Hydrology and Earth System Sciences Discussions

Evaluation of areal precipitation estimates based on downscaled reanalysis and station data by hydrological modelling

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Abstract

In data sparse regions, as in many mountainous catchments, it is a challenge to generate suitable precipitation input fields for hydrological modelling, as station data do not provide enough information to derive areal precipitation estimates. This study presents a method using the spatial variation of precipitation from downscaled reanalysis data for the interpolation of gauge observations. The second aim of this study is the evaluation of different precipitation estimates by hydrological modelling. Study area is the Karadarya catchment in Central Asia ($11\,700\,km^2$). ERA-40 reanalysis data are downscaled with the regional climate model Weather Research and Forecasting Model (WRF). Precipitation data from gauge observations are interpolated (i) using monthly accumulated WRF precipitation data, (ii) using monthly fields from multiple linear regression against topographical variables and (iii) with the inverse distance approach. These precipitation data sets are also compared to (iv) the direct use of the precipitation output from the WRF downscaled ERA-40 data and (v) precipitation from the APHRODITE data set. Our study suggests that using monthly fields from downscaled reanalysis data can be a good approach for the interpolation of station data in data sparse mountainous regions. Compared to mean annual precipitation from continental and global scale gridded data sets our precipitation estimates for the study area are considerably higher. The introduction of a calibrated precipitation bias factor for the comparison of different precipitation estimates by hydrological modelling allows for a more informed differentiation with regard to the temporal dynamics, on the one hand, and the overall bias, on the other hand. Uncertainty and sensitivity analyses suggest that our results are robust against uncertainties in the calibration parameters, other model parameters and inputs, and the selected calibration period.

1 Introduction

Precipitation is one of the most important inputs for hydrological modelling, but also one of the most difficult to estimate. Areal precipitation estimates are generally afflicted with relatively large uncertainties due to errors in the measurement (e.g. wind under-catch error) and the scale difference between the point measurements and the areal estimate. This is amplified in mountainous regions, where, despite the high spatial variability of precipitation, the density of the gauge network is often low. In addition, the gauges are often unequally distributed, and exposed high elevation locations receiving the largest amounts of rainfall are usually underrepresented.

Orography affects the spatial pattern and the amount of precipitation through various processes (Houze, 1993). Orographic uplift results in cooling of the air and the formation of an orographic cloud. If the horizontal extent of the mountain is sufficiently large, there is enough time for the microphysical processes to generate precipitation from the cloud particles. For mountains with a smaller horizontal extent the seeder-feeder mechanism plays a larger role; in this process the generation of precipitation from an orographic cloud is triggered by precipitation from a pre-existing upper level cloud. Furthermore, precipitation may also be generated by orographically induced convection; for example, an unstable air mass may be raised to the level of free convection by forced orographic lifting, or strong thermal heating of the mountain slopes can lead to convective cells. Despite complex relations between orography and precipitation, in general, these processes often result in an increase of precipitation with elevation, particularly on windward slopes, and lower precipitation on the leeward side of a mountain ridge (rain shadow effect).

For the spatial interpolation of precipitation in mountainous areas, methods which consider the orography are therefore often advantageous over methods neglecting the relation with the terrain (Goovaerts, 2000; Hevesi et al., 1992; Martinez-Cob, 1996; Phillips et al., 1992; Tobin et al., 2011). Exceptions from this occur when the correlation between precipitation and elevation is low, or in regions where the station density is so

high that the relation between precipitation and topography is already represented by the observations (Haberlandt et al., 2005; Ly et al., 2011).

Elevation may be taken into account using geostatistical methods like modified residual kriging, external drift kriging or co-kriging with elevation (Garen et al., 1994; Goovaerts, 2000; Hevesi et al., 1992; Lloyd, 2005; Martinez-Cob, 1996; Phillips et al., 1992; Tobin et al., 2011) or using multi-linear or polynomial regression against various topographical variables (Basist et al., 1994; Brown and Comrie, 2002; Cheval et al., 2003; Daly et al., 1994; Goodale et al., 1998; Hay et al., 1998; Johansson and Chen, 2003, 2005; Marquinez et al., 2003; Ninyerola et al., 2000, 2007; Perry and Hollis, 2005; Prudhomme and Reed, 1998; Sun et al., 2008).

All of these statistical approaches require that the spatial variability of precipitation is captured by the gauges, or that the part of the spatial variability which is not captured by the gauges can be represented by relations to elevation and other topographic variables, and that these relations can be derived from the observed precipitation. In sparsely gauged areas with a more complex topography this may not be possible. In this case precipitation from reanalysis data downscaled by a regional climate model could be a helpful source for deriving the spatial variability of precipitation within the catchment. As the regional climate model considers the interactions between the orography and the wind field for simulating precipitation, it should be able to represent orographic precipitation and rain shadowing effects in a suitable and physically based way. A few studies already started to work in this direction. Haberlandt and Kite (1998) for example used daily precipitation output from the NCAR reanalysis (without downscaling) for the geostatistical interpolation of station-based precipitation time series, and recently Tobin et al. (2011) interpolated precipitation data from gauge observations by external drift kriging with precipitation fields from event accumulated COSMO7 reanalysis data as trend variable.

Precipitation data from regional climate models are often biased and also the correlation to measured precipitation data is usually low for smaller (e.g. daily) time steps. For example, Hurkmans et al. (2008) reported a squared correlation coefficient between

REMO downscaled ERA-15 data and observations averaged over the Rhine basin of 0.73 for monthly compared to 0.42 for daily data. This also implicates a lower performance of runoff simulations driven with these data. We therefore propose to combine monthly accumulated spatial fields from downscaled reanalysis data with daily station data for the estimation of areal precipitation in data sparse regions. We compare this interpolation method with the direct use of downscaled reanalysis precipitation data, precipitation estimates based on multi-linear regression against topographical variables, data interpolated by inverse distance and with the gauge based daily gridded precipitation data set APHRODITE (Yatagai et al., 2012).

Traditionally different precipitation data sets are often evaluated based on measured values from precipitation gauges, e.g. by cross validation. This might however lead to wrong conclusions, if the precipitation gauges are not representative of the areal precipitation, which is likely to happen in cases with a low gauge density, high variability of precipitation and bias of gauges toward lower elevation. In such situations, the comparison of observed runoff with simulated runoff from a hydrological model driven by the different precipitation data sets can be a more suitable method for the evaluation of the areal precipitation estimates (Heistermann and Kneis, 2011; Stisen and Sandholt, 2010). This has the advantage that the scale problem between point measurements and areal estimates is eliminated, as discharge measurements represent an integrated response from the entire catchment. Discharge measurements are also usually afflicted with smaller measurement errors than precipitation measurements. On the other hand, it has to be considered that this approach also introduces other uncertainties related to model uncertainties, discharge measurement errors, errors in the catchment runoff from unknown subsurface inflow/outflow and unknown abstractions or flow diversions. However, we expect that in many mountain catchments these uncertainties may still be smaller than the uncertainties in the areal precipitation estimates.

A model calibrated with one precipitation input data set cannot simply be run with different precipitation data sets, because model parameters are input dependent. They are basically effective parameters that compensate for errors among others in the

precipitation estimate (Andreassian et al., 2001). The model may instead either be recalibrated for each precipitation data set (Yilmaz et al., 2005; Stisen and Sandholt, 2010; Bitew and Gebremichael, 2011a,b; Behrangi et al., 2011; Artan et al., 2007) or applied within a Monte-Carlo framework (Heistermann and Kneis, 2011; Gourley
5 and Vieux, 2005). The different precipitation data sets are then typically evaluated using various measures for the model performance. However, if a precipitation estimate strongly over- or underestimates precipitation, it is not possible to assess whether the problem of this data set is only in the bias, while the timing of precipitation is estimated well, or whether the precipitation data set shows a poor performance with respect to its
10 mean and also with respect to its temporal dynamics. Scaling all precipitation estimates to a reference precipitation data set allows evaluating the precipitation estimates independent of their biases (Stisen and Sandholt, 2010). Another solution, which is adopted here, is to add a precipitation bias factor to the calibration parameters and evaluate the bias within the calibration framework. Thus it is not necessary to define a reference pre-
15 cipitation data set, which may also be afflicted with an unknown bias. Furthermore, one can also evaluate the uncertainties in the estimated bias, given the applied hydrological model and the observed discharge.

   This study thus has two main aims. First, it is tested whether spatial precipitation fields from downscaled reanalysis data can be used to interpolate station observations.
20 Second, the approach for comparing and evaluating areal precipitation estimates by hydrological modelling is further developed to separately consider the performance of different precipitation data sets with respect to their overall bias and their temporal dynamics, and to account for different sources of uncertainties.

   With respect to the case study region – the Karadarya catchment in Central Asia –
25 this work aims at estimating and evaluating different areal precipitation inputs. Water resources from mountain catchments are important for irrigation, hydropower generation and for the Aral Sea, and there is a demand in setting up hydrological models for the evaluation of possible climate change effects on water availability. Assessing

the precipitation input contributes to a better understanding of the hydrology in such a sparsely gauged region, and is a prerequisite for reliable hydrological modelling.

2 Methods

2.1 Study area

Study area is the Karadarya catchment – a mountainous catchment located in Kyrgyzstan, Central Asia. The confluence of the Karadarya and Naryn River in Uzbekistan forms the Syr Darya, the second largest tributary to the Aral Sea. The study area upstream of the Andijan Reservoir has an area of $11\,700\,km^2$. The catchment is bordered by the Fergana Range in the northeast and by the Alay Range in the south, where elevations go up to 4709 m (Fig. 1). Dominant land cover types are grasslands (59 %) and croplands (23 %), followed by smaller fractions of shrub land (5 %), woody vegetation (5 %), and glaciated areas (1 %). Mean annual precipitation, based on the 1961–1990 time series at the precipitation stations, ranges from 350 to $1050\,mm\,a^{-1}$. The precipitation regime shows a maximum in spring and a second smaller maximum in autumn.

