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CLIMATE MODEL PRECIPITATION IN HYDROLOGICAL IMPACT STUDIES: LIMITATIONS AND POSSIBILITIES

Nederbörd från klimatmodeller i hydrologiska effektstudier: begränsningar och möjligheter

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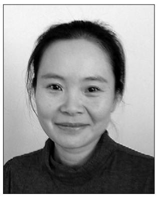


Abstract

Hydrology is strongly precipitation-dependent and hence hydrological modeling and forecasting requires accurate precipitation input for good performance. Hydrological climate change impact assessment thus requires good estimates of future precipitation. Climate modeling is the main means of estimating future precipitation, but it is seldom possible to directly use the precipitation output from climate models for meaningful hydrological simulation. This is because (i) climate model precipitation is generally biased, i.e. it deviates from observations in a historical reference period, and (ii) the model grid cells are often far larger than catchments, which creates scale effects. In this paper we give an overview of how climate model precipitation differs from observations in Sweden, at different scales. Then two approaches to bias correction and downscaling that has been developed and applied within HYDROIMPACTS2.0 are described: Delta Change and Distribution-Based Scaling. We close the paper with some reflections on on-going and future research directions.

Key words – climate change; hydrology; bias correction; downscaling

Sammanfattning

Hydrologi är starkt nederbördsberoende och alltså kräver hydrologisk modellering och prognosering korrekta nederbördsdata för att ge ett bra resultat. En bedömning av klimatförändringens påverkan på hydrologiska processer kräver således bra uppskattningar av den framtida nederbörden. Klimatmodellering är det huvudsakliga sättet att uppskatta framtida nederbörd, men det är sällan möjligt att använda nederbördsutdata direkt från klimatmodeller för meningsfull hydrologisk simulering. Detta beror på att (i) klimatmodellernas nederbörd har systematiska fel, d.v.s. den skiljer sig från observationer i en historisk referensperiod, och (ii) klimatmodellernas gridceller är ofta avsevärt större än avrinningsområden, vilket skapar skaleffekter. I denna artikel ger vi en översikt av hur nederbörden från klimatmodeller skiljer sig från observationer i Sverige, på olika skalor. Därefter beskrivs två olika angrepp för korrigering av systematiska fel samt nedskalning till avrinningsområdesskala som utvecklats och använts inom HYDROIMPACTS2.0: Delta Change och Distribution-Based Scaling. Vi avslutar artikeln med några reflektioner kring pågående och framtida forskningsinriktningar.

1 Introduction

Hydrology is very closely linked to climate, as variations in river discharge and lake water levels are mainly controlled by the recent development of meteorological variables. Thus any changes in the climate will directly affect hydrological processes. Precipitation is considered the main hydrological driver and therefore changes in the precipitation regime are of particular importance.

The main tools for obtaining estimates of future precipitation are General Circulation Models (GCMs; also called Global Climate Models), that simulate the climate of the Earth on a coarse grid based on prescribed forcing in terms of e.g. solar radiation and greenhouse gas concentrations. Often, Regional Climate Models (RCMs) are used to increase the level of detail in the result for specific regions. The description of the precipitation process in GCMs and RCMs is basically the same as in the atmospheric models used for day-to-day weather forecasting, modified to allow for continuous, long-term simulation.

Generally, the physics behind precipitation generation are extremely complex, involving interacting processes over a wide range of scales. Even if the state of the atmosphere is perfectly known, numerically specifying exactly under which conditions precipitation will be formed is very difficult. In practice the state of the atmosphere must always be approximated with large uncertainty, which of course makes precipitation estimation even more difficult. Also the grid scale of the models imposes limitations. Large-scale precipitation fields (e.g. associated with fronts) can be explicitly represented in the climate models. Smaller-scale fields (e.g. associated with local convection), on the other hand, cannot be explicitly resolved in the coarse grids but needs to be parameterized, i.e. expressed as a function of the grid scale conditions. In summary, simulating precipitation is very challenging.

As climate models normally describe a generalized climate, on a specific historical day (or even when averaged over a month (or even a year)) simulated meteorological variables will always differ from the observed values. However, when averaged over very long periods (30 years or more) they should agree reasonably well for the climate model to be considered reliable. Climate models generally perform better for e.g. air pressure and temperature, but because of the difficulties outlined above, and others, the simulated precipitation will often differ substantially from observations even over very long periods (model bias). It must be emphasized that also precipitation observations have uncertainties and that it is difficult to create suitable data with which to compare climate model output. As the latter is expressed as large-scale averages, observations from stations are normally interpolated to gridded fields in order to be comparable. This interpolation requires assumptions of how precipitation varies with e.g. altitude and wind characteristics.

Because of the close link between precipitation and hydrological processes, even a limited climate model bias can substantially affect hydrological response. For example, a quite small but continuous overestimation of winter precipitation (as snow) may build up a far too thick snow cover, which may produce a drastically overestimated spring flood when temperature rises. Besides regional-scale bias, also the climate model grid scale limits the applicability in hydrological modeling. Catchments are often far smaller than the model grid size and, if so, the average grid cell precipitation values from the model will underestimate the variability (and extremes) at the catchment scale. In light of these limitations, there is a need to develop and apply methods for post-processing climate model precipitation data prior to using them in hydrological modeling. This post-processing may include only a bias adjustment but often this is combined with a downscaling to the relevant catchment scale.

