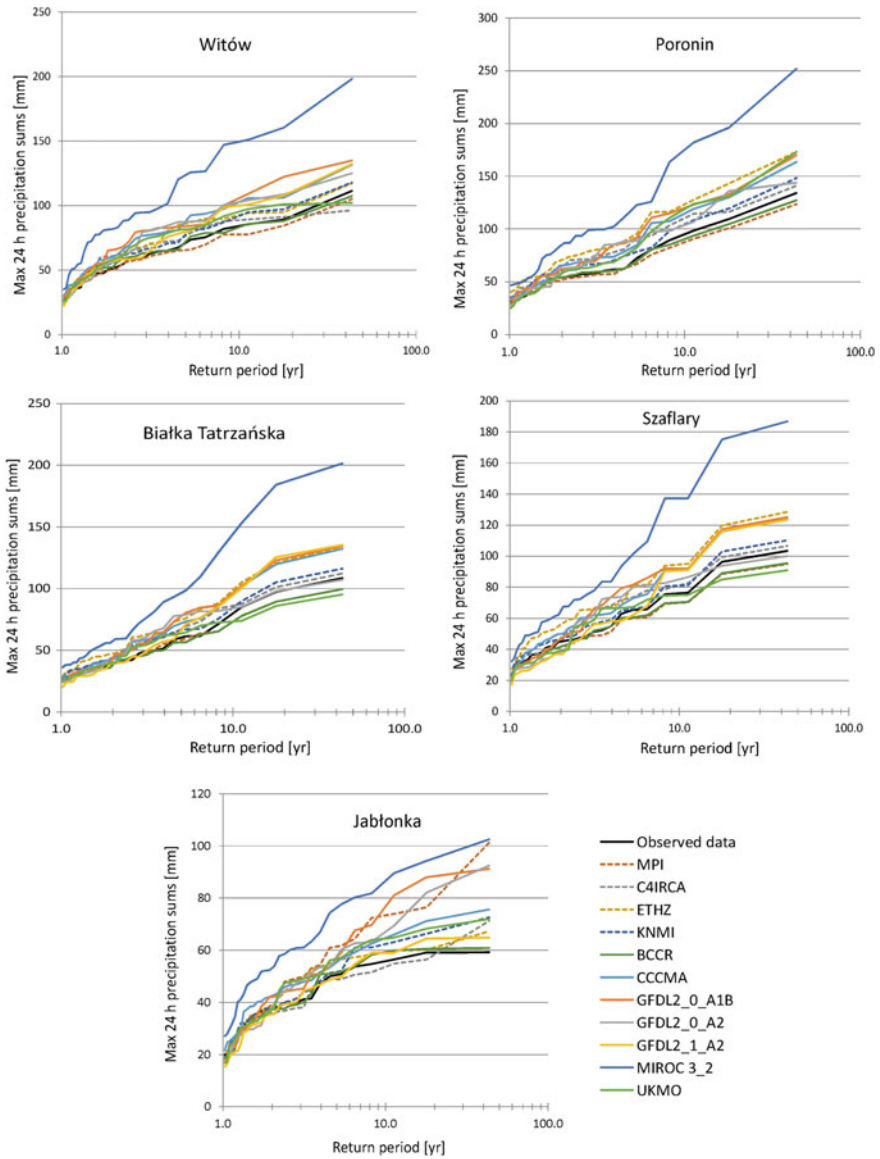


Fig. 4 (continued)

found that the range of projections of change in precipitation for the future across the four-member RCM ensemble is similar to the results from the GCM ensemble.

One of the highest values we can observe for the GCM model MIROC. For three stations, also the highest values are given by RCMs: MPI, ETHZ and GCMs: BCCR and GFDL2.0 (scenario A2). The plots show a similar change in higher values and a larger range between the values for the greater return periods. For

some stations, two or three models (GCMs and RCMs) indicate a decrease in precipitation for the highest return period (for 10 stations the highest return period is 43.4 years, for Hala Ornak it is 30.6 years). But most of RCMs and GCMs models suggest an increase in the maximum 24 h precipitation.