The focus of our study is on six headwater subcatchments, for which discharge data are available and which are assumed to be only marginally influenced by water management. The location of these six subcatchments is shown in Fig. 1 and important characteristics are listed in Table 1. For most of these subcatchments the mean annual runoff over the period 1960–1990 has values of $400\,mm\,a^{-1}$ to $600\,mm\,a^{-1}$, outliers are Ak-Tash with nearly $800\,mm\,a^{-1}$ and Gulcha in the south with less than $300\,mm\,a^{-1}$. The discharge regime is strongly seasonal with maximum discharges during the snowmelt season in spring and early summer. In accordance with increasing average elevation maximum monthly discharges occur in April in Tosoi and Donguztoo, in May in Salamalik, and in June in Gulcha, Cholma and Ak-Tash.

2.2 Precipitation data

2.2.1 Downscaled reanalysis data

A relatively good performance of global reanalysis data in Central Asia was shown by Schär et al. (2004) and Schiemann et al. (2008). This was attributed to the fact that weather systems typically move into the region from the west and reanalysis data for Central Asia therefore benefit from the denser observation network in Europe and the Middle East, which partly compensates the sparse data coverage in the region. In order to resolve orographic precipitation and rain shadowing effects at smaller scales, it is necessary to downscale the reanalysis data by a regional climate model.

In this study data from the ERA-40 reanalysis (Uppala et al., 2005) with a horizontal resolution of 1° are downscaled to a 12 km grid using the regional climate model (RCM) Weather Research and Forecasting Model (WRF, Skamarock et al., 2008). A two-way nesting approach is applied, with the first nest at a horizontal resolution of 36 km covering a region between 35 to 47° N and 62 to 83° E and the second nest at a resolution of 12 km covering an area between 38 to 45° N and 65 to 80° E. The model is run with daily restarts in order to keep it close to the ERA-40 boundary and initial conditions; the simulation time for each day is 30 h, of which the first 6 h are used for model initialisation and discarded. Figure 2 shows the elevation as represented in the regional climate model compared to the elevation from SRTM (Jarvis et al., 2008). The general features of the topography are captured well, but due to the much coarser resolution the highest model elevations are much lower than the actual peaks and narrow mountain ridges, for example southwest of the Karadarya catchment, are not resolved.

2.2.2 Precipitation station data

Daily precipitation data for 11 gauges within or close to the Karadarya catchment are retrieved from the National Climatic Data Center (NCDC, 2005) and complemented by data from the National Hydro-Meteorological Services of Uzbekistan and Kyrgyzstan.

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Precipitation measurements are affected by systematic errors due to evaporation, wetting and wind-losses. Precipitation undercatch of the Tretyakov gauge, which is the common gauge in this region, due to wind losses is corrected using the approach of Yang et al. (1995). Measured temperature and wind data, which are required as inputs for this approach, are not available for all gauges. Therefore, temperature data are derived from the WRF downscaled ERA-40 data and, after consulting the WRF output and the available measurement data, an average wind speed of $2\,\mathrm{m\,s^{-1}}$ is assumed. The undercatch correction results on average in an increase of the measured value by 10 %.

2.2.3 Interpolation of station data using spatial fields from downscaled reanalysis data

The approach developed here interpolates daily time series of station data using spatial fields from downscaled reanalysis data. The WRF-ERA-40 precipitation data are first aggregated to monthly maps. For the generation of daily precipitation maps, a scaling factor at the station locations is calculated by dividing the daily observed precipitation by the mean monthly precipitation from the WRF-ERA-40 data. In order to avoid abnormally large precipitation values when dividing by very small numbers, stations where the mean monthly precipitation is less than $1\,\mathrm{mm\,month^{-1}}$ are excluded from the calculation of the scaling factor for that month. The calculated factor is next interpolated to a $1 \times 1\,\mathrm{km^2}$ grid using the inverse squared distance weighting (IDW) method. Multiplication of the interpolated scaling factor map with the WRF-ERA-40 data then results in the daily precipitation map. Two different variants of this method are tested: (i) In the variant WRFadj-all the monthly maps are calculated as means over the whole period 1960–1990, i.e. for the interpolation of station data in January 1960 a map of the mean monthly precipitation over all Januaries is used; (ii) in the variant WRFadj-ind the monthly maps are calculated for each year individually, i.e. for the interpolation of station data in January 1960 a map of the monthly precipitation of January 1960 is used.

2.2.4 Interpolation of station data using monthly fields derived by multi-linear regression

Due to the topography and the main wind direction from the west, precipitation in the catchment generally increases with increasing elevation and decreases to the south and east. Precipitation is therefore also interpolated by multiple linear regression against elevation, x and y. Since the correlations between precipitation and these three variables are higher for monthly than for daily data, the multi-linear regression is performed on monthly data. We apply the stepwise backwards approach, setting the p-value for exclusion and inclusion to 0.1 and 0.05 respectively. An initial analysis showed lower standard errors for the stepwise backward compared to the stepwise forward approach.

After calculating the monthly regression maps, daily precipitation maps are calculated in the following way: for each day scaling factors between the daily precipitation and the monthly regression at the stations are calculated and interpolated to a $1 \times 1 \, \text{km}^2$ grid using IDW. The interpolated scaling factors are multiplied with the monthly map derived by multi-linear regression to generate the daily precipitation fields. Again two variants of this method are applied using (i) monthly means over a month in all years (MLR-all) and (ii) monthly means of individual years (MLR-ind).

2.2.5 Interpolation of station data by inverse distance weighting

For comparison, the daily precipitation data are also interpolated using the inverse squared distance weighting approach.

2.2.6 Gridded precipitation data

APHRODITE (Yatagai et al., 2012) is a daily gridded precipitation data set at a resolution of 0.25° covering Asia, the former Soviet Union and the Middle East. It is based on gauge observations from GTS, precompiled data sets like GHCN, NCDC, FAO and

others, and additional data from national hydro-meteorological services. The spatial interpolation scheme takes into account the effect of mountain ranges by giving a high weight to gauges on slopes inclined to the target location and a low weight to gauges on the leeward side behind a mountain ridge.

5　　Other, globally available precipitation data are only assessed with respect to their spatial distribution and subcatchment mean values and not included in the evaluation by hydrological modelling. We use three different data sets based on interpolated station data: the Global Precipitation Climatology Centre (GPCC) full data reanalysis version 6 (Schneider et al., 2011), the University of Delaware (UDEL) precipitation data

10　set version 2.01 (Legates and Willmott, 1990), and the University of East Anglia Climate Research Unit (CRU) TS 3.10.01 (Mitchell and Jones, 2005). These data are all available as monthly time series with a spatial resolution of 0.5°. Furthermore we also inspected the precipitation data from the ERA-40 reanalysis (Uppala et al., 2005) at their original resolution, which is a spectral resolution of T159, regridded to a regular

15　geographic coordinate system of 1°. For an overview, Table 2 lists all precipitation data sets used in this study.

2.3　Point based evaluation of the precipitation data

In the first step, the precipitation data sets are evaluated by comparison to observed station data. The precipitation data generated by downscaling the ERA-40 reanalysis

20　data with WRF are directly compared to observed station time series. For this, WRF data from the pixel which contains the station location are extracted. There are limitations to such a comparison between point observations and pixel-based data, as gauge observations cannot be considered as ground truth for a $12\,\mathrm{km} \times 12\,\mathrm{km}$ WRF pixel area, and due to errors in the undercatch correction or in the observation data themselves.

25　However, a first indication of the performance of the WRF precipitation data for the Karadarya catchment is provided.

The interpolated precipitation data sets are evaluated by cross validation. In this method only a part of the stations is used for the interpolation, and the others are

employed for the evaluation of the interpolated values at these locations. As the error statistics are only calculated at the locations of the stations, the value of such an analysis may be very limited, if the gauges are not representative for the catchment precipitation (for example in a situation where precipitation increases with elevation,
5 but most stations are located in relatively low elevations). Also, in regions with only few stations, the interpolated fields may be strongly changed, if stations with a high weight in the interpolation are left out. In this study we only remove one station from the data set at a time. The interpolated time series at this location is compared to the observed time series and evaluated using bias and mean absolute error of the daily time series.

10 ## 2.4 Evaluation of areal precipitation estimates based on simulated discharge

2.4.1 Approach

The suitability of different precipitation estimates is tested by comparing observed discharge and discharge simulated by a hydrological model driven with the different precipitation estimates. Running a hydrological model with a different precipitation data set
15 than the one it has been calibrated with usually results in lower model performance, and is therefore not a suitable approach for the comparison of precipitation data sets. Generally there are two possibilities to evaluate different precipitation data sets by hydrological modelling: calibrating the model for each precipitation data set, and Monte Carlo simulations using various parameter values between defined bounds.
20 The Monte Carlo approach easily allows evaluating the model for various subsets of the data, but may in some cases lead to wrong conclusions, i.e. a precipitation data set with larger differences from the true precipitation might lead to lower mean deviations between simulated and observed flow and would therefore be classified as the better one. For a detailed discussion readers are referred to Heistermann and Kneis (2011).
25 Particularly problematic are cases, where parameters have a linear influence on the fraction of rainfall generating runoff and precipitation estimates do not have random errors but a systematic bias. While very obvious ill-posed settings may be avoided by

careful analysis of the model, less obvious cases may not always be avoided from the outset.

One solution to the problem of false rankings is to evaluate not all but only a percentage of the best Monte Carlo simulations. Heistermann and Kneis (2011) showed that reducing the number of the evaluated best performing Monte Carlo runs reduces the number of false rankings, though it also decreases the discriminatory power between different precipitation data sets. This can be seen as a transition to the model calibration approach.

Calibrating the model for each precipitation data set may have the disadvantage that model parameters can partly compensate for inadequacies of the precipitation data sets, which might result in different precipitation data sets being hardly distinguishable with respect to the simulated hydrograph. On the other hand, the approach is less prone to false rankings, as ill-posed settings would rather result in indistinguishable precipitation data sets so that setting the parameter bounds and analysing the model for possible ill-posed settings becomes a less sensitive issue. Another advantage is that by using an optimisation algorithm instead of random Monte Carlo runs, usually better model performances are achieved with a lower number of simulations. As it is seen as more important to avoid false rankings than to discriminate between already similar precipitation data sets, the model calibration approach is selected for this study.