Bias adjustment and downscaling of climate model precipitation have been main activities in the research project HYDROIMPACTS2.0. The main objectives of this paper are (i) to give an overview of how climate model precipitation differs from observations in Sweden and (ii) to describe methods for bias adjustment and downscaling that have been developed and used within HYDROIMPACTS2.0. Before these sections, a general description of climate models and their representation of precipitation is given. In the end of the paper, some remarks on future developments in this field are included.

2 Climate model precipitation

GCMs are the most advanced tools used in climate-related studies. They are physically-based models that integrate various components of the climate system such as the ocean, the atmosphere, the land and the sea ice via a number of mathematical equations. They are designed to reproduce the large-scale evolution of the climate system by accounting for the internal and external driving forces and feedbacks in the climate system. As such, GCMs can be used to study the climate in the past and the present, and help us to understand the anthropogenic influence on the future climate as well as the associated uncertainties of the changing climate.

Typically, GCMs run at a horizontal resolution of hundreds of kilometers (250–600 km) and generate results at 10 to 20 vertical layers in the atmosphere over the globe (sometimes 20 layers in the ocean). The models are capable of incorporating complex processes in the global system and produce outcomes at continental and/or hemispheric spatial scales and at monthly temporal scales. They are, however, still weaker in representing the local sub-grid features and dynamics (Houghton et al., 2001), for instance, cloud formation and moist convention. The coarse resolution as well as incomplete understanding of small-scale physical processes is one source of uncertainty in GCM simulated precipitation under past, present and future climate.

In climate research, different types of emission scenarios are used to assess the long-term impact of atmospheric greenhouse gases and pollutants based on assumptions of population growth, economic development level, etc. Scenarios previously approved by the IPCC include SA90 (IPCC, 1990), IS92 (Leggett et al., 1992) and SRES (Nakicenovic et al., 2000). The latest

Table 1. *RCP description and citations (IPCC).*

	Description	*IA Model	Publication – IA Model
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100.	MESSAGE	Riahi et al. (2007) Rao and Riahi (2006)
RCP6	Stabilization without overshoot pathway to 6 W/m^2 at stabilization after 2100	AIM	Fujino et al. (2006) Hijioka et al. (2008)
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100	GCAM (MiniCAM)	Smith and Wigley (2006) Clarke et al. (2007) Wise et al. (2009)
RCP2.6	Peak in radiative forcing at ~ 3 W/m^2 before 2100 and decline	IMAGE	van Vuuren et al. (2006; 2007)

*IA Model = Integrated Assessment Model

scenarios developed by the research community are denoted by Representative Concentration Pathways (RCPs; van Vuuren et al., 2011). There are four RCPs defined by their level of the total radiative forcing pathway in the year 2100, and are representative for the existing literature about emission scenarios. The definition of the RCPs allows for a parallel development of new socio-economic, technical and policy scenarios that provide insights into the impact of policy decisions on the future climate (van Vuuren et al., 2011).

To tackle the weakness of GCMs, dynamical downscaling (DD) has been developed since decades. DD is a process-based method using a limited-area, high-resolution climate model to derive small-scale information. There are three commonly used DD approaches (Rummukainen, 1997; Rummukainen, 2010):

– Running a Regional Climate Model (RCM) with the coarse GCMs output as geographical or spectral boundary conditions
– Performing global-scale experiments with a high-resolution atmospheric global model using the coarse GCMs as initial and partial boundary conditions
– Using variable-resolution global models that enable to run at the high-resolution over the area of interests

To date, RCMs become more attractive because of their localized, high-resolution outputs, and because of being consistent with large-scale GCM simulation. TheRCM runs on a regional scale using GCM's output or re-analysis data (see Section 2.1 below) as its initial and boundary conditions. No feedback from the nested model to the GCM is considered. A RCM normally outperforms a GCM with respect to representing local climate, due to (i) a better representation of geographical features such as orography due to the finer spatial resolution (25–50 km) and (ii) a better description of the physical processes by means of e.g. sub-grid scale parameterization and more detailed land surface schemes (Giorgi and Marinucci, 1996; Hagemann et al., 2009; Samuelsson et. al., 2010). Both GCMs and RCMs are affected by physically-based model disadvantages. In fact, the model weaknesses caused by an incomplete understanding of the physics governing the atmospheric systems are more significant that those caused by using a coarse resolution (Risbey and Stone, 1996). Biases in the RCM statistics of key hydro-meteorological variables such as precipitation are often clear (e.g. Kotlarski et al., 2005; Key et al., 2006).

2.1 Initial and boundary conditions of RCMs

As described in the previous section, RCMs are commonly used to dynamically downscale the results of GCMs, i.e. increase the resolution of climate simulations by using more detailed descriptions of processes and geographical properties. Thus the initial conditions as well as the conditions at the RCM domain boundaries are given by GCM output. However, in order to assess RCM performance it is also possible to use initial and boundary conditions that reflect the actual, observed states of the atmosphere as closely as possible. Typically, a meteorological re-analysis is used for this type of observation-based forcing, e.g. ERA-40 (Uppala et al., 2005). In a meteorological re-analysis, atmospheric observations (of e.g. pressure, winds, temperature, humidity and precipitation) are assimilated into gridded fields by using an atmospheric model. Thus a re-analysis represents model output but it is supposed to be the best possible estimation of the historical states of the atmosphere in any point in time and space.

