

# LARGE-SCALE EFFECTS OF CLIMATE CHANGE ON WATER RESOURCES IN SWEDEN AND EUROPE

## Storskaliga effekter av klimatförändring på vattenresurser i Sverige och Europa

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### Abstract

According to the future scenarios from global and regional climate models, the climate change will profoundly affect hydrological processes at different scales in time and space. This paper presents results from a new generation of hydrological climate change impact studies, combining new methods for downscaling and bias correction of climate projections with new methods for large-scale hydrological modelling. Several water variables have been extracted to distinguish large-scale emerging patterns across Europe and Sweden, to describe climate change impact on future water resources. Maps are available at the web site of SMHI with information on potential changes in temperature, precipitation, water discharge, specific/local runoff, relative groundwater level, soil moisture, snow, low and high flows and water quality. Several variables show 50 % increase or 50 % decrease depending on geographical location. However, results are uncertain and should be treated with caution, especially on the local scale and when there is a large discrepancy between climate projections.

*Key words* – Catchment modeling, multi-basin, multi-variable, climate change, impact, hydrology

### Sammanfattning

Framtidsscenarier från globala och regionala klimatmodeller antyder att klimatförändringen kommer att ha en djupgående påverkan på hydrologiska processer i olika tids- och rumsskalor. Den här artikeln presenterar resultat från en ny generation av hydrologiska klimateffektstudier, som kombinerar nya metoder för nedskalning och felkorrigering av klimatmodellens resultat med nya metoder för storskalig hydrologisk modellering. Flera vattenvariabler har tagits fram för att kunna analysera effekterna klimatförändringens storskaliga mönster för framtida vattenresurser i Europa och Sverige. Kartor finns tillgängliga på SMHIs hemsida med information om möjliga förändringar i temperatur, nederbörd, vattenföring, specifik avrinning, relativ grundvattenyta, markfuktighet, snö, låg- och högvatten och vattenkvalitet. Flera av resultaten visar på mellan 50 % ökning eller 50 % minskning i flera variabler beroende på geografiskt läge. Resultaten är dock osäkra och ska hanteras varsamt, speciellt på lokal skala och där det är stora avvikelser mellan olika klimatprojektioner.

### Introduction

Climate change effect studies on large-scale water resources play a key role for planning and management in a range of fundamental societal functions such as water and energy supply, security and environment. The water sector in Europe must manage both excess and scarcity of water in future society (e.g. Bates et al., 2008). It is likely that anthropogenic climate change will, among

other consequences, lead to an acceleration of the hydrological cycle on various scales (Huntington, 2006) as well as causing strong regional gradients in water availability across Europe (Bates et al., 2008). So far, impact studies using hydrological models have focused on specific basins (e.g. Middelkoop et al., 2001; Arheimer et al., 2005) while large-scale analysis across the continent have been based on land-surface schemes from climate models (e.g. Dankers, and Feyen, 2008) or global water

models (Water GAP, VIC, etc.). Few large-scale models have been carefully evaluated against observed data of water discharge.

In the Formas-funded project HYDROIMPACTS2.0 (running 2010–2013) we developed large-scale multi-basin hydrological models, based on open data and closely linked to observations of present climate, to improve the estimates of future climate change impact. The models were used to simulate long-term water balance as well as changes in high flows and droughts. Also other environmental changes (e.g. land use or remedial programs) were simulated for comparison of various sources to future changes, for instance in water quality.

The large-scale modelling and effect analysis presented below include a) High-resolution pan-European and Swedish assessments of water variables, and b) High resolution assessments of nutrient load on the Baltic Sea. Results from climate models are down-scaled and bias corrected using the new methods developed in HYDROIMPACTS2.0 for large geographical domains (see e.g. Olsson et al., 2013; this issue). Future water resources are mapped and emerging large-scale patterns are analysed for a large number of hydrological variables (such as mean water discharge, return periods of extreme high and low flows, ground water fluctuations, snow cover, soil moisture, water quality). The results are published for open access in web products covering Sweden and Europe, and have been presented to end-user in various outreach activities (see e.g. Arheimer et al., 2013; this issue).