In order to gain more information on different aspects of the performance of the precipitation data set, a precipitation bias factor is introduced as additional calibration parameter. The precipitation estimate is then evaluated with respect to the bias based on the precipitation bias factor, and evaluated with respect to the temporal dynamics based on the objective function used for model calibration.

Three different sources of uncertainties are considered in this study. Uncertainties in the precipitation bias factor (as part of the parameter uncertainties) need to be considered, because the precipitation factor of the best optimised parameter set might differ from other equally good performing parameter sets. The model calibration is then repeated for different time periods in order to evaluate the robustness of the precipitation

bias factor and ranking of the objective function value with respect to the selected time period. Finally the robustness of the results with respect to uncertainties in model inputs and parameters not varied during model calibration is investigated using sensitivity analyses.

2.4.2   Description of the hydrological model

The hydrological model WASA (Güntner, 2002; Güntner and Bronstert, 2004) is a semi-distributed daily time step model based on process-oriented and conceptual approaches. It was recently extended for high mountain areas by introducing elevation zones, and a snow and glacier mass balance module based on the temperature index method. The model calculates evaporation from the interception storage and open water bodies with the Penman-Monteith equation (Monteith, 1965), evapotranspiration using the two layer model of Shuttleworth and Wallace (1985), infiltration with the Green-Ampt approach (Green and Ampt, 1911), the generation of infiltration and saturation excess surface runoff, and percolation through a multiple layer soil store. In the model version applied for this study, surface and subsurface flow between model units within a subcatchment (i.e. lateral flow redistribution) are neglected, and subsurface flow is separated between interflow and groundwater based on a calibration parameter. The simulation of small events during the low flow period is improved by introducing an additional parameter for the fraction of the catchment where rainfall directly leads to runoff, like riparian areas, roads or rock areas connected to a stream.

The spatial discretisation of WASA is originally based on hillslopes with characteristic toposequences (Güntner and Bronstert, 2004; Francke et al., 2008). For this study a much simpler approach based on hydrologic response units defined by elevation bands is selected in order to reduce the computation time and allow for a higher number of model simulations for calibration and uncertainty analysis. For each 200 m elevation band the dominant soil and vegetation cover and the glacier fraction are taken into account.

For the model calibration 11 parameters are selected (Table 3). These affect the snow and glacier melt routine (snowmelt factor, glacier melt factor, melt temperature), the soil hydraulic conductivity for infiltration and percolation (kf_corr_f, k_sat factor), the subsurface runoff (frac2gw, interflow delay factor, groundwater delay factor), the frac-tion of the catchment area leading to direct runoff (frac_riparian), the occurrence of saturated areas as a function of the current soil moisture state (sat_area_var) and the precipitation input (precipitation bias factor).

2.4.3 Hydrological model set-up

The model is set up for the Karadarya catchment based on the SRTM (Shuttle Radar Topography Mission) digital elevation model (Jarvis et al., 2008) for elevations, slope angles and the delineation of subcatchments. As land cover input the MODIS land cover product (MOD12Q1; Friedl et al., 2002) is applied using the most frequent land cover class over the time period 2001–2008. Mean monthly leaf area index (LAI) values by elevation zone, subcatchment and land cover class were calculated from the 8 day MODIS LAI product for 2001–2008 (MOD15A2, Myneni et al., 2002). For the soil data a digitized map from the Kyrgyz Atlas (Academy of Science of the Kyrgyz SSR, 1987) is used and missing soil hydraulic parameters are assigned using pedo-transfer functions from the literature. Glacier areas are delineated from a LANDSAT image in summer 1977 using a combination of automated classification and manual digitizing. Daily time series of solar radiation, temperature, temperature lapse rate and humidity are taken from the WRF downscaled ERA-40 data described above. The temperature data are corrected for the difference between the SRTM DEM and the WRF topography using daily lapse rates as simulated by the WRF model. All meteorological input data are aggregated to subcatchment mean values.

2.4.4 Model optimisation and analysis of parameter uncertainties

The model is automatically calibrated against observed discharge using six years simulation periods (1961–66, 1967–72, 1973–78, 1979–84, 1985–90); prior to this the model is initialized using an additional simulation period of two years. In order to consider both high and low flows and to keep the overall bias low, the following objective function is applied:

$$\text{Obj.function} = 0.5 \times (\text{NSE} + \text{LogNSE}) - 2 \times \max(\text{Bias} - 0.05, 0) \tag{1}$$

where NSE is the Nash-Sutcliffe efficiency value, LogNSE is the Nash-Sutcliffe efficiency calculated on logarithmic flows, and Bias is the absolute value of the overall volume bias. The Nash-Sutcliffe efficiency is particularly responsive to errors in high discharge values, while the Nash-Sutcliffe efficiency for logarithmic flows is more sensitive also for errors in low flows so that the average of these two measures results in a more balanced evaluation. The maximum possible value of the objective function is 1, which would indicate perfect agreement between simulated and observed discharge. Additionally, the objective function is penalised, if the bias is greater than 0.05 or 5 % of the observed discharge.

Despite the lack of hard data, two further constraints for the snow and glacier mass balance modules are introduced in order to avoid unrealistic simulations. First, an elevation is defined below which snow is not expected to accumulate over several years. This elevation is derived from LANDSAT images in summer and set to 4200 m for the Karadarya catchment. For each year, the number of elevation zones where simulated snow does not melt away in elevation zones below this elevation is counted, and if it is above a threshold of one per year, the simulation is discarded. For example, for a model evaluation period of six years as in this study, the simulation will still be accepted, if in one year the minimum snow water equivalent is above zero in up to six elevation zones below the threshold elevation. It will also be accepted, if in all six years the minimum simulated snow water equivalent is above zero in only one elevation zone

below the threshold elevation, but if the number of elevation zones or years where snow accumulates is higher, the simulation is discarded. Second, no measured glacier mass balances are available for the Karadarya catchment, but based on measured mass balances in other catchments in Central Asia a wide range of $-1000\,\mathrm{mm\,a^{-1}}$ up to $+200\,\mathrm{mm\,a^{-1}}$ is set as a further constraint.

The model optimisation and parameter uncertainty analysis is performed using the DDS-AU algorithm (Tolson and Shoemaker, 2008). The analysis of parameter uncertainties is particularly important to investigate how much the calibrated precipitation bias factor varies between the best and other equally good parameter sets. The DDS-AU algorithm is an informal method (in contrast to formal Bayesian approaches) similar to GLUE (Generalised Likelihood Uncertainty Estimation, Beven and Binley, 1992), but instead of simple Monte-Carlo simulations, which usually result in a high fraction of runs very far from the objective function maximum, a number of short optimisation runs are started. These short optimisation runs are meant to get into the region of the parameter optimum, but the length of the optimisation run is also short enough that they mostly do not reach the objective function maximum. For each optimisation, 200 of these short DDS runs are started. The number of model evaluations in each DDS run (the length of the DDS run) is set randomly between three and seven times the number of calibration parameters resulting in 33 to 77 model evaluations. In order to assure that at least one very good parameter set is found one run with 3000 model evaluations is performed.

2.4.5 Sensitivity to inputs and parameters

Analysing the uncertainty in the calibration parameters only reveals a part of the uncertainty. In order to get a better understanding of uncertainties in further model inputs, we perform sensitivity analyses of inputs which were fixed based on literature, maps, and observed or modelled climate data and not changed during calibration. These inputs include the climate variables solar radiation, and wind velocity; the plant parameters plant height, rooting depth, stomata resistance, and the matrix potential values below

which transpiration is reduced or ceases; and soil depth (Table 5). Solar radiation, wind velocity and plant height directly influence the potential evapotranspiration. Root depth and soil depth determine the amount of soil water available to plants for transpiration. Minimum stomata resistance influences the potential transpiration rate, and the two matrix potential values determine how this rate changes with decreasing soil water. The model is recalibrated for each variation factor of each of the parameters listed in Table 5 varying one parameter at the time. This analysis is performed for all of the six subcatchments and all precipitation data sets, but in order to restrict computing time the analysis is constrained to one time period (1979–1984) and one long DDS run with 3000 model evaluations per subcatchment and precipitation data set (parameter uncertainties resulting from equifinality are not considered).

3   Results and discussion

3.1   Characteristics of the precipitation data sets

3.1.1   Point based evaluation

Comparison of downscaled ERA-40 precipitation data to observations

First, the precipitation data generated by downscaling the ERA-40 reanalysis data with WRF are evaluated relative to observed station time series. As this comparison can deliver information about the performance of the downscaled precipitation data at a few points in the catchment only, it is complemented by visual inspection of the spatial distribution of precipitation (Sect. 3.1.2). Large deviations in terms of volume and/or an unrealistic spatial pattern may indicate a priori, that in these areas the downscaled precipitation data are not suitable as input for water balance modelling or as spatial fields for the interpolation of station data.

For mean annual precipitation, the bias of the WRF downscaled ERA-40 data compared to the gauge observations in the study area is in the range of +20 % to −30 % (Table 5). There is no relationship of the bias with elevation. The squared correlation coefficients for daily time series only reach values around 0.3 for the stations at lower elevations and are even lower for the high elevation stations. Monthly precipitation time series from the WRF model at the station locations generally correspond much better to the station data, with squared correlation coefficients around 0.6. Nevertheless, large disagreements may exist for individual months or seasons, for example a strong overestimation in summer 1983 in Chaar-Tash, or a considerable underestimation in June 1981 in Kyzyl-Jar (Fig. 3).

The agreement between gauge and WRF precipitation data is similar to RCM applications in other mountainous regions. For example, Frei et al. (2003) studied the performance of five RCMs (CHRM, HadRM, HIRHAM, REMO, ARPEGE) at a resolution of 0.5° with boundary conditions from ERA15 in the European Alps. The bias of the areal mean of simulated precipitation ranged from +3 % to −23 % in winter and −5 % to −27 % in summer. Suklitsch et al. (2011) evaluated four high resolution (10 km) RCMs (WRF, MM5, REMO, CLM) driven by ERA-40 data over a simulation period of 1 yr and found bias values up to −50 % and +100 % for individual seasons and sub-regions of the Alps. Higher correlation values between observed and simulated time series at monthly as compared to daily resolution are typical (e.g. Hurkmans et al., 2008); this can be explained by the fact that only a part of the precipitation can be modelled deterministically, and errors from random processes partly average out on a monthly time scale.