There are some notable differences between the two types of RCM forcing, i.e. GCM and re-analysis. In the former case, any deviation from observed climate in a historical reference period is a combined effect of uncertainties in both the GCM and the RCM. In the latter case, however, deviations only reflect the RCM uncertainty (provided that the re-analysis is close to reality, which is generally assumed) which may thus be assessed and quantified. Further, GCMs have the freedom to develop their own climate, which possibly deviates from the observed one regarding the day-to-day and up to decadal variability. Re-analysis-based forcing, on the other hand, ensures that observed weather sequences are reproduced in the RCM simulations.

3 Systematic deviations from observations

As discussed above, climate model precipitation typically deviates from observations. The deviation may be manifested in long-term mean values and/or variability and extremes. The deviation need not be the same for different aspects, e.g. extreme values in climate model precipitation may deviate more from observations than long-term means. Further, the deviation includes contributions from different sources at different scales, as touched upon in Section 1. At the regional scale, deviations may be considered pure model bias. At the local scale, however, deviations also reflect the difference in scale between the climate model grid size and the catchment area. This scale difference may have a small impact on long-term means, unless the catchment differs substantially from the grid box average with respect to e.g. altitude. The scale difference will, however, always substantially affect variability and extremes which are strongly area-dependent. In a hydrological context, this scale effect may be small for large catchments with slow temporal fluctuations but large for small, fast-responding catchments with a pronounced diurnal variability. In the sections below, deviations at different scales are exemplified and discussed.

3.1 The regional scale

At Rossby Centre, SMHI, systematic deviations from observations in Pan-European simulations with the regional model RCA3 (Samuelsson et al., 2010) run at resolution 50×50 km have been estimated (Kjellström et al., 2011; Nikulin et al., 2011), and here we focus on the results for Sweden. As the reference data used is a data base of interpolated precipitation observations on the same grid as the RCA3 model (E-OBS; Haylock et al., 2008), no scale effect is present but the results reflect pure model bias.

When forced with ERA-40, total winter precipitation in RCA3 is generally within ±20 % of the observed (Kjellström et al., 2011; Fig. 3). In a region in the Swedish mountains, however, an overestimation up to 50–100 % was found. In summer there is a systematic overestimation in essentially all of Sweden, generally below 50 % but in the mountains reaching 100 %. An area with a small negative bias was found in western Sweden.

Concerning GCM forcing, the results from six RCA3-simulations forced with different GCMs were averaged in Kjellström et al. (2011). In winter, RCA3 systematically overestimates precipitation in entire Sweden, generally between 20 % and 60 % but in some places more. As the bias is substantially larger than when RCA3 was forced by ERA-40, this indicates that the GCMs add bias. In summer, however, the result from the GCM-based ensemble is very similar to the ERA-40 driven run. Thus, in this case bias seems to be mainly related to the RCA3 model.

In terms of daily maximum precipitation, expressed as 20-year values (i.e., that occurs on average once every 20 years), RCA3 generally overestimates this value in winter, normally by up to 20–30 % but regions with both higher values and underestimations were found (Nikulin et al., 2011; Fig. 4). In summer the values are within ±20 % of the observed values in all Sweden, except in the northern mountains where an overestimation of up to almost 100 % is indicated. The differences between the ERA-40-based and the GCM-based simulations are overall small, implying that bias is mainly related to RCA3.

3.2 The catchment scale

In a Swedish context, the term "catchment scale" represents a wide range of sizes. Whereas the largest rivers have a total catchment area of 20 000 – 30 000 km², single sub-catchments may be < 1 km². In terms of hydrological modeling, in the most recent version of the HYPE model (Lindström et al., 2010) set-up for Sweden (S-HYPE) the country is divided into ~40 000 sub-catchments with a mean size of ~10 km². Here, we mainly consider catchments on the order of 1000–2000 km², i.e. below the typical RCM grid size.

An estimate of the average precipitation over a catchment is uncertain as it is generally based on data from only a few observation stations in, near, or at least not too far away from the catchment. In the case of widespread precipitation over a flat catchment simple interpolation procedures such as Thiessen weighting may be reasonably accurate, but in case of localized precipitation fields or strong altitudinal gradients the interpolated estimate will be much more uncertain. In more advanced spatial interpolation of precipitation, factors such as altitude and wind speed are taken into account which improves the catchment-scale estimates. At SMHI, this procedure is used to produce the so-called PTHBV data base with gridded (4×4 km), daily fields of precipitation and temperature (Johansson, 2002). This