## Methods and Material

### Climate model data

Concerning climate model results, precipitation and temperature were used from two projections based on different general circulation models (GCMs); HadCM3Q0 (Johns et al., 2003; Collins et al., 2006; denoted HADLEY below) and ECHAM5r3 (Roeckner et al., 2006; denoted ECHAM below). The projections were chosen to represent different signals concerning the future temperature change. Within the ensemble of 16 climate projections studies by Kjellström et al. (2011), projection HADLEY is among the ones with the largest future temperature increase in Scandinavia whereas projection ECHAM is in the small-to-medium range. Both projections simulate effects of the emission scenario A1B (Nakićenović et al., 2000). GCM results from both models were first down-scaled dynamically to 50 km with the RCA3 model (Samuelsson et al., 2011). Thereafter, daily surface temperatures and precipitation were further down-scaled to 4 km and bias corrected, using

the Distribution-Based Scaling (Yang et al., 2010) with era-interim/GPCC as reference data for Europe and the PTHBV as reference data for Sweden (period 1981–2010). Finally, gridded values were interpolated to each sub-basin for the period 1961–2100 to force the HYPE models. For impact studies on water quality in the Baltic region, two additional ECHAM projections were also used to complement the ensemble (Meier et al., 2011).

There are large differences when assessing future climate change dependent on which climate model and scenarios that are used. It is therefore recommended that results from many different climate scenarios are used as basis for decisions and for impact modeling. The two projections shown here are far from covering the full range of uncertainty; however, the resulting water discharge coincide relatively well with 25%–75% of the interval in the ensemble of 16 climate scenarios calculated by SMHI for Sweden (Bergström et al., 2012). Use of additional hydrological models is also preferred for more accurate conclusions.

### Hydrological impact modelling

The effect modeling was based on the hydrological model HYPE (Lindström et al., 2010) version 3.6.0, applied to Europe in E-HYPE (version 2.0) and S-HYPE (version 2010) developed at SMHI. Both model applications are multi-basin and the E-HYPE model make calculations for 35000 catchments covering Europe (Donnelly et al., 2013), and the S-HYPE for 37000 catchments covering Sweden (Strömqvist et al., 2012). The Balt-HYPE model is part of the E-HYPE model domain and covers the Baltic Sea drainage basin with some 5000 catchments (Arheimer et al., 2012). The difference between Balt-HYPE and S-HYPE is described more in detail by Arheimer et al. (2012).

In each model, catchment divides are defined based on topography and linked according to the river network. The landscape is further divided into classes according to soil type and vegetation. The soil representation is stratified and can be divided in up to three layers. The flow paths include surface runoff, macropore flow, tile drainage and groundwater outflow from the individual soil layers. Rivers and lakes are described separately with routines for outlet flow, including turnover, sinks and sources for nutrients. Several processes in the model concept are weather dependent as precipitation and temperature force the dynamics at each time-step, and thus, the model results reflect the effects of weather and climate. Observed data are used to evaluate model performance at the locations in the model domain where these are available. The HYPE model has many rate coefficients, constants and parameters, which in theory could be adjusted. In multi-basin modelling a step-wise,

simultaneous calibration technique is used (Donnelly et al., 2009; Arheimer and Lindström, 2013). Data from many water gauges are also used to evaluate the model. For instance, the latest version (2012) of S-HYPE has an average NSE (Nash-Sutcliffe Efficiency) for water discharge of 0.7 and an average relative error of 5 % for the period 1999–2010, using about 400 water gauges including both regulated and unregulated rivers with catchments ranging from ten to several thousands of km<sup>2</sup> of various land-uses.

In the climate change impact studies, we extract 30-year means of current climate for each of the climate projections studied (reference period) and compare with 30-years means in the future, to distinguish possible future changes. In the present study, the following time-slices were used in the analysis:

- Reference period: 1981–2010
- Half century: 2036–2065
- Turn of the century: 2071–2100

## Results and Discussion

### Future changes in water resources

Daily values of several modelled variables describing the water resources have been aggregated to average annual values and plotted on maps with high spatial resolution to analyse emerging geographical patterns for Europe and Sweden.

The results for the reference period (1981–2010) are similar for the two climate projections (HADLEY and ECHAM) since precipitation and temperature have been scaled against the same observed data. For future climate change, however, there are in many cases large differences and sometimes conflicting results between the climate models, in particular for local conditions. It is well known that climate models differ considerable in precipitation pattern for parts of Europe (e.g., van Ulden and van Oldenborgh, 2013). Hence, there is a large uncertainty in the calculations and the results should be treated with caution.