Cross validation of interpolated precipitation data sets

The precipitation data sets interpolated from gauge observations using monthly fields from WRF downscaled ERA-40 data (WRFadj-all and WRFadj-ind), multi-linear regression (MLR-all and MLR-ind) and inverse distance weighting are also compared using leave-one-out cross validation. Generally this analysis shows large errors for the

stations Chaar-Tash in the north, Kyzyl-Jar in the east and Sary-Tash in the south of the catchment, while for the clustered stations to the west of the catchment, the errors are low (Fig. 4). In particular the methods MLR-all and MLR-ind strongly overestimate at the station Kyzyl-Jar by around 160 % and at Sary-Tash by around 35 % and 50 %, and underestimate at Chaar-Tash by approximately 35 %. By comparison, the method WRFadj-all shows a more balanced performance with bias values of 40 %, −7 % and +8 % at these three stations. The performance of the IDW method with respect to bias is between the methods MLR and WRFadj. Regarding the mean absolute error, the methods IDW and WRFadj-all have approximately comparable results with higher errors in Chaar-Tash of the method WRFadj-all and higher errors in Kyzyl-Jar of the method IDW. Both with respect to bias values and mean absolute errors, the performance of WRFadj and MLR with monthly fields averaged over all years ("-all") is similar or slightly better than the versions which use monthly fields for individual years ("-ind").

The low performance of the methods MLR-all and MLR-ind results from the fact that omitting a station from the interpolation changes both the mean monthly fields generated by linear regression and the adjustment factors for the particular day interpolated by IDW. Omitting the stations Kyzyl-Jar or Sary-Tash results in very different monthly regression fields, so that then IDW and WRFadj clearly outperform this method. The method WRFadj is similar to MLR, in that also first monthly fields are calculated, and second these are adjusted to daily stations values. However, as the precipitation stations are not used in the calculation of the monthly fields, this method shows a more robust behaviour, when individual stations are omitted.

3.1.2 Spatial distribution and temporal dynamics of subcatchment mean values for the different precipitation data sets

Despite only relatively small differences at the station locations, the precipitation data sets are very different with respect to their spatial distribution (Fig. 5). There are a few agreements, for example all precipitation data sets indicate relatively high precipitation

along the mountain ridge to the north and northeast of the catchment, and relatively low precipitation in the valley close to the station Kyzyl-Jar.

The precipitation data sets estimated by multi-linear regression show a strong increase of precipitation with increasing elevation; additionally precipitation also decreases to the south and to the east. The WRF downscaled ERA-40 precipitation data indicates spots with very high precipitation values in the southern part of the catchment. This is likely to be caused by the coarser topography and the poor representation of one of the mountain ridges in the southwest of the catchment (Fig. 2). Thus in the WRF model the valley in the southern part of the catchment is less sheltered from the wind than in reality, which might cause too high precipitation of the WRF model at this location.

The mean annual precipitation maps of the precipitation data set interpolated using monthly maps of the WRF precipitation (Fig. 5a, b) are very similar to the WRF precipitation map (Fig. 5c), with the main difference that in the former the precipitation at the station locations are closer to the observed values. The spatial distribution of precipitation in the IDW interpolated and the APHRODITE precipitation data sets both markedly differ from the other precipitation data sets in that they both indicate only very little precipitation in the southern and southeastern part of the catchment.

Naturally there is much more agreement among the different data sets in terms of the temporal dynamics, as all data sets except for the WRF data originate from the same station data. The subcatchment mean monthly precipitation data show a bimodal regime with a major peak in April/May and a minor peak in October (Fig. 6). There is a strong agreement between the different precipitation data sets for the three northern subcatchments; only the WRF downscaled ERA-40 precipitation data exhibit a slightly late seasonality with high precipitation also in June/July (Fig. 6, top row). In the three eastern and southern subcatchments, the different precipitation data sets still agree on the general seasonal distribution, but they strongly differ in the magnitude.

3.1.3 Comparison to global gridded data sets

Maps of mean annual precipitation from APHRODITE and GPCC show a very similar spatial distribution in the study area, with a distinctive precipitation maximum in the north. By comparison, the other two gauge based precipitation data sets UDEL and CRU indicate a much lower mean annual precipitation and only show a very weak precipitation increase to the north of the catchment (Fig. 7). In contrast to the gauge based data sets, the ERA-40 reanalysis data shows higher precipitation in the southern compared to the northern part of the Karadarya catchment.

The differences between the precipitation data sets applied in this study and global gridded data sets are clearly demonstrated in the values of the subcatchment mean precipitation (Fig. 8). If the precipitation data set MLR-all is used as a reference, UDEL and CRU underestimate precipitation by around −50 % and −60 % in the six subcatchments, for GPCC this varies from about −15 % in the two northern subcatchments to −50 % in Gulcha and Cholma, and for the ERA-40 the differences are about −50 % for the two northern subcatchments up to +20 % in Cholma.

As the number of stations included in the GPCC and APRODITE data in this region is higher than in CRU and UDEL, this is likely to be the cause for the differences between APHRODITE and GPCC on the one hand and CRU and UDEL on the other hand. The ERA-40 data are obviously too coarse to derive areal precipitation estimates for catchments of the size as in this study. The higher precipitation of the ERA-40 cells in the southern part of the catchment is probably caused by the higher elevation of these cells in the ERA-40 model. At this resolution smaller scale features such as the Fergana range in the north or the valley around Kyzyl-Jar in the west of the catchment cannot be represented.

3.2 Evaluation of the precipitation data based on simulated discharge

3.2.1 Parameter distributions and correlations between parameters

Parameter distributions for the best 20, 50, 100 and 150 parameter sets are shown as an example for one subcatchment, precipitation data set and calibration period (Fig. 9). Most importantly for this study, the precipitation bias factor is confined to a very narrow range, indicating that the problem of identifying the precipitation bias factor is well defined. For many other parameters, good models are achieved nearly over the whole parameter range. For example, the parameters k_sat factor, kf_corr factor and sat_area_var are not constrained at all. The remaining parameters are between these two extremes; while the best 150 parameter sets may still include parameters from the whole parameter range, the parameters are confined to a more narrow range, if one considers the best 20 or best 50 parameter sets only. As a consequence of this equifinality, i.e. the fact that very different parameter sets result in comparable model performances, unconstrained parameters can for example not be used for catchment characterisation, and it is not possible to transfer individual parameters to catchments with similar characteristics.

Scatter plots of parameter pairs for the best 50 or 150 parameter sets (not shown here) demonstrate that there are hardly any or only very low correlations between the precipitation bias factor and any other parameter. This is in accordance with the relatively narrow ranges of the precipitation bias factor after calibration. In some cases, there is a weak correlation of the bias factor to the glacier melt factor and to frac_riparian. Higher glacier melt increases the total runoff at the expense of a more negative glacier mass balance, and an increase in frac_riparian would result in a higher percentage of direct runoff thus decreasing actual evapotranspiration. The correlation to the glacier melt factor implies that it may be possible to further confine the precipitation bias factor, if glacier mass balance data were available to further constrain the glacier melt factor. However, due to the small glacier fraction and relatively high precipitation, glacier melt is only a small fraction of the total annual runoff so that the reduction

in the range of the precipitation bias factor is expected to be comparatively small for the catchment studied here. In other catchments where glacier melt accounts for a higher percentage of total runoff it may not be possible to constrain the precipitation bias factor to a narrow range without glacier mass balance data.

3.2.2 Objective function values and predictive uncertainties resulting from parameter uncertainties

Despite the differences between the precipitation estimates, most of the time they result in rather similar simulated discharge time series. This is also reflected in the objective function values (Fig. 10), which in many cases reach very similar values, both for the best and also for the best 20, best 50 or best 150 parameter sets. Most noticeable exceptions from this are the consistently lower values of the objective function values in the subcatchments Tosoi and Donguztoo for the model driven with WRF precipitation data; lower objective function values for the model driven with WRF precipitation data are also observed in Salamalik and Ak-Tash for 1979–1984 and 1985–1990. Additionally, some precipitation products result in lower objective function values at only few gauges and time periods: MLR-ind in Cholma 1973–1978, WRF-ind in Cholma 1979–1984, WRF-ind in Gulcha 1961–1966.

Lower objective function values of the model driven with WRF precipitation data may be explained by the difficulty of WRF to correctly predict the precipitation amount on a particular day (see comparison to observed gauge precipitation, Sect. 3.1.1). A possible reason why lower objective function values of the models driven with WRF data are predominantly observed in Tosoi and Donguztoo is the smaller size of these subcatchments. This results in less spatial averaging and smoothing of precipitation. Another possible cause is the higher percentage of rainfall in total precipitation due to the lower elevation of these two subcatchments. For snowfall the temporal dynamics of precipitation is less important for the temporal dynamics of discharge, as snow accumulates until the melting season.

In this study the uncertainty bands for the simulated discharge are meant to describe only the parameter uncertainties, i.e. the part of the total uncertainty caused by different parameter sets reaching equally good objective function values. If a higher number of parameter sets is included in the analysis, one also includes models with a clearly lower performance. For the subcatchment Salamalik considerably worse models are included, if the analysis is based on the best 100 parameter sets (Fig. 10, column 3). It is therefore decided to focus the evaluation on the best, best 20 and best 50 parameter sets. The width of the uncertainty bands based on the 50 best simulations is roughly half of the mean observed flow, and the uncertainty intervals include around 70 % of the observed discharge data in Tosoi and Donguztoo, between 50 % and 60 % in Cholma, around 50 % in Gulcha and between 35 % and 60 % in Salamalik. This shows that parameter uncertainties can only explain some part of the uncertainties and that a relevant part of the uncertainty is also caused by errors in the model structure and in the model input.