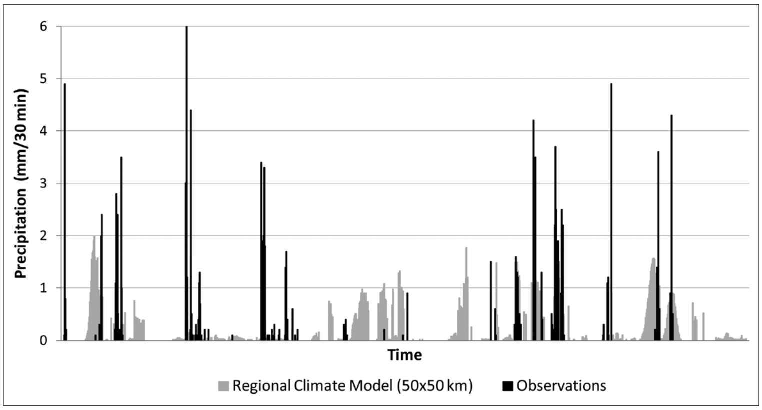

Figure 1. *Illustration of the difference between 30-min precipitation as represented in point observations and in an RCM with 50×50 km grid size.*

is the main reference data used for assessing the systematic deviations of catchment-scale precipitation in climate model output.

At this daily resolution, simulated precipitation is normally characterized with two weaknesses: (i) spurious drizzle and (ii) inaccurate frequency distribution of precipitation intensity, which are shown as an overestimated frequency of wet period, as compared with observations. For many Swedish catchments, the bias in mean basin precipitation is shown as a higher percentage of wet days (i.e. < 50 %) and higher annual precipitation amount (i.e. > 70 %) (e.g., Yang et al., 2010). The biases differ from season to season, with the largest overestimation in spring and summer. The bias in precipitation, along with bias in temperature in winter and early spring can lead to large hydrological modeling errors in the accumulation of snow and subsequent snowmelt.

3.3 The point scale

In a hydrological context, point scale precipitation (i.e. as observed in one single station) is relevant for the very smallest catchments, and especially those located in an urban environment with a high degree of impervious surface that makes flow response to (liquid) precipitation extremely fast. Urban hydrological modeling and design is based on statistical analyses of single-station precipitation data, i.e. the point intensity is assumed to be the catchment average intensity. The fast response means that very short time steps must be considered, in the modeling and consequently also in the precipitation input data. Often time steps of single minutes are used and the precipitation input comes from tipping-bucket gauges that allow precipitation events to be sampled up to a resolution of seconds.

In this case, there is always a clear mismatch in spatial resolution between the RCM grid size and the point precipitation data. Concerning time scale, RCMs can often provide output on time steps of 15–30 min, which may be sufficient in urban hydrological climate change impact assessment, but because of the discrepancy in spatial scale there are large differences in temporal variability. This is schematically illustrated in Figure 1, showing 30-min precipitation during a 1-month period. Point observations are very intermittent with short and "spiky" events. In RCM data on a 50×50 km grid, on the other hand, events become longer and smoother with far lower peaks. In a statistical sense, the time series are totally different and it is obvious that the hydrological response will be different, too.

It is clear that urban hydrological climate change impact assessment requires estimation of precipitation at a spatial resolution higher than that of today's RCMs, and the development towards higher-resolution RCMs is very fast. For example, the RCA3 model has been run on resolutions from 50×50 km down to 6×6 km, using ERA-40 as initial and boundary conditions. In Figure 2, 10-year Intensity-Duration-Frequency (IDF) curves for Göteborg derived from RCA3 grid cell time series are

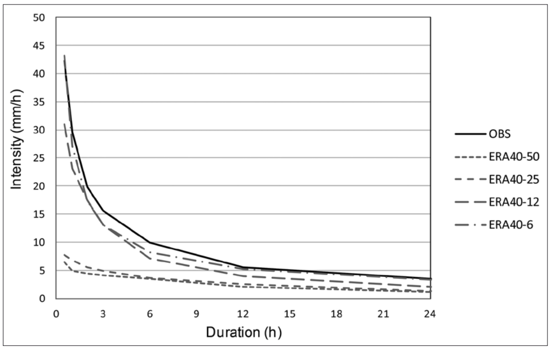

Figure 2. *10-year IDF-curves derived from observations and from ERA-40-driven RCA3-simulations with grid sizes between 50×50 km and 6×6 km.*

compared with the curve derived from observations for durations between 30 min and 1 day. It appears that when using a grid size of ~10 km or below, the simulated extremes can agree well with observations, even at sub-hourly time scales. Principally similar results have been indicated also for other locations in Sweden but further studies are required to e.g. investigate regional differences and produce uncertainty estimates.

4 Bias correction and downscaling

The systematic deviations shown in the previous section will to some extent affect hydrological simulations that use climate model precipitation as input, and generally decrease the agreement with observed discharge as compared to using observed precipitation as input. This may not be a major problem, as long as the mean level and variability of the simulated discharge and water levels stay within a range that is physically realistic and acceptable with respect to structural limitations in terms of e.g. flood bank heights and dam crests. It is, however, not uncommon that the result from hydrological simulations with climate model precipitation as input is outside this acceptable range, which makes any meaningful climate change impact assessment virtually impossible.

One solution to this problem is to use only relative future changes in precipitation characteristics from the climate model results, and apply these changes to historical observations in order to generate more realistic estimated future precipitation data. Thus how well the climate model represents historical climate does not matter, i.e. model bias is not considered. This approach is known as Delta Change, DC (Section 4.1).