The estimated effects of climate change impact also differ between the E-HYPE model and the S-HYPE model, which has higher resolution for Sweden. Often the S-HYPE model gives more extreme results than the E-HYPE model for the same domain. This is probably caused both by the resolution of the impact model and by the downscaling/bias correction method, as the latter uses more observed stations for adjusting the climate model results to observations for the Swedish domain. When the resolution and data density is higher, more local phenomena and spatial variations will be distin-

guished. The difference in results using different impact models for the same domain is also a way to explore uncertainties in climate change results.

Results are described below and also presented as a library of maps, which are available on internet, for Europe and Sweden, respectively:

<http://e-hypeweb.smhi.se/ehypeclimate/>

<http://vattenwebb.smhi.se/shypeclimate/>

### Temperature

According to both projections the mean temperature will increase with between 3 and 5 degrees for different parts of Europe and also within Sweden. The increase is faster in the HADLEY model compared to ECHAM, although ECHAM eventually shows high temperature for more extended areas by the end of this century.

### Precipitation

In general, we can expect an increase in precipitation for the northern parts of Europe and a decrease for the southern parts. Using E-HYPE, the change means up to 300 mm more or less precipitation per year for some parts of Europe, while using S-HYPE, the average increase is 100–400 mm per year depending on location in Sweden. The HADLEY projection shows a faster and more significant increase in precipitation.

### Water discharge

The predicted change in water discharge varies between a 50 % increase and 50 % decrease for different parts of Europe ( $\pm 30$  % for Sweden). For Europe, both simulations show a decrease in water discharge for the southern parts of Europe, while HADLEY simulation also shows an increase in water discharge for northern Europe. For Sweden, the model results based on the ECHAM projection show higher mean annual discharge in the northern mountains and a decrease in discharge for the rest of the country. The decrease is most pronounced at the mid-century. HADLEY, on the other hand, shows increased discharge in all of northern Sweden and a decrease mainly in the south-western part of the country. The difference in water discharge is mainly a combined effect of precipitation and evapotranspiration in the hydrological model. The precipitation is received directly from the climate models (see above) while the evapotranspiration is calculated in HYPE based on temperature from the climate models. The large difference between the results of the climate projections means that the uncertainty in estimating future conditions is large.

### Specific runoff – local water discharge

The change in local runoff can vary between an increase of 50 % and a decrease of 50 % for different parts of Europe. Both simulations give a large decrease in the southern parts of Europe while the HADLEY simulation shows an increase in the northern parts. In Sweden, the specific runoff varies between 150–200 mm less per year for different parts of the country. The patterns of future change are similar to the changes in mean annual water discharge. Again, the large differences between climate scenarios indicate that local results are very uncertain.

### Groundwater level

A decrease or increase of up to 30 % for mean annual values of shallow groundwater levels can be expected for different parts of Europe. The changes are in general more extreme in the HADLEY simulation. In Sweden, the mean groundwater levels were estimated to become 10 cm lower or 10 cm higher for different parts of the country. The emerging patterns for each climate projection correspond well to the spatial patterns of mean annual discharge and specific runoff (above).

### Soil moisture

It can be expected that the mean annual soil moisture deficit decreases with 10–80 % for different parts of Europe. The HADLEY simulation shows more extensive patterns and pronounced deficit than the ECHAM simulation. Differences in soil moisture deficit can be derived from change in precipitation and evaporation (partly dependent on temperature). The number of days with low soil moisture deficit is expected to increase all over Europe with up to 100 %, as well as the intensity soil moisture deficit in the root zone. The pace of the increase differs between the two scenarios and is thus rather uncertain.

### Snow

In both projections there is an expected decrease in the number days with a snow cover > 1 cm. The decrease is largest in the southern parts of Sweden, around Gulf of Finland, and mountainous regions in southern Europe. For Sweden the decrease is 30–70 % depending on site for both model projections, with most reduction in days for Svealand and parts of Småland. The HADLEY projection results in a faster decline and an extended area with large impact. The snow depth, on the other hand, is assumed to be reduced by 70 % in the south and along the Swedish coast, while the Swedish mountains show

an increase in snow depth up to 40 %. The lower depths are caused by higher temperatures and change from snow to rain in the south, while the larger depths in the colder mountains are caused by increased precipitation and thereby more snow.