3.2.3 Variation of the precipitation bias factor by precipitation estimate, subcatchment and time period

For a well performing precipitation data set, the precipitation bias factor should be close to one, show little variability between different time periods and little variability between the different subcatchments. According to this, the two precipitation data sets based on multi-linear regression seem to be the most suitable precipitation estimates (Fig. 11). The corresponding precipitation factors are very close to one in all subcatchments, except in Ak-Tash, where there is an underestimation of 16 % to 41 %. Based on the variability between different time periods, the precipitation estimate MLR-all, which uses monthly regression estimates averaged over 1960–1990, should be preferred over MLR-ind, which uses monthly regression estimates from individual years, as the latter shows a higher variability in the subcatchments Gulcha and Cholma. The good performance of the discharge simulations with precipitation data interpolated by MLR-all and MLR-ind despite the low performance in the cross validation, is likely due

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to the fact that the gauging stations and thus also the results of the cross validation are not representative for the areal precipitation of the modelled subcatchments. If one is interested in areal precipitation estimates, cross validation can be misleading and an evaluation of different precipitation data sets using simulated discharge should be pre-ferred. On the other hand, the cross validation also indicates the dependence of this approach from individual stations with potentially strong changes to the interpolated precipitation, if individual stations are removed from the data set.

In contrast to the precipitation data sets interpolated by MLR, the direct use of WRF precipitation results in a precipitation bias which varies both between subcatchments and between time periods. For four of the subcatchments (Tosoi, Donguztoo, Salamalik and Cholma) the bias varies from precipitation underestimation in the early 1960s to overestimation in the early 1980s (Fig. 11, and more clearly visible for one subcatch-ment in Fig. 12), while there is a clear overestimation over all time periods in Gulcha and a clear underestimation over all time periods in Ak-Tash. The decrease of the bias factor indicates an artificial trend in the WRF downscaled ERA-40 precipitation data that is not consistent with the observed discharge data. Such trends in reanalysis data can result from changes in the observing system (Bengtsson et al., 2004). The over-estimation for the subcatchment Gulcha is likely to be at least partly caused by a too coarse topography in the WRF model, which results in the valley and mountain ridges to the west of this subcatchment being not well resolved (see Fig. 2).

Using spatial maps of WRF precipitation for the interpolation of gauge observations (WRFadj-all and WRFadj-ind) results in relatively low over- and underestimations for Tosoi, Donguztoo, Salamalik and Cholma, an underestimation of up to 30 % in Ak-Tash, and a stronger overestimation of 33 % to 50 % in Gulcha. WRFadj-ind and WRFadj-all result in much less variation of the precipitation factor between time periods than the direct use of the WRF precipitation. However, the overestimation in the southern part of the catchment remains. Due to the lack of precipitation gauges in this part of the catchment, this overestimation cannot be corrected by the combination of the spatial precipitation fields of WRF with observed precipitation time series. The variability of

the bias factor between time periods and between subcatchments is similar for the two precipitation estimates WRFadj-all and WRFadj-ind. However, due to the slightly lower objective function values for the period 1979–1984 in Cholma and Gulcha, WRFadj-all should be preferred to WRFadj-ind.

Thus, in all subcatchments except Gulcha we find WRFadj and MLR as the most suitable methods. Tobin et al. (2011), who estimated areal precipitation for two alpine catchments in Switzerland, found that kriging with elevation as external drift variable outperformed kriging with event accumulated precipitation from the COSMO7 downscaled reanalysis data. Due to the differences in the methods and study area, this study is not directly comparable to our study. However, one possible reason for the comparable performance of an interpolation method using downscaled reanalysis data compared to other interpolation methods in our study may be the fact that for the basin in Switzerland a larger number of stations was available, which probably allowed a better identification of the observed variability and the precipitation elevation relationship from the data, while methods using simulated precipitation fields from reanalysis data are particularly advantageous in situations where the variability of precipitation cannot be derived from the observed data.

The precipitation estimate based on interpolation of the observed data by IDW resulted in an underestimation of precipitation in all subcatchments. There is a strong variation of the bias factor between subcatchments, with values around 10 % in the subcatchments in the northern part (Tosoi, Donguztoo and Salamlik), around 95 % and 65 % in Ak-Tash and Cholma located in the west, and about 40 % in Gulcha located in the south of the Karadaya catchment. However, the variation of the precipitation bias factor between the different time periods remains low. The higher bias factors of the subcatchments Ak-Tash, Cholma, and Gulcha are probably caused by the fact that the precipitation gauges in this part of the catchment are located in less exposed positions (e.g. Kyzyl-Jar is located within a valley, and Sary-Tash, despite being located at a high elevation, is sheltered by higher mountains) so that the precipitation amount at these stations is not representative for the catchment precipitation. In contrast, there is

at least one precipitation gauge at an exposed mountain position in the northern part of the catchment (Chaar-Tash), and thus the measured precipitation amount is more likely to be representative for the areal catchment precipitation in Tosoi, Donguztoo and Salamalik.

The APHRODITE data also underestimate precipitation in all subcatchments. To some extent (probably around 10 %), the underestimation can be explained by the fact that for the APHRODITE data gauge observations are not corrected for undercatch errors before interpolation. In Ak-Tash, Gulcha and Cholma there is a relatively strong variation of the bias factor between the different time periods. This seems not to be due to a change in the number of stations used for the generation of the data set, as with respect to this region and time period the number of stations remains relatively constant.

3.2.4 Sensitivity of results with respect to uncertainties in inputs and parameters

In order to check how robust the results are with regard to changes in inputs and parameters that were not varied during model calibration (see Sect. 2.4.5), a sensitivity analysis is performed. Varying these inputs and parameters and re-calibrating the model has hardly any influence on the objective function values. This shows that the parameters can compensate for input errors. Changes in the precipitation bias factor are shown in Fig. 13. The boxplots summarise the changes in the precipitation bias factor for the seven precipitation data sets and six subcatchments. An increase in the precipitation bias factor of 0.1 in Fig. 13 would for example mean that a precipitation bias factor of 1.1 would change to 1.2, meaning that the respective precipitation data set underestimates precipitation by 20 % and not by 10 %. The largest uncertainties result from radiation, soil depth, root depth and wind speed. For these parameters the median changes in the precipitation bias factor are between ±0.03 and ±0.07, but changes can be up to 0.2 for individual precipitation data sets and subcatchments. Changes in temperature, plant height and stomata resistance have a lower influence

with median values of about ±0.03. Effects of changes in the matrix potential below which transpiration is reduced and in the matrix potential below which transpiration ceases are negligible.

In summary, uncertainties of the precipitation bias factor due to uncertainties in individual parameters and inputs are less than 0.2 and in most cases even less than 0.1. The combined uncertainties might be higher and different from simply additive – for example the effect of an increase in root depth would be higher, if the soil depth was increased at the same time. However, it is unlikely that the default estimates of all of the analysed climate, soil and plant inputs are biased in a way that they would result in the same direction of change of the precipitation factor.

4   Conclusions

This study indicates that spatial fields from downscaled reanalysis data can provide useful information for the spatial interpolation of precipitation data in regions where the spatial variability of precipitation cannot be derived from ground-based observations alone. The method depends on the assumption that the spatial variability is in general correctly represented in the downscaled reanalysis data. While this assumption cannot be fully validated, plausibility tests, like (1) inspecting the simulated precipitation fields for any conspicuous features, (2) checking that the major orographic characteristics of the region are also captured by the model orography and (3) the comparison of simulated and observed precipitation data at locations of available stations, were generally successful for the Karadarya catchment. In the southern part of the catchment, simulated precipitation tends to be overestimated due to mountain ridges to the west of this area that are not represented in the model orography. Compared to the direct use of the WRF downscaled ERA-40 data, hydrological modelling indicates a clearly better performance of the precipitation data set WRFadj, both with respect to the goodness of fit and with respect to the stability of the precipitation bias factor over different time periods. The evaluation by hydrological modelling further shows that, except for the

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subcatchment Gulcha, the method using monthly fields from WRF performs equally well as the best performing method for this area based on monthly fields from multi-linear regression. Besides, cross validation suggests that this method behaves more robust against omitting individual stations than the interpolation method which derives

5 the monthly fields from multi-linear regression.

Using a calibrated precipitation bias factor as an additional performance criterion for the evaluation of precipitation estimates by hydrological modelling allows a more informed differentiation between the precipitation data sets. For our case study, it is for example shown that the main difference between the precipitation data sets based on

10 interpolated station data is in the bias values, while the performance with respect to the time course is rather similar. The evaluation approach was further extended by an assessment of uncertainties resulting from the calibration parameters, other (usually fixed) model inputs and parameters, and different calibration periods.

Uncertainties in the calibrated bias factor resulting from parameter uncertainties and

15 from other model inputs and parameters are not very large and on average both in the order of 0.1, corresponding to a precipitation bias of 10 %. Thus, these uncertainties are often smaller than the differences between different precipitation estimates. This demonstrates the robustness of our results with respect to uncertainties in the calibration parameters and other model inputs and parameters. The evaluation of the

20 precipitation bias factor for different calibration periods revealed a variation of this factor between time periods for two precipitation data sets, the WRF downscaled ERA-40 data and the APHRODITE data. Ideally, the precipitation input to a hydrological model should have zero bias, but a bias which is largely constant over time could usually be handled for most applications. A variation of the bias factor over time could indicate in-

25 consistencies in gridded precipitation data sets (Mizukami and Smith, 2012). It shows that with these precipitation inputs the observed variability can only be captured by adjusting the precipitation bias factor. The fact that such a variation of the bias factor over time is not necessary for the other precipitation estimates suggests that this is caused by the precipitation input and not for example by changes in the catchment or deficits of

the model. Currently the bias factor represents a mean value over a calibration period. Future work should also investigate whether variations of this bias factor within this period, for example a seasonal variation, can be identified.