Another possibility is to statistically adjust the climate model precipitation towards the observed characteristics, prior to the hydrological modeling. This is known as the Model Output Statistics (MOS) approach (Maraun et al., 2010). In this approach, climate model results are compared with observations in a long enough historical reference period and mathematical transformations are developed that when applied to the climate model data make them agree with observations in a statistical sense. The same transformations are finally applied to future climate projection data. This type of statistical adjustment is generally termed "bias correction". The expression implies that the reference observations are correct in the sense un-biased, but as this can be seldom verified but only assumed, "bias adjustment" is a more proper expression (i.e. the RCM data are adjusted to reproduce observations including any bias they may have with respect to the "true" precipitation). However, as "bias correction" is the established term, we use it here. The MOS approach is here represented by the Distribution-Based Scaling method (Section 4.2).

By transformation using e.g. DC or MOS, meaningful hydrological simulation generally becomes possible, but it must be emphasized that the approach is far from problem-free. In the case of Delta Change, important aspects of the future change risk to be missed when designing the way observations are modified. In the case of statistical adjustment, it is not certain that the transformation developed for a historical period is valid also for future periods. Further, when modifying climate model simulated variables, inter-variable dependencies may be disturbed and physically unrealistic conditions might occur. Despite these, and other, limitations, statistical post-processing of climate model precipitation is essentially always done in connection with hydrological climate change impact studies. In Section 4.3 some examples of how post-processing of climate model precipitation may improve hydrological simulation are given.

4.1 Delta Change

In the simplest possible version of Delta Change (DC), an estimate of the future relative change in total precipitation amount over all seasons, e.g. 15 % increase, is applied to a historical precipitation time series by multiplying all values by 1.15 (DC factor). Such approaches were made already in the early days of climate modeling (e.g. Niemczynowicz, 1989). However, as the change is normally different at different times of the year, using seasonal or monthly DC factors is now common practice (e.g. Hay et al., 2000).

One limitation of the basic DC approach is that future relative changes may depend on the precipitation statistic considered. In particular, the future estimated changes in extremes may differ substantially from the changes in total amounts. The change may even be of different sign, such as in summer the total precipitation may decrease but the highest intensities increase (e.g. Olsson et al., 2009). This suggests that intensity level need to be considered in a more advanced DC procedure. In Semadeni-Davies et al. (2008), separate DC factors are used for low ("drizzle") and high ("storm") intensities. In Olsson et al. (2009), DC factors were expressed as a function of the frequency distribution percentile.

A further limitation in the DC approach is that precipitation frequency is assumed not to change, i.e. all dry periods in the historical data remain dry and all wet periods remain wet (although with a different amount). However, in climate model projections it is not uncommon that the frequency of precipitation changes between the reference and future periods. Ntegeka et al. (2008)

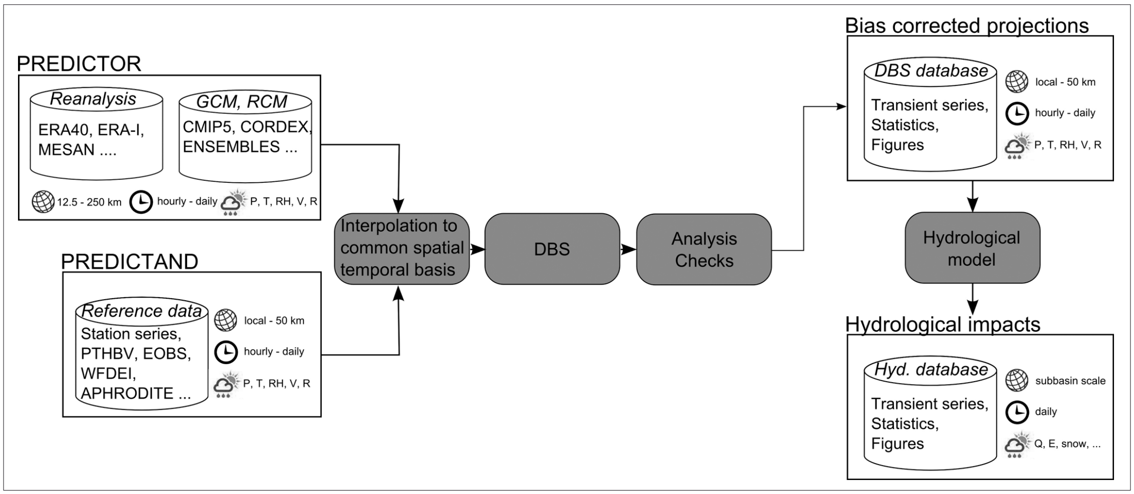

Figure 3. *Schematic of the DBS production environment at SMHI.*

developed a DC version with the possibility to randomly add or remove wet periods to allow for frequency changes in the procedure. Olsson et al. (2012) argued that changes in frequency are generally related to changes in the number of events occurring, rather than changes in their duration. They developed a frequency adjustment approach based on adding or removing "representative events" from the historical data.