Table 3 illustrates the maximum daily precipitation and 5-day sum of precipitation at each of the stations and the year of occurrence of this maximum precipitation for the available period of observations. Both daily precipitation and 5-day precipitation totals are of importance for flood hazard.

According to the observed data, most of 24-h maximum precipitation, as well as maximum 5-day precipitation appeared in examined control period: 1961–1990. Only in five cases, the maximum value of these indices occurred in 1997 (the year with large flood) and in 2007. The maximum values of 24-h precipitation for stations: Poronin in 1997 and for Jablonka in 2007 are at the level of future maximum values downscaled based on control period 1961–1990 (Fig. 4).

Figure 5 presents box plots with observed maximum 5-day precipitation for the reference period 1961–1990 and projected value of this index for RCMs and GCMs for particular stations. As previously, for maximum 5-day precipitation we can observe that the maximum value for Poronin in 1997 is nearly at the level of the maximum value projected by RCMs.

The future changes in maximum 5-day precipitation during warm season obtained by RCMs and GCMs are likely to be stronger. For all stations, increases of the median value, the 75 percentile and also the extreme values are projected. The future

Table 3 The maximum daily precipitation and the year of occurrence of this maximum precipitation, as well as the maximum 5-day precipitation for the available period of observations for 11 meteorological stations

Station	The available period	Max 24-h precipitation (mm)	Year of occurrence	Max 5-day precipitation (mm)	Year of occurrence
Kasprowy Wierch	1951–2013	232.0	1973	388.7	1980
Hala Gasienicowa	1951–2011	300.0	1973	425.2	1980
Morskie Oko	1954–2011	168.4	1958	296.3	1970
Hala Ornak	1970–2011	205.3	1973	343.6	1980
Kuznice	1954–1996	172.7	1973	263.5	1980
Zakopane	1951–2013	138.7	1970, 1973	235.9	1972
Witow	1954–2011	111.3	1970	200.4	1972
Poronin	1951–2011	156.1	1997	248.2	1997
Bialka Tatrzańska	1951–2011	112.0	1997	188.3	1997
Szaflary	1951–2011	103.4	1970	179.1	1997
Jablonka	1955–2011	70.1	2007	144.7	1972

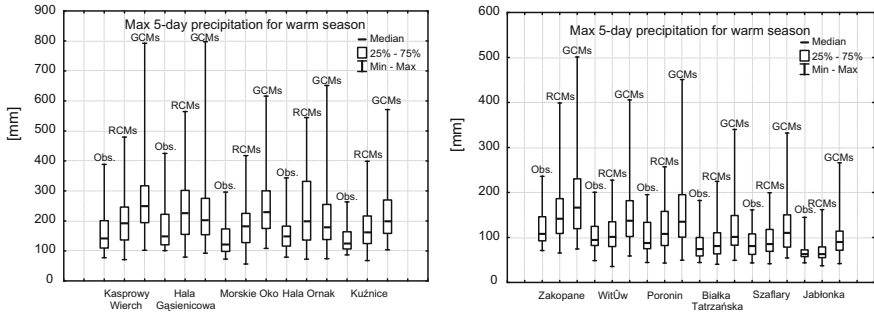


Fig. 5 The observed maximum 5-day precipitation for the reference interval 1961–1990 and projected maximum 5-day precipitation for RCMs (2061–2090) and GCMs (2081–2100) for stations located at elevation above 1000 m a.s.l. (*left*) and below 1000 m a.s.l. (*right*)

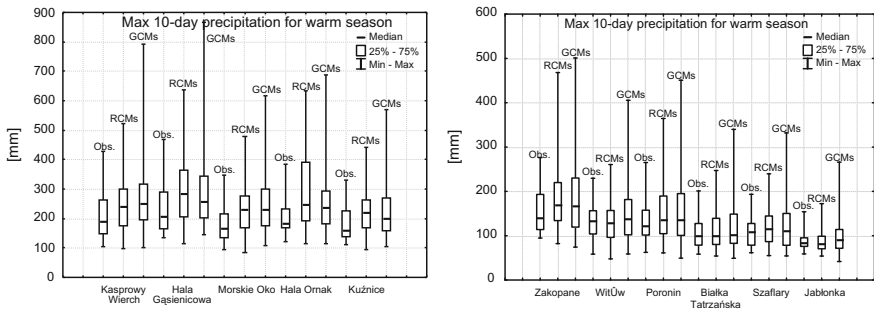


Fig. 6 Observed maximum 10-day precipitation for 1961–1990 and projected maximum 10-day precipitation for RCMs (2061–2090) and GCMs (2081–2100) at stations located at the elevation above 1000 m a.s.l. (*left*) and below 1000 m a.s.l. (*right*)