With respect to the Karadarya catchment, the different precipitation data sets show
5 very large differences for subcatchment mean precipitation. Based on our evaluation, the precipitation data set MLR-all, which uses monthly fields from multi-linear regression, is judged as the most suitable precipitation input for the studied headwater subcatchments of the Karadarya catchment. It shows good performance with respect to the objective function values – in common with all precipitation data sets based on
10 interpolated station data – low bias and only very small variations of the bias factor between different time periods. Our estimates of the precipitation input to these mountain subcatchments are considerably higher than those from continental or global scale gridded data sets. This demonstrates the large uncertainties in these data, if they are applied to small to mesoscale mountain catchments. This also has implications for
15 the use of these data for the evaluation or bias correction of regional climate models, applied for climate impact studies. If the focus is on areas with sparsely gauged mountain regions, all precipitation estimates based on gauge observations are afflicted with large uncertainties and an evaluation of the precipitation using hydrological modelling and observed runoff might provide more reliable information.

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Table 1. Area, glaciation, elevation range and mean annual runoff of the studied subcatchments of the Karadarya basin.

	Area (km^2)	Glacier (%)	Elevation (m)			Runoff (mm a^{-1})[*]
			min.	max.	mean	
Tosoi	222	0.0	1276	3009	1978	442
Donguztoo	173	0.0	1310	3271	1988	515
Salamalik	1136	0.5	1323	4187	2565	589
Ak-Tash	912	2.3	1746	4582	3106	792
Cholma	4178	1.9	1346	4709	3094	420
Gulcha	1086	0.7	1563	4227	2781	264

[*] Mean annual runoff over the period 1960–1990.

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Table 2. Overview of the precipitation data sets used in this study.

Abbrevation	Description
WRF	Precipitation from the ERA-40 reanalysis data downscaled using WRF to a resolution of 12 km.
WRFadj-ind	Station data interpolated using monthly precipitation maps of WRF, monthly maps from individual years.
WRFadj-all	Station data interpolated using monthly maps of WRF, monthly maps averaged over all years.
MLR-ind	Station data interpolated using monthly precipitation maps from multi-linear regression, monthly maps from individual years.
MLR-all	Station data interpolated using monthly maps from multi-linear regression, monthly maps averaged over all years.
IDW	Station data interpolated using the inverse squared distance method.
APHRODITE	Gridded observation based daily precipitation data set with a resolution of 0.25° (Yatagai et al., 2012).
GPCC v6	Gridded observation based monthly precipitation data set with a resolution of 0.5° (Schneider et al., 2011).
CRU TS 3.10.01	Gridded observation based monthly precipitation data set with a resolution of 0.5° (Mitchell and Jones, 2005).
UDEL 2.01	Gridded observation based monthly precipitation data set with a resolution of 0.5° (Legates and Willmott, 1990).
ERA-40	Precipitation data from the ERA-40 reanalysis data at a resolution of 1° (Uppala et al., 2005).

Table 3. Calibration parameters including values for the lower and upper bounds.

Routine	Parameter	Unit	Lower bound	Upper bound
Snow and glacier melt	snowmelt factor	$°C\,day^{-1}$	1	7
	melt temperature	$°C$	−2	2
	glacier melt factor	$°C\,day^{-1}$	0	7
Infiltration and percolation	kf_corr_f	–	0.01	100
	k_sat factor	–	0.01	100
Subsurface flow	frac2gw	–	0	1
	interflow delay factor	days	10	100
	groundwater delay factor	days	30	400
Generation of direct runoff from areas connected to the stream	frac_riparian	–	0	0.05
Spatial variability of saturated areas within a model unit	sat_area_var	–	0	0.3
Precipitation input	precipitation bias factor	–	0.5	2.0

Table 4. Climate, plant and soil inputs selected for the sensitivity analyses.

Input	Original value	Variation
Solar radiation	WRF downscaled ERA-40 data	Multiply original value by 0.7 and 1.3 (based on differences between the WRF downscaled ERA-40 data and satellite based data from the NASA Surface Radiation Budget (SRB) product, version 3.1, http://eosweb.larc.nasa.gov/sse/; mean seasonal differences over 1984–2001 are 21 % in spring and 12 % in summer)
Wind	Constant value of 2 m s^{-1}	Multiply original value by 0.5 and 2 (based on values of WRF downscaled ERA-40 data and available station data)
Plant height	Varies by land cover; e.g. grassland 30 cm	Multiply original value by 0.25 and 4
Root depth	Varies by land cover; e.g. grassland 20 cm	Multiply original value by 0.5 and 2
Soil depth	Varies by soil type between 35–140 cm; mostly 50–100 cm	Multiply original value by 0.5 and 2
Minimum stomata resistance	Varies by land cover; grassland 126 s m^{-1} (based on values from Körner, 1994)	Multiply original value by 0.5 and 2 (according to ranges as given in Körner, 1994)
Matrix potential below which transpiration is reduced (minsuction)	−600 hPa (according to values from Feddes and Raats, 2004)	Apply a value of −200 hPa and −15 000 hPa throughout the whole catchment
Matrix potential below which transpiration is only 1 % of the potential transpiration (maxsuction)	−15 000 hPa	Apply a value of −8000 hPa and −22 000 hPa throughout the whole catchment

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Table 5. Comparison of observed and WRF simulated precipitation at the station locations: bias, daily and monthly squared correlation coefficient calculated over the period 1960–1990.

Station	Elevation (m)	Bias (%)	r^2 month	r^2 day
Chaar-Tash	2748	18	0.53	0.29
Djalal-Abad	971	−16	0.61	0.28
Kyzyl-Jar	2230	−12	0.53	0.16
Sary-Tash	3155	10	0.41	0.16
Uzgen	1014	−31	0.65	0.32
Dzhergital	1198	−25	0.65	0.32
Gulcha	1542	3	0.69	0.27
Savay	753	4	0.58	0.28
Kara-Suu	866	2	0.64	0.32
Osh	887	10	0.59	0.30
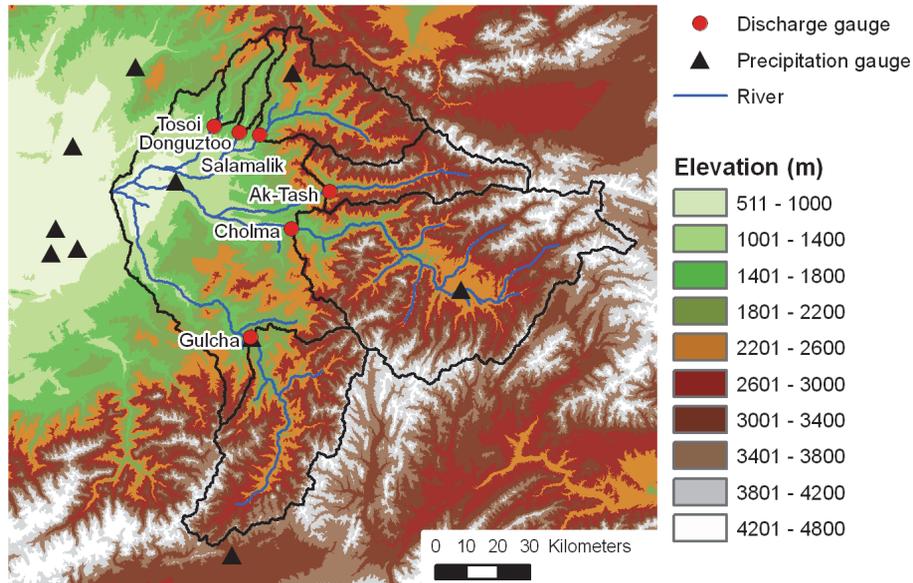
Fig. 1. The Karadarya basin upstream of the Andijan reservoir. Shown are the headwater sub-catchments where the hydrological model is applied (black outlines), and their corresponding discharge gauges (red dots), as well as the precipitation gauges (black triangles).

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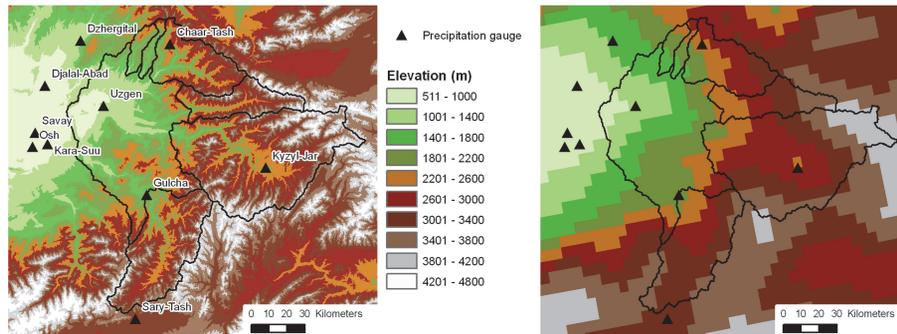
Fig. 2. SRTM elevation (left) and elevation in the WRF model (right) for the Karadarya basin. The black outline shows the Karadarya basin upstream of the Andijan reservoir with the studied headwater subcatchments, and the triangles indicate the precipitation gauges.