4.2 Distribution-Based Scaling

Distribution-Based Scaling (DBS) aims to adjust systematic bias in GCM/RCM outputs whilst preserving the temporal variability in meteorological variables resulting from climate projections. Comparable to other well-known quantile-mapping methods (Piani et al., 2010; Themeßl et al., 2010), DBS implements parametric distributions to describe the variables of interest to correct the variable outside the reference period. Additionally, co-variation between precipitation and temperature is taken into consideration.

Adjusting precipitation is a two-step process: (i) days with precipitation lower than a calibrated threshold are changed to 0 mm to remove 'drizzle' generated by GCM/RCM, thus the simulated and the observed number of wet days are matched; (ii) the simulated precipitation amount is transformed to the observed value that has the same non-exceedance probability of a fitted double-gamma distribution. With the DBS tool, normal and extreme precipitation events are separated by a 95th percentile value calculated from the whole precipitation series. Their respective main properties are captured by individual distribution parameters.

Considering the dependency between precipitation and temperature, the systematic bias in temperature is presently adjusted conditioned on the wet or dry state of the day. The conditioned temperature is described by a normal distribution whose distribution parameters, the mean and the standard deviation, are smoothed using a 15-day moving window and described by Fourier series. Details can be found in Yang et al. (2010).

Hydrological climate change impact studies may require bias correction of a large ensemble of RCM projections over large regions or even continents. To facilitate application of the DBS procedure to large amounts of RCM data, a "DBS production environment" has been developed at SMHI (Figure 3). After the predictor (i.e. the simulated data) and the predictand (i.e. the reference observations) have been specified, interpolation to common temporal and spatial scales is performed. Then the DBS adjustment parameters are calculated for the historical reference period. An important step is to analyze the result of the parameter fitting, to verify the accuracy of the result. There are several pitfalls in automatically applying DBS to arbitrary data, such as the risks of having too few data points for accurate fitting or that the double-gamma distribution is a poor approximation at the specific location. Checks for such cases are included in the procedure. When the DBS fitting has been verified, the adjustment is applied to future data and the result may be directly evaluated in terms of e.g. descriptive statistics or graphical presentation.

4.3 Hydrological impacts

Figure 4 shows schematically, what effects a bias in the meteorological input data from the climate models could have on the projection hydrological impacts. Most impact models are non-linear. Therefore, depending on the offset to which the same climate change signal in the meteorological input data is applied, the impacts in the hydro-climatic projections might have a different magnitude. The strongest non-linearities are threshold processes in the impact model (e.g. snow/rain temperature transition). When such thresholds are present, a bias-correction is highly important to get a better estimate of the hydro-climatic impacts.

Case studies in catchments in all parts Sweden have shown that the runoff simulated using raw precipitation and temperature from RCM simulations deviates considerably from observed runoff. The deviation is mainly manifested in an overestimation of the runoff during the entire year. The overestimation was most pronounced during the spring flood for the northern catchments where overestimation could be at most above 100 %, because of an overestimated depth of the snow pack. The large biases in both runoff and snow depth were almost entirely eliminated using DBS-adjusted precipitation and temperature. Bias reduction is, on average, 90 % for runoff and 87 % for snow depth (Yang et al., 2010). Similar findings have been reported by e.g. Graham et al. (2007) and Veijalainen et al. (2012).

However, even though that RCM bias correction generally greatly improves runoff simulation, this does not mean that all bias is eliminated. For example, as DBS and similar methods focus on the frequency distribution of individual values, any deviations from observations with respect to patterns in temporal sequences are likely to remain in the RCM data also after the correction (or even be amplified). The frequency and length of wet and dry spells may still differ from observations, and this may lead to runoff biases that are not apparent in a general evaluation. Dahné et al. (2013) found indications that even after DBS application, the contributions to total flow from different flowpaths in RCM-driven runoff simulations differed from observation-driven simulations. Remaining bias in temporal sequences were put forward as one source of the discrepancy.

5 Future outlook

We conclude the paper with an overview of some ongoing and future research directions related to climate model precipitation and hydrological impacts.

- Although bias correction methods such as DBS have been established in hydrological impact studies, there is clear a need for further validation and development. Open issues include: How to ascertain that bias correction does not negatively affect spatial correlations as well as relationships with other meteorological variables? How to correct biases also in temporal sequences, i.e. the characteristics of and alternations between wet and dry spells? How to correct a negative bias in precipitation frequency, i.e. create new precipitation?
- Generally, hydrological impacts are estimated using a model calibrated against observations. This calibration often includes a simple form of precipitation bias correction to make simulated runoff totals agree with the observed. Alternatively, one possibility is to cali-