### Low flows

The mean annual low water discharge is expected to change by  $\pm 30$  % for different parts of Europe ( $\pm 50$  % for Sweden). Both simulations show an increase in the northern parts of Europe and the Alps and a decrease in southern parts of Europe (Fig. 1c–d). Higher temperatures in the summer can result in drought during the summer in the southern parts, while higher temperatures during the winter can result in a more regular snow melt during the winter. For Sweden, both projections resulted in higher mean low flow in the Northern parts of the country and lower in the southern parts and along the coast.

The duration of low flow was also analysed and the number of days with low flow can be expected to decrease with 36 days in the northern parts of Europe and the mountain areas and increase with up to 100 days in southern parts. The two simulations show a relatively large agreement for the European scale, but differ from the simulation with higher resolution for Sweden, in which the days with low flow increase up to 70 days for the southern part and decrease up to 50 days in the mountains. The changes in level of low flow show large spatial variation with changes of  $\pm 80$  % in different parts of the country. The climate change develops faster in the ECHAM projection and the inner Northern Sweden show no changes according to HADLEY.

### High flows

The mean high flow as well as the magnitude of the 10- and 50-year flood show similar patterns and trends; they can increase or decrease with up to 30 % in different parts of Europe (Fig. 1a–b). The two different climate scenarios, however, show partly different patterns. For Sweden the S-HYPE model estimated the spatial variation between 50 % increase and 50 % decrease, but for most of the country the change is on 15 %. Highest levels are estimated for Northern part of the mountain range and in southwestern Sweden. Lower 10- and 50-year floods were detected in the mountains of Jämtland. There is a large spread in results between the two projections so results on high flows should be treated carefully on the local scale. The HADLEY projection result in larger changes for the whole country while ECHAM indicates smaller changes compared to the reference period.