median of maximum 5-day precipitation for high stations (above 1000 m a.s.l.) and also for Zakopane could be on the level of 75 ‰ (for the control period 1961–1990).

A similar situation can be observed for maximum 10-day precipitation for the warm season. The changes of median for higher located stations are projected to be higher than observed in 1961–1990. Present 75 ‰ can become a median in the future for projections (with both RCMs and GCMs). In the case of lower placed meteorological stations, the median value of maximum 10-day precipitation could be on the similar level as the one observed in the 20th century. The future 75 ‰ and maximum value of this index are likely to be higher for all stations (Fig. 6).

The RCM and GCM simulations show increase in median value as well as in 75 percentile and maximum value for maximum monthly sum of precipitation in the warm season for higher located stations and Zakopane. For other studied stations, the increases of this index could be lower. Figure 7 presents observed ranges for maximum monthly sum of precipitation and projected changes according to RCMs and GCMs.

Similar behavior of projections of changes in the number of days with intense precipitation (greater than or equal to 30 and 50 mm) during the warm season can be observed (Fig. 8). For the stations above 1000 m a.s.l. for both thresholds (i.e.

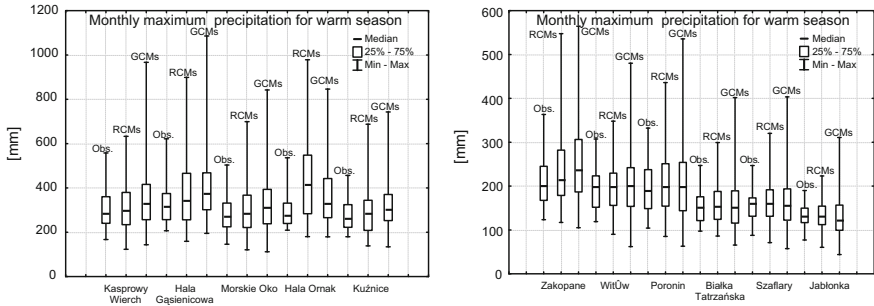


Fig. 7 Observed maximum monthly sum of precipitation for 1961–1990 and projected value for RCMs (2061–2090) and GCMs (2081–2100) at stations located at the elevation above 1000 m a.s.l. (*left*) and below 1000 m a.s.l. (*right*)