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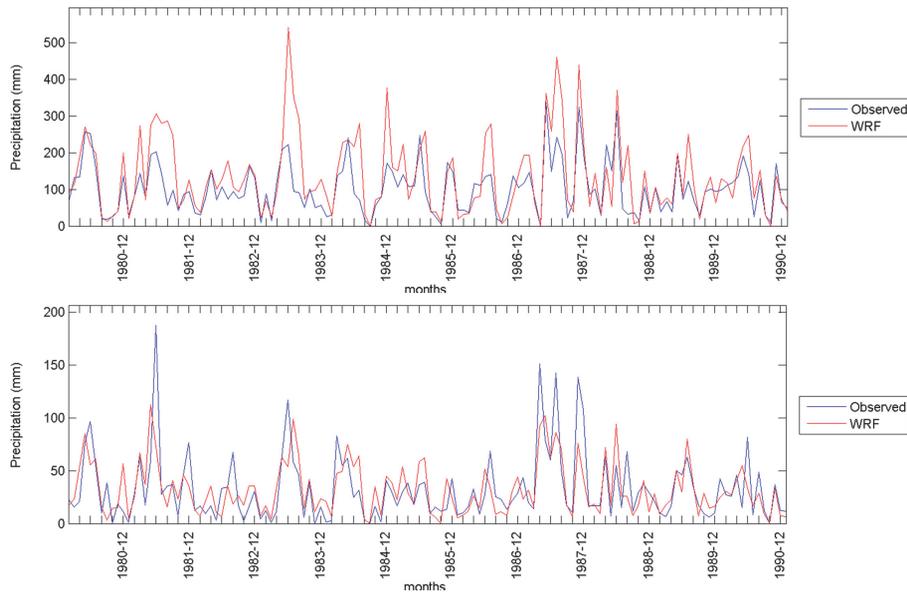
Fig. 3. Comparison of monthly time series over the period 1980–1990 of observed precipitation and WRF downscaled ERA-40 data at the gauge location for Chaar-Tash (top) and Kyzyl-Jar (bottom).
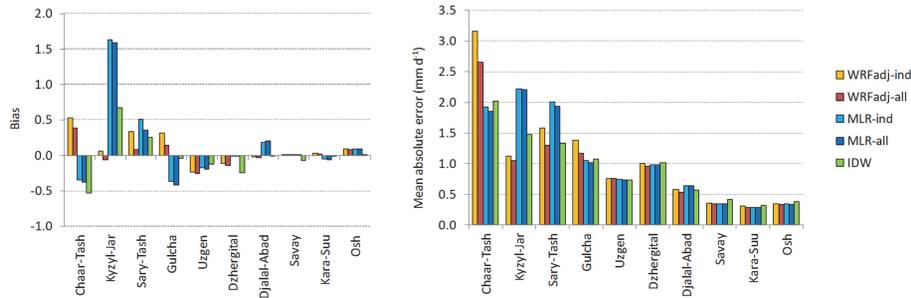
Fig. 4. Bias and mean absolute error calculated from cross validation for the interpolation methods WRFadj-all, WRFadj-ind, MLR-all, MLR-ind and IDW for precipitation stations in or close to the Karadarya catchment.
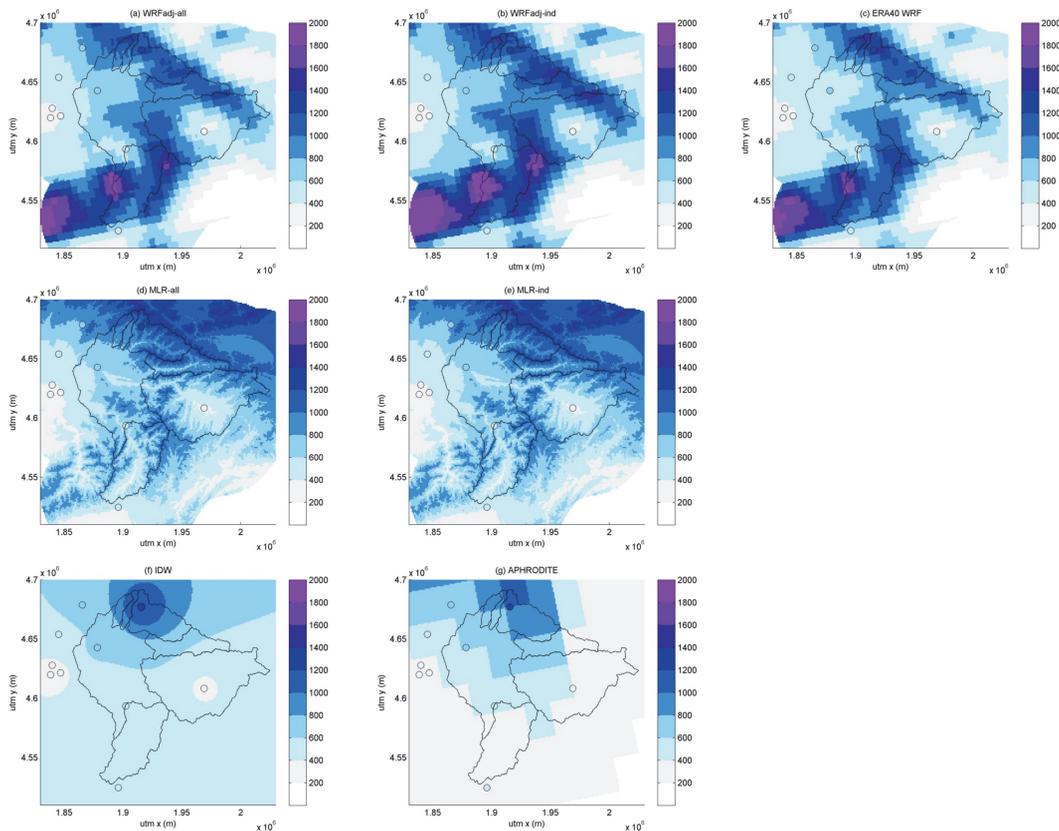
Fig. 5. Estimates of the mean annual precipitation (1960–1990; in mm a^{-1}) over the Karadarya catchment using different methods. The circles indicate the measured precipitation at the stations. The lines indicate the subcatchment borders.
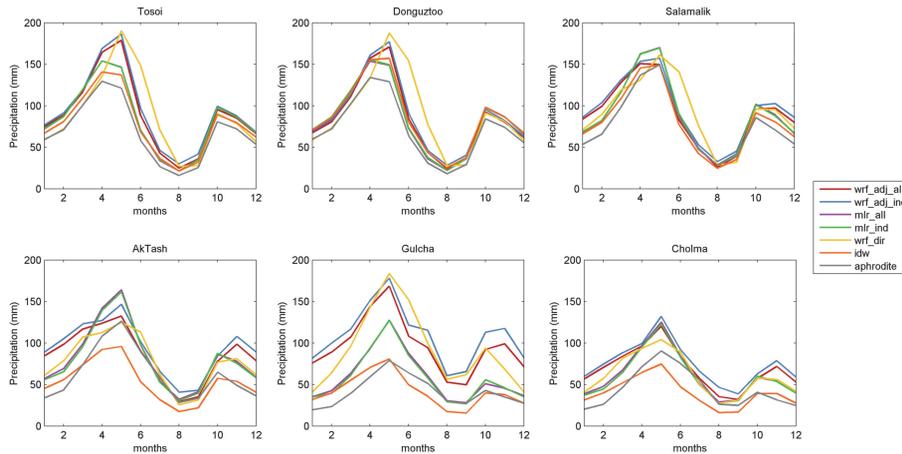
Fig. 6. Monthly subcatchment mean precipitation (1960–1990) for 6 subcatchments of the Karadarya basin and 7 different precipitation estimates.
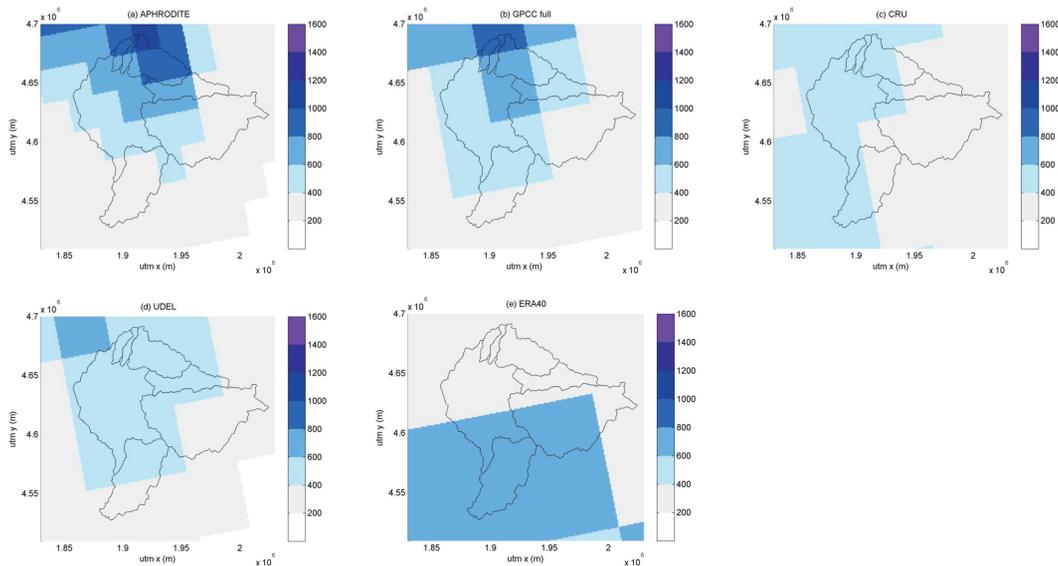
Fig. 7. Mean annual precipitation (1960–1990; in mm a^{-1}) for the Karadarya catchment from APHRODITE and four globally available gridded precipitation data sets GPCC, UDEL, CRU and ERA-40.