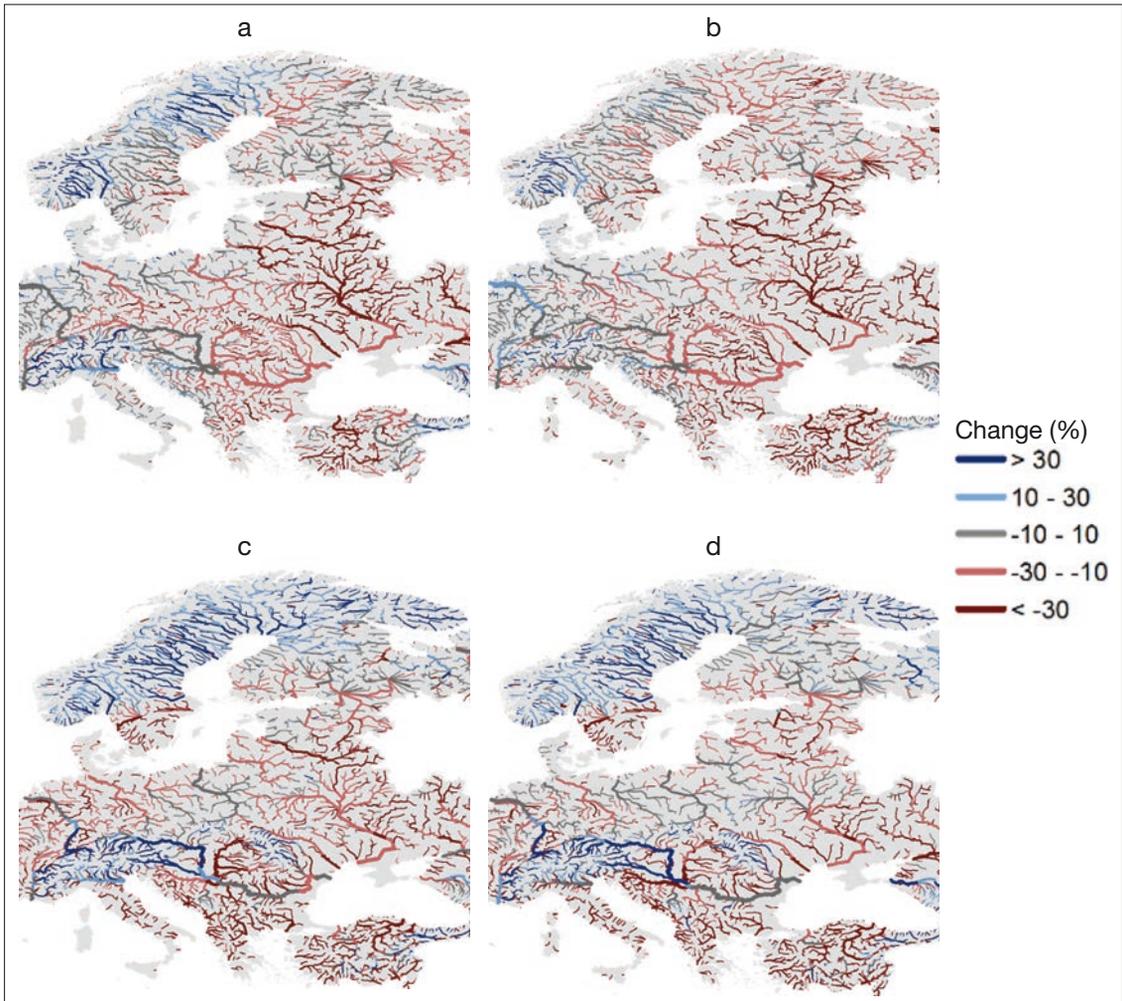


Figure 1. Change from period 1981–2010 to period 2071–2100 in terms of mean annual high flow in projection HADLEY (a) and ECHAM (b) and in terms of mean annual low flow in projection HADLEY (c) and ECHAM (d).

### Water quality – Nutrients

The results from modeling climate-induced changes in nutrient transport from land to the Baltic Sea did not show any dramatic trends in annual discharge or nutrient loads in the future (Arheimer et al., 2012). Nevertheless, the model results suggest that the total mean load to the Baltic Sea may decrease for nitrogen and increase for phosphorus by 2100. The variations between years were found to be much larger than any long-term trend for each climate projection. On the other hand, the seasonal variation during an average year was found to change significantly. This could be of major importance for the biological response in the marine environment, as the ecosystem will react differently depending

on season and the biological activity at the time when the water and nutrients reach the sea.

Simulation experiments with combined climate change and remedial nutrient management scenarios (as defined in the Baltic Sea Action Plan, BSAP) indicate that the impact of climate change may be of the same order of magnitude as the expected nitrogen reductions from the remedial measures simulated. For the Baltic Sea, both improved wastewater treatment and agricultural measures are needed to reach the BSAP target reductions by 2100. Yet, for half of the climate projections the targets were not reached and the variation in the quantified impact is large between different projections.

## Conclusions

Several hydrological variables describing future water resources under climate change are now available with high resolution over Europe and Sweden at the SMHI website. These are free to be used in societal planning and water management. According to the model results, several variables show an increase or a decrease by 50 % as an effect of climate change, depending on geographical location. However, the results are still associated with large uncertainties, as different climate projections may result in very different effects. In addition, uncertainties are caused by the downscaling technique and the impact models, so the results should thus be treated with caution, especially on the local scale. Yet, the large-scale models can give a hint about magnitudes of emerging patterns. Further, when different projections results in similar results the findings are more reliable.

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## References

Arheimer, B, Andréasson, J., Fogelberg, S., Johnsson, H., Pers, C.B., Persson, K. (2005) Climate change impact on water quality: model results from southern Sweden. *Ambio* 34(7):559–566.

Arheimer, B., Dahné, J., Donnelly, C. (2012) Climate change impact on riverine nutrient load and land-based remedial measures of the Baltic Sea Action Plan. *Ambio* 41 (6):600–612.

Arheimer, B., Dahné, J., Donnelly, C., Lindström, G., Strömqvist, J. (2012) Water and nutrient simulations using the HYPE model for Sweden vs. the Baltic Sea basin – influence of input-data quality and scale. *Hydrology research* 43(4):315–329.

Arheimer, B. and Lindström, L. (2013) Implementing the EU Water Framework Directive in Sweden. Chapter 11.20 in: Bloeschl, G., Sivapalan, M., Wagener, T., Viglione, A. and Savenije, H. (Eds). *Runoff Predictions in Ungauged Basins – Synthesis across Processes, Places and Scales*. Cambridge University Press, Cambridge, UK. (p. 465) pp. 353–359.

Arheimer, B., Olsson, J., Strömbäck, L. (2013) Dissemination and end-user interactions of climate change impact on water resources. *Journal of Water Management and Research (VATTEN)*, this issue.

Bates, B.C., Kundzewics, Z.W., Wu, S., Palutikof, J.P. (2008) *Climate Change and Water*. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Bergström, S., Andréasson, J., Graham, L.P. (2012) Climate adaptation of the Swedish guidelines for design floods for dams. *ICold 24th Congress Kyoto 2012*, Q94.