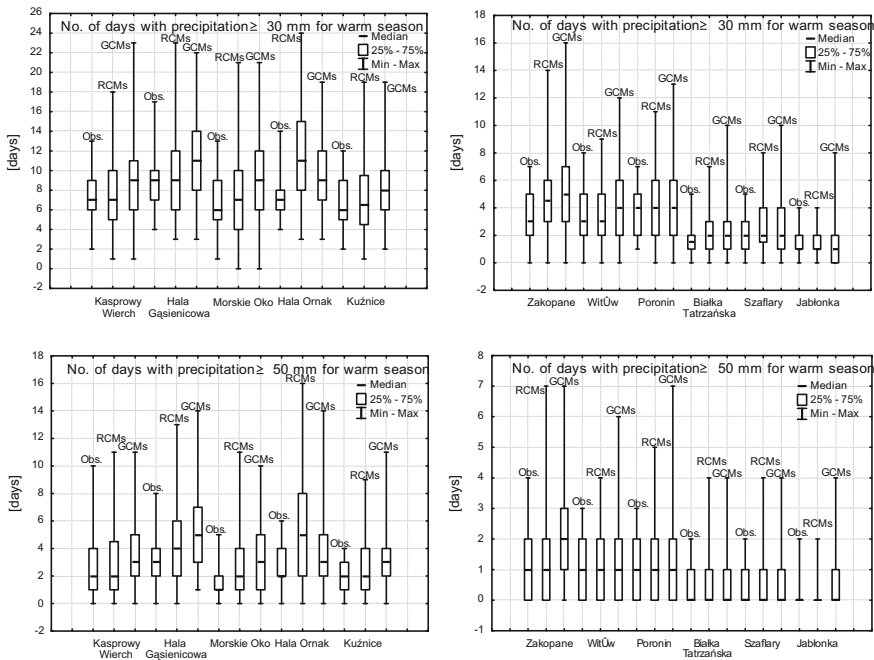


Fig. 8 Observed number of days with 24 h precipitation equal to or greater than the threshold of: 30 mm (*top*) and 50 mm (*bottom*) for the warm season, for 1961–1990 and projected value for RCMs (2061–2090) and GCMs (2081–2100) for stations located at the elevation above 1000 m a.s.l. (*left*) and below 1000 m a.s.l. (*right*)

30 and 50 mm), regional and global models show an increase in median value and also in higher values of these indices. The projected changes are lower for other stations. In the future, occurrence of days with intense precipitation (above 30 and 50 mm) may be very rare. Projections show increase rather in extreme value.

5 Discussion and Conclusions

This study allows to get insight into possible future changes in annual sum of precipitation as well as in intense and extreme precipitation in the northern foothills of Tatra Mountains. Use of four regional climate models and seven global climate models for two SRES climate scenarios A1B and A2 made it possible to obtain the likely range of changes in precipitation during last decades of the 21st century. In most cases, the range of projections of annual and extreme precipitation for the future across the results from the GCM ensemble is slightly higher than across the four-member RCM ensemble. Projections obtained from GCMs cover further period of the 21st century, i.e. 2081–2100 when changes in precipitation, in association with the greater increases of temperature simulations in the end of the 21st century could be more pronounced than for RCMs projections for earlier period 2061–2090.

The knowledge about changes in precipitation extremes is very important for climate adaptations to future flood risk (Zhang et al. 2013). Use of 11 climate model simulations covers a range of plausible changes in extremes.

Models in this study belong to generation of CGCMs which were submitted to the Coupled Model Intercomparison Project Phase 3 (CMIP3) in support of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (Kharin et al. 2007). The recent generation of global climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) are employing the new radiative forcing scenarios, called Representative Concentration Pathways (RCPs, Moss et al. 2010). However, apart from the different forcing scenarios in the CMIP5 protocol, the performance of the CMIP5 multi-model ensemble in simulating temperature and precipitation climate extremes is comparable to that in the CMIP3 ensemble (Kharin et al. 2013).

All RCM and GCM models under examination project an increase in mean annual precipitation totals as well as in heavy precipitation in future time horizons studied. However, the changes in mean precipitation were not as pronounced as for extreme indices, such as maximum 24 h, 5-day; 10-day, monthly maximum sum of precipitation and also number of days with intense precipitation (30 and 50 mm). The increasing change is projected especially for stations located above 1000 m a.s.l. For most stations located in the area of the northern foothills of the Tatra Mountains, the maximum observed daily precipitation occurs in summer, so that the increase in precipitation can result in more severe flash floods and landslides in small catchments and can generate flood events in basins of the mountainous, right-hand tributaries of the River Vistula (such as the River Dunajec).

Similarly changes can be found in the case of projected return period of late 20th century (1981–2000) 20-year return values of annual maximum 24-h precipitation in the study of Seneviratne et al. (2012). The 20-year return period for area of Central Europe for the reference interval is likely to become more frequent, e.g. a 1-in-10 to 1-in-15 year event by the end of 21st century (the median models value).

These findings are compatible with those in Tebaldi et al. (2006) where future changes produced by the IPCC-AR4 model ensemble in maximum 5-day precipitation, precipitation intensity measured as SDII (Simple Daily Intensity Index, defined as the annual total precipitation divided by the number of wet days) and fraction of total precipitation exceeding the 95th percentile are considered significant by a majority of models across the mid- to high latitudes of the northern hemisphere.