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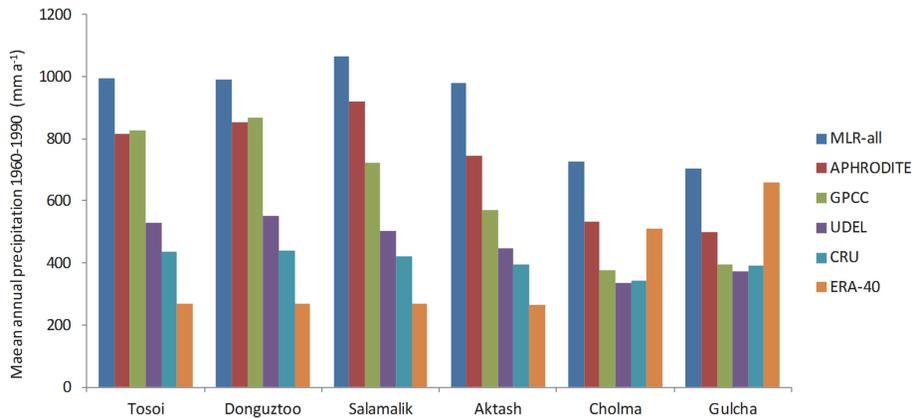
Fig. 8. Mean annual precipitation (1960–1990) for 6 subcatchments of the Karadarya basin for the precipitation data sets MLR-all, APHRODITE and four global precipitation data sets.
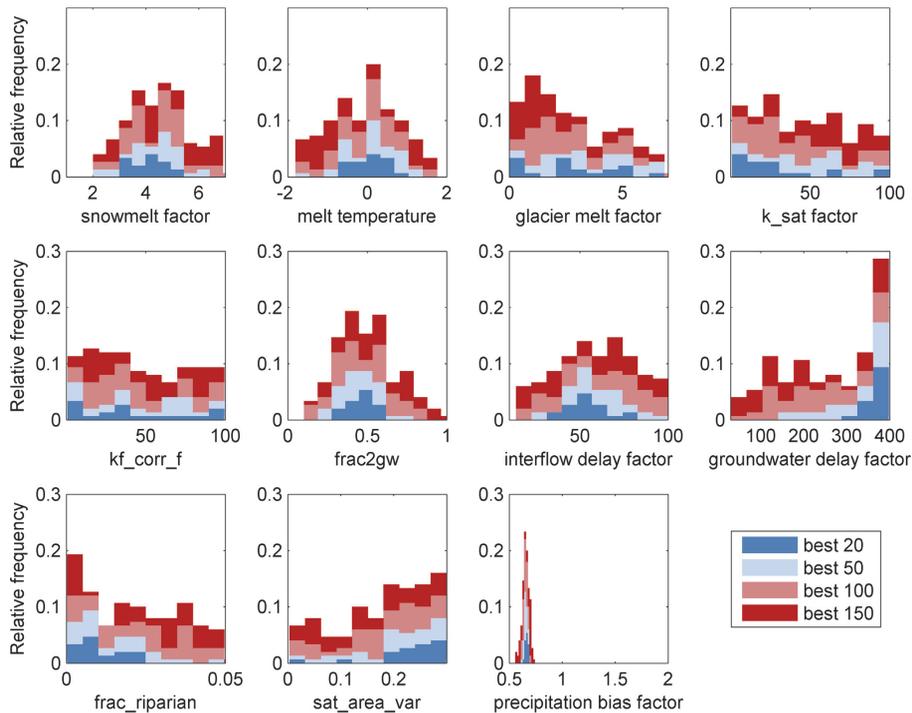
Fig. 9. Histograms of the parameter distributions for the best 20, 50, 100 and 150 parameter sets for the subcatchment Gulcha, precipitation estimate "WRF-all" and time period 1979–1984.
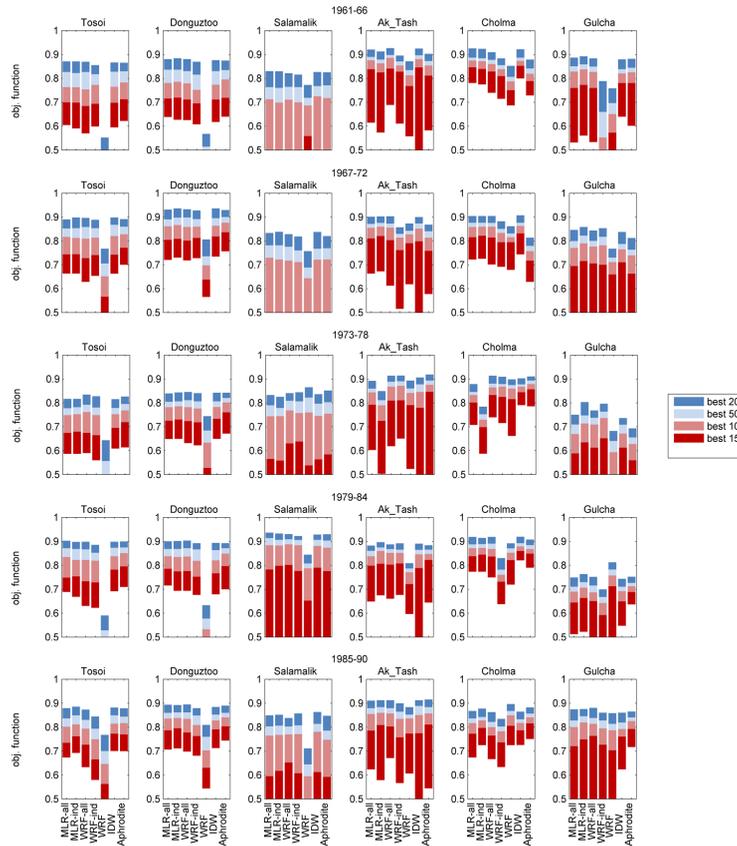
Fig. 10. Variation of the objective function values for different precipitation data sets (bars in each plot), different time periods (rows), and different subcatchments (columns). The colors indicate the range of objective function values for the best 20, 50, 100 and 150 parameter sets.
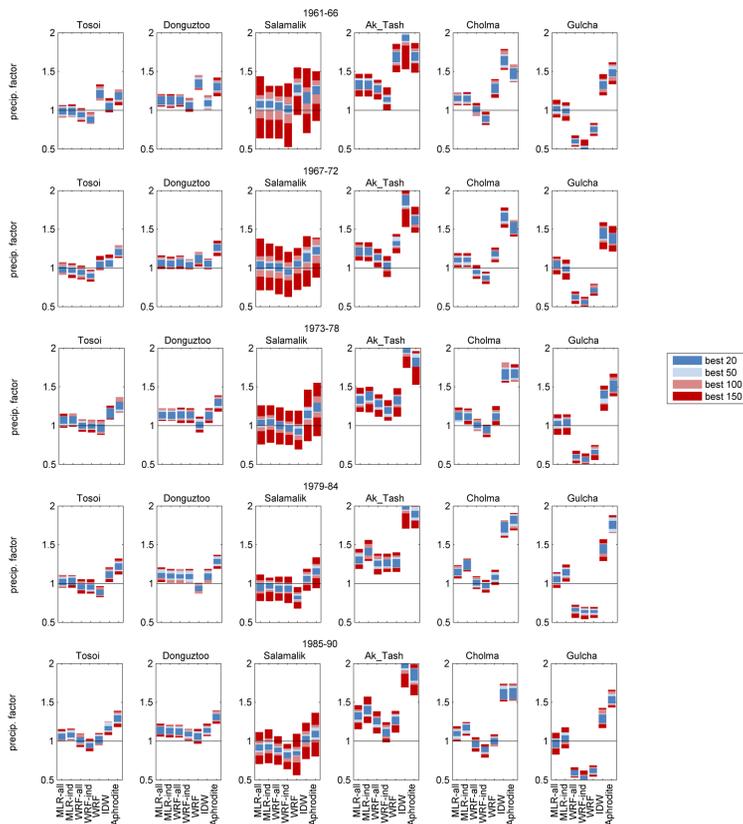
Fig. 11. Variation of the precipitation bias factor for different precipitation data sets (bars in each plot), different time periods (rows), and different subcatchments (columns). The colours indicate the range of the precipitation bias factor for the best 20, 50, 100 and 150 parameter sets.
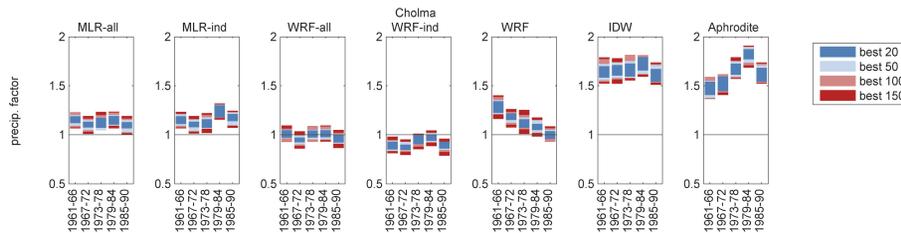
Fig. 12. Variation of the precipitation bias factor by time period for the subcatchment Cholma as an example. The data are the same as also shown in Fig. 11, but they are sorted in a different way in order to better demonstrate the variation by time period (particularly noticeable for the WRF and APHRODITE precipitation data sets).
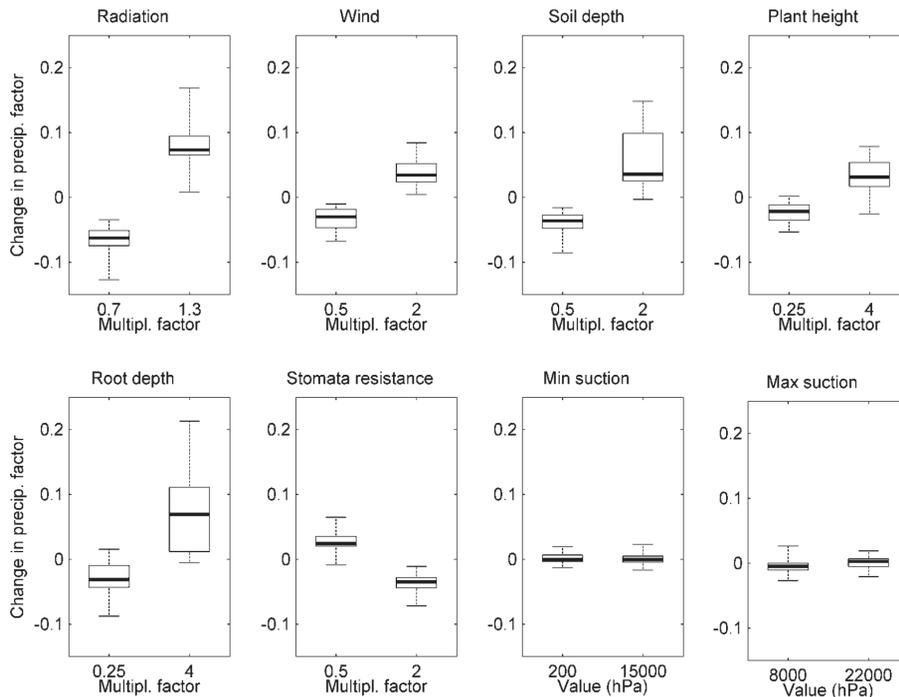
Fig. 13. Sensitivity analysis of the change in the calibrated precipitation bias factor as a result of changes in inputs and parameters for the time period 1979–1984. The boxplots show summaries of the results averaged over the six subcatchments and seven precipitation data sets with the thick black line indicating the median, the boxplot area the interquartile range and the whiskers the minimum and maximum change.