Collins, M., Booth, B.B.B., Harris, G.R., Murphy, J.M., Sexton, D.M.H., Webb, M.J., (2006) Towards quantifying uncertainty in transient climate change. *Climate Dynamics*, 27, 127–147, DOI 10.1007/s00382-006-0121-0

Dankers, R., Feyen, L. (2008) Climate change impact on flood hazard in Europe: An assessment based on high-resolution climate simulations. *Journal of Geophysical Research: Atmospheres*, 113, D19105. doi:10.1029/2007JD009719.

Donnelly, C., Dahné, J., Lindström, G., Rosberg, J., Strömqvist, J., Pers, C., Yang, W., Arheimer, B. (2009) An evaluation of multi-basin hydrological modelling for predictions in ungauged basins. *IAHS publ.* 333:112–120.

Donnelly, C., Arheimer, B., Capell, R., Dahné, J., Strömqvist, J. (2013) Regional overview of nutrient load in Europe – challenges when using a large-scale model approach, E-HYPE. *IAHS Publ.* 359.

Huntington, T. (2006) Evidence for intensification of the global water cycle: review and synthesis. *J. Hydrol.* 319, 83–95.

Johns, T.C., Gregory, J.M., Ingram, W.J., Johnson, C.E., Jones, A., Lowe, J.A., Mitchell, J.F.B., Roberts, D.L., Sexton, D. M.H, Stevenson, D.S., Tett, S.F.B., Woodage, M.J. (2003) Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios, *Climate Dynamics*, 20, 583–612, DOI 10.1007/s00382-002-0296-y

Kjellström, E., Nikulin, G., Hansson, U., Strandberg, G., Ullerstig, A. (2011) 21st century changes in the European climate: uncertainties derived from an ensemble of regional climate model simulations. *Tellus* 63A:24–40. doi. 10.1111/j.1600-0870.2010.00475.x

Lindström, G., Pers, C.P., Rosberg, R., Strömqvist, J., Arheimer, B. (2010) Development and test of the HYPE (Hydrological Predictions for the Environment) model – A water quality model for different spatial scales. *Hydrology Research* 41.3-4:295-319.

Meier, H.E.M., Höglund, A., Döscher, R., Andersson, H., Löptien, U., Kjellström, E. (2011) Quality assessment of atmospheric surface fields over the Baltic Sea of an ensemble of regional climate model simulations with respect to ocean dynamics. *Oceanologia* , 53 (1-T1):193–227.

Middelkoop H, Daamen, K., Gellens, D., Grabs, W., Kwadijk, J.C.J., Lang, H., Parmet, B.W.A.H., Schädler, B., Schulla, J., Wilke, K. (2001) Impact of climate change on hydrological regimes and water resources management in the Rhine Basin. *Clim Change* 49:105–128.

Nakićenović, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A. (2000) *Emission scenarios*. A Special Report of Working Group III of the

- Intergovernmental Panel on Climate Change. Cambridge University Press, 599 pp.
- Olsson, J., Yang, W., Bosshard, T. (2013) Climate model precipitation and hydrological impact studies, *Journal of Water Management and Research (VATTEN)*, 69, 221–230 (this issue).
- Roeckner, E., Brokopf, R. Esch, M. Giorgetta, M. Hagemann, S. Kornbluh, L. Manzini, E. Schlese, U., Schulzweida, U. (2006) Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model, *J. Climate*, 19, 3771–3791.
- Samuelsson, P., Jones, C.G., Willén, U., Ullerstig, A., Gollvik, S., Hansson, U., Jansson, C., Kjellström, E., Nikulin, G., Wyser, K. (2011) The Rossby Centre Regional Climate model RCA3: Model description and performance. *Tellus A* 63:4–23. doi. 10.1111/j.1600-0870.2010.00478.x
- van Ulden, A.P. and van Oldenborgh, G.J. (2013) Large-scale atmospheric circulation biases and changes in global climate model simulations and their importance for climate change in Central Europe *Atm. Chem. Phys.*, 2006, 6, 863–881, sref:1680-7324/acp/2006-6-863.
- Yang, W., Andréasson, J., Graham, L.P., Olsson, J., Rosberg, J., Wetterhall, F. (2010) Distribution based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies. *Hydrology Research*, 41(3–4), 211–229.