Every increase in extreme precipitation can contribute to more severe floods in the future. However, recent studies indicate that the projection of precipitation extremes is associated with uncertainties related to GCMs, RCMs and statistical downscaling methods as well as by natural variability of the climate (Seneviratne et al. 2012). Nevertheless, records of precipitation during the latest large floods in the studied region, i.e. in 2001 and 2010 also show that the observed values of maximum monthly sum of precipitation reached new heights.

Acknowledgments This study was carried out within the FLORIST project (Flood risk on the northern foothills of the Tatra Mountains), supported by a grant from the Swiss Government through the Swiss Contribution to the enlarged European Union (PSPB No. 153/2010).

References

- Böhm U, Kücken M, Ahrens W, Block A, Hauffe D, Keuler K, Rockel B, Will A (2006) CLM—the climate version of LM: brief description and long term application. *COSMO News* 6:225–235
- Collins M, Tett SFB, Cooper C (2001) The internal climate variability of HadCM3, a version of the Hadley Centre coupled model without flux adjustments. *Clim Dyn* 17:61–81
- Czarnecka H (ed) (1983) Atlas podziału hydrograficznego Polski. Seria Atlasy i monografie IMGW, Warszawa (in Polish)
- Delworth TL, Broccoli AJ, Rosati A, Stouffer RJ, Balaji V, Beesley JA, Cooke WF, Dixon KW, Dunne J, Dunne KA, Durachta JW, Findell KL, Ginoux P, Gnanadesikan A, Gordon CT, Griffies SM, Gudgel R, Harrison MJ, Held IM, Hemler RS, Horowitz LW, Klein SA, Knutson TR, Kushner PJ, Langenhorst AR, Lee H-Ch, Lin S-J, Lu J, Malyshev SL, Milly PCD, Ramaswamy V, Russell J, Schwarzkopf MD, Shevliakova E, Sirutis JJ, Spelman MJ, Stern WF, Winton M, Wittenberg AT, Wyman B, Zeng F, Zhang R (2006) GFDL's CM2 global coupled climate models part I: formulation and simulation characteristics. *J Clim Spec Sect* 19:643–674
- Hagemann S, Chen C, Haerter JO, Heinke J, Gerten D, Piani C (2011) Impact of a statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrology models. *J Hydrometeorol* 12:556–578. doi:10.1175/2011jhm1336.1
- Hasumi H, Emori S (eds) (2004) K-1 coupled GCM (MIROC) description. Center for Climate System Research (CCSR), University of Tokyo, National Institute for Environmental Studies

- (NIES), Frontier Research Center for Global Change (FRCGC). http://ccsr.aori.u-tokyo.ac.jp/~hasumi/miroc_description.pdf
- IPCC (2007) Climate change 2007: synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Pachauri RK, Reisinger A. (eds) IPCC, Geneva, p 104
- IPCC (2012) A special report of working groups I and II of the intergovernmental panel on climate change. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds) Managing the risks of extreme events and disasters to advance climate change adaptation. Cambridge University Press, Cambridge, New York, p 582
- Jacob D (2001) A note to the simulation of the annual and inter-annual variability of the water budget over the Baltic Sea drainage basin. *Meteorol Atmos Phys* 77(1):61–73
- Jacob D, Van den Hurk BJJM, Andr e U, Elgered G, Fortelius C, Graham LP, Jackson SD, Karstens U, K pken Ch, Lindau R, Podzun R, Rockel B, Rubel F, Sass BH, Smith RNB, Yang X (2001) A comprehensive model inter-comparison study investigating the water budget during the BALTEX-PIDCAP period. *Meteorol Atmos Phys* 77(1):19–43
- Kharin VV, Zwiers FW, Zhang X, Hegerl GC (2007) Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations. *J Clim* 20:1419–1444
- Kharin VV, Zwiers FW, Zhang X, Wehner M (2013) Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Clim Change* 119:345–357
- Kjellstr m E, B rring L, Gollvik S, Hansson U et al (2005) A 140-year simulation of European climate with the new version of the Rossby Centre regional atmospheric climate model (RCA3). *SMHI Rep Meteorol Climatol* 108 (SMHI, Norrk ping)
- Kundzewicz ZW, Stoffel M, Kaczka RJ, Wyzga B, Niedzwiedz T, Pinskiwar I, Ruiz-Villanueva V, Lupikasza E, Czajka B, Ballesteros-Canovas JA, Malarzewski L, Chorynski A, Janecka K, Miku s P (2014) Floods at the Northern Foothills of the Tatra Mountains—a Polish-Swiss research project. *Acta Geophys* 62(3):620–641
- Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, Stouffer RJ (2008) Stationarity is dead: whither water management? *Science* 319 (5863):573–574
- Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, Stouffer RJ, Dettinger MD, Krysanova V (2015) On critiques of “Stationarity is dead: whither water management?”. *Water Resour Res* 51(9):7785–7789
- Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463:747–756
- Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Gr bler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) IPCC special report on emissions scenarios. Cambridge University Press, Cambridge, New York, p 599
- Niedzwiedz T, Lupikasza E, Pinskiwar I, Kundzewicz ZW, Stoffel M, Malarzewski L (2015) Variability of heavy rainfall events and related synoptic situations causing floods at the northern foothills of the Tatra Mountains. *Theoret Appl Climatol* 119:273–284
- Ottera OH, Bentsen M, Bethke I, Kvamst  NG (2009) Simulated pre-industrial climate in Bergen Climate Model (version 2): model description and large-scale circulation features. *Geosci Model Dev* 2:197–212
- Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S, Kossin J, Luo Y, Marengo J, McInnes K, Rahimi M, Reichstein M, Sorteberg A, Vera C, Zhang X (2012) Changes in climate extremes and their impacts on the natural physical environment. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds) Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the

- Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, New York, pp 109–123
- Srikanthan R, McMahon TA (2001) Stochastic generation of annual, monthly and daily climate data: a review. *Hydrol Earth Syst Sci* 5(4):653–670
- Starkel L (1991) Rzeźba terenu. In: Dynowska I, Maciejewski M (eds) *Dorzecze górnej Wisły. Cześć 1*. Państwowe Wydawnictwo Naukowe, Warszawa–Kraków, pp 42–54 (in Polish)
- Tebaldi C, Hayhoe K, Arblaster JM, Meehl GA (2006) Going to the extremes. An intercomparison of model-simulated historical and future changes in extreme events. *Clim Change* 79:185–211
- Van der Linden P, Mitchell JFB (eds) (2009) ENSEMBLES: climate change and its impacts: summary of research and results from the ENSEMBLES project. Met Office Hadley Centre, Exeter. http://ensembles-eu.metoffice.com/docs/Ensembles_final_report_Nov09.pdf
- Van Meijgaard E, van Ulft LH, van de Berg WJ, Bosveld FC, van den Hurk BJM, Lenderink G, Siebesma AP (2008) The KNMI regional atmospheric climate model RACMO, version 2.1. KNMI Tech Rep 302, KNMI, De Bilt. www.knmi.nl/bibliotheek/knmi/TR302.pdf
- Van Pelt SC, Beersma JJ, Buishand TA, Van den Hurk BJM, Kabat P (2012) Future changes in extreme precipitation in the Rhine basin based on global and regional climate model simulations. *Hydrol Earth Syst Sci* 16:4517–4530
- Wilby RL, Wigley TML (1997) Downscaling general circulation model output: a review of methods and limitations. *Prog Phys Geogr* 21:530–548
- Wilby RL, Wigley TML, Conway D, Jones PD, Hewitson BC, Main J, Wilks DS (1998) Statistical downscaling of general circulation model output: a comparison of methods. *Water Resour Res* 34(11):2995–3008
- Wyzga B, Zawiejska J (2010) Large wood storage in channelized and unmanaged sections of the Czarny Dunajec River: implications for the restoration of mountain rivers. *Folia Geogr Ser Geogr-Phys* 41:5–34. Jagiellonian University, IGI
- Xu C-Y, Singh VP (2004) Review on regional water resources assessment models under stationary and changing climate. *Water Resour Manage* 18:591–612
- Zhang X, Hegerl GC, Seneviratne SI, Stewart R, Zwiers FW, Alexander LV (2013) WCRP grand challenge: understanding and predicting weather and climate extremes. <http://www.wcrp-climate.org/gc-extremes-documents>