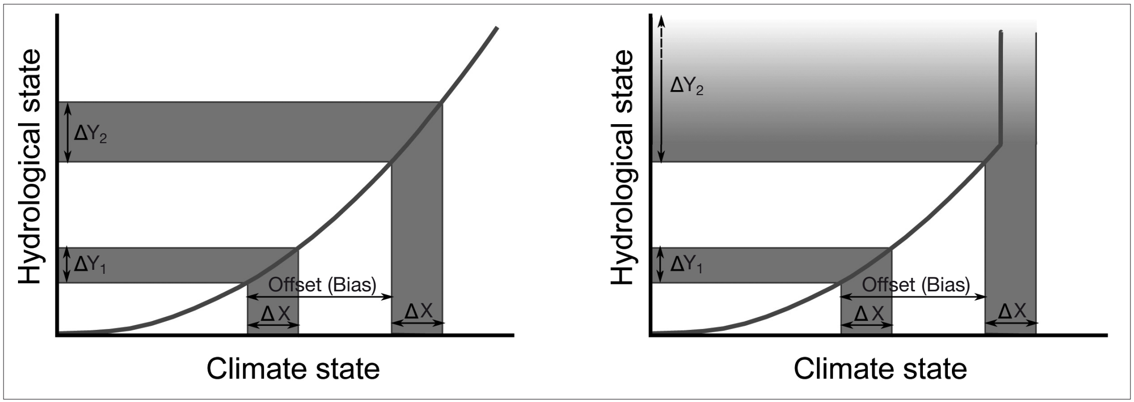

Figure 4. *Scheme explaining the effect of biases (offsets) in the meteorological climate change signal on the hydrological impacts. ΔX represents a climate change signal which, depending on the bias (offset) in the modelled climate state, is transformed in the a hydrological climate impact signal ΔY_1 and ΔY_2. Left: a case of a slightly non-linear impact model, Right: a case with a strong non-linearity, i.e. a threshold.*

brate the hydrological model against RCM data and use a more advanced bias correction, such as the DBS method, in the calibration step.
- In the climate modeling community, there is a very active on-going development of a new generation of RCMs with a spatial resolution (2–4 km) which is high enough to resolve e.g. individual convective precipitation fields. This makes it possible to better describe the small-scale variability and may lead to smaller biases overall. However, the simulations are extremely computationally demanding and it will take many years before ensembles of regional projections with such a high resolution will become available.

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References

Clarke, L., Edmonds, J., Jacoby, H., Pitcher, H., Reilly, J., Richels, R. (2007) Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations. Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Energy, Office of Biological and Environmental Research, Washington, 7 DC., USA, 154 pp.

Dahné, J., Donnelly, C., Olsson, J. (2013) Post-processing of climate projections for hydrological impact studies, how well is reference state preserved? IAHS Publications 359, 53–59.

Fujino, J., Nair, R., Kainuma, M., Masui, T., Matsuoka, Y. (2006) Multi-gas mitigation analysis on stabilization scenarios using AIM global model. Multigas Mitigation and Climate Policy. The Energy Journal, 3 (Special Issue).

Giorgi, F., Marinucci, M.R. (1996) Improvements in the simulation of surface climatology over the European region with a nested modelling system. Geophys. Res. Lett. 23, 273–276.

Graham, L.P., Hagemann, S., Jaun, S., Beniston, M. (2007b) On interpreting hydrological change from regional climate models. Climatic change 81, 97–122.

Hagemann, S., Göttel, H., Jacob, D., Lorenz, P., Roeckner, E. (2009) Improved regional scale processes reflected in projected hydrological changes over large European catchments. Clim. Dyn. 32, 767–781.

Hay, L.E., Wilby, R.L., Leavesley, G.H. (2000) A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. J. Am. Water Resour. Assoc. 36, 387–398.

Haylock, M.R., N. Hofstra, A.M.G. Klein Tank, E.J. Klok, P.D. Jones, M. New. (2008) A European daily high-resolution gridded dataset of surface temperature and precipitation. J. Geophys. Res (Atmospheres), 113, D20119.

Hijioka, Y., Matsuoka, Y., Nishimoto, H., Masui, M., Kainuma, M. (2008) Global GHG emissions scenarios under GHG concentration stabilization targets. Journal of Global Environmental Engineering 13, 97–108.

Houghton, JT., Ding, Y., Griggs, DJ., Noguer, M., van der Linden, PJ., Xiaosu, D. (eds) (2001) Climate change 2001: the scientific basis. Cambridge University Press, Cambridge, UK, pp 944.

IPCC (1990) Emissions scenarios from the response strategies working group of the intergovernmental panel on climate change, Appendix 1. In Climate Change: The IPCC Scientific Assessment. Prepared for IPCC by Working Group I. Cambridge University Press, Cambridge, UK.

Johansson, B. (2002) Estimation of areal precipitation for hydrological modelling in Sweden. Ph.D. Thesis. Report No. A76. Earth Sciences Centre, Göteborg University.

Kay, A.L., Jones, R.G., Reynard, N.S. (2006) RCM rainfall for UK flood frequency estimation. I. Method and validation. J. Hydrol. 318, 151–162.

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 A, 63:24–40.

Kotlarski, S., Block, A., Böhm, U., Jacob, D., Keuler, K., Knoche, R., Rechid, D., Walter, A. (2005) Regional climate model simulations as input for hydrological applications: evaluation of uncertainties. Adv. Geosci. 5, 119–125.

Leggett, J., Pepper, W.J., Swart, R.J. (1992) Emissions Scenarios for IPCC: an update. In Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment eds Houghton, J.T., B.A. Callander and S.K. Varney. Cambridge University Press, Cambridge, UK. 69–95.

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.

Maraun, D., Wetterhall, F., Ireson, A.M., Chandler, R.E., Kendon, E.J., Widmann, M., Brienen, S., Rust, H.W., Sauter, T., Themessl, M., Venema, V.K.C., Chun, K.P., Goodess, C.M., Jones, R.G., Onof, C., Vrac, M., Thiele-Eich, I. (2010)Precipitation Downscaling under climate change. Recent developments to bridge the gap between dynamical models and the end user, Rev. Geophys. 48, RG3003, DOI: 10.1029/2009RG000314.

Nakićenović, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., and Grübler, A. (2000) Emission scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, 599 pp.

Niemczynowicz, J. (1989) Impact of the greenhouse effect on sewerage systems—Lund case study. Hydrol. Sci. J. 34, 651–666.

Nikulin, G., Kjellström, E., Hansson, U., Strandberg, G., and Ullerstig, A. (2011) Evaluation and future projections of temperature, precipitation and wind extremes over Europe in an ensemble of regional climate simulations. Tellus 63A, 41–55.

Ntegeka, V.; Baguis, P.; Boukhris, O.; Willems, P.; Roulin, E. (2008) Climate Change Impact on Hydrological Extremes along Rivers and Urban Drainage Systems. II. Study of Rainfall and ETo Climate Change Scenarios; Belgian Science Policy-SSD Research Programme; Technical Report for CCI-HYDR Project; K.U. Leuven-Hydraulics Section and Royal Meteorological Institute of Belgium: Leuven, Belgium.

Olsson, J., Berggren, K., Olofsson, M., Viklander, M. (2009) Applying climate model precipitation scenarios for urban hydrological assessment: a case study in Kalmar City, Sweden. Atm Res 92:364–375.

Olsson, J., Gidhagen, L., Gamerith, V., Gruber, G., Hoppe, H., Kutschera, P. (2012) Downscaling of short-term precipitation from Regional Climate Models for sustainable urban planning, Sustainability, 4, 866–887.

Rao, S., Riahi, K. (2006) The role of non-CO2 greenhouse gases in climate change mitigation: Long-term scenarios for the 21st century. Multigas mitigation and climate policy. The Energy Journal. 3 (Special Issue), 177–200.

Riahi, K. Gruebler, A., Nakicenovic, N. (2007) Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting and Social Change 74, 7, 887–935. Available at http://dx.doi.org/10.1016/j.techfore.2006.05.026.

Risbey, J., Stone, P. (1996) A case study of the adequacy of gcm simulations for input to regional climate change assessments. Journal of climate, 9:1441–1466.

Rummukainen, M. (2010) State-of-the-art with regional climate models. WIREs Climate Change 1, 82–96.

Rummukainen, M. (1997) Methods for statistical downscaling of GCM simulations. RMK, 80.

Samuelsson, P., Jones, C.G., Willén, U., Ullerstig, A., Gollvik, S., Hansson, U., Jansson, C., Kjellström E., Nikulin, G., Wyser, K. (2010) The Rossby Centre Regional Climate model RCA3: model description and performance. Tellus.

Semadeni-Davies, A., Hernebring, C., Svensson, G., Gustafsson, L-G. (2008) The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Suburban stormwater. J Hydrol 350:114–125.

Smith, S.J., Wigley, T.M.L. (2006) Multi-Gas Forcing Stabilization with the MiniCAM. The Energy Journal (Special Issue #3) 373–391.

Themeßl, M.J., Gobiet, A., Leuprecht, A. (2011) Empirical-statistical downscaling and error correction of daily precipitation from regional climate models. Int. J. Climatol., 31: 1530–1544.

Uppala, S. M., KÅllberg, P. W., Simmons, A. J., Andrae, U., Bechtold, V. D. C., Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Berg, L. V. D., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., Mcnally, A. P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P., Woollen, J. (2005) The ERA-40 re-analysis. Q.J.R. Meteorol. Soc., 131: 2961–3012.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, JF., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, SJ., Rose, S.K. (2011) The representative concentration pathways: an overview. Climatic Change (2011) 109:5–31, DOI 10.1007/s10584-011-0148-z

van Vuuren, D. P., Eickhout, B., Lucas, P. L. & den Elzen, M. G. J. (2006) Long-term multi-gas scenarios to stabilise radiative forcing — Exploring costs and benefits within an integrated assessment framework. Multigas mitigation and climate policy. The Energy Journal. 3 (Special Issue), 201–234.

van Vuuren, D., M. den Elzen, P. Lucas, B. Eickhout, B. Strengers, B. van Ruijven, S. Wonink, R. van Houdt, (2007) Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Climatic Change. Available at http://dx.doi.org/10.1007/s10584-006-9172-9.

Veijalainen, N., Korhonen, J., Vehviläinen, B., Koivusalo, H. (2012) Modelling and statistical analysis of catchment water balance and discharge in Finland 1951–2099 using transient climate scenarios. Journal of Water and Climate Change 3(1), 55–78.

Wise, MA, Calvin, KV., Thomson, AM., Clarke, LE., Bond-Lamberty, B., Sands, RD., Smith, SJ., Janetos, AC. and Edmonds, JA. (2009) Implications of Limiting CO2 Concentrations for Land Use and Energy. Science. 324:1183–1186.

Yang, W., Andreásson, 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. Hydrol Res. 41(3–4): 211–228.