Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-326
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 17 August 2017

Hydrology and Earth System Sciences
Open Access
Discussions

Near real-time adjusted reanalysis forcing data for hydrology

Peter Berg[1], Chantal Donnelly[1], and David Gustafsson[1]

[1]Hydrology Research Unit, Swedish Meteorological and Hydrological Institute, Folkborgsvägen 17, 601 76 Norrköping, Sweden

Correspondence to: Peter Berg (peter.berg@smhi.se)

Abstract. Updating climatological forcing data to near current data are compelling for impact modelling, e.g. to update model simulations or to simulate recent extreme events. Hydrological simulations are generally sensitive to bias in the meteorological forcing data, especially relative to the data used for the calibration of the model. The lack of daily resolution data at a global scale has previously been solved by adjusting re-analysis data global gridded observations. However, existing data sets of this type have been produced for a fixed past time period, determined by the main global observational data sets. Long delays between updates of these data sets leaves a data gap between present and the end of the data set. Further, hydrological forecasts require initialisations of the current state of the snow, soil, lake (and sometimes river) storage. This is normally conceived by forcing the model with observed meteorological conditions for an extended spin-up period, typically at a daily time step, to calculate the initial state. Here, we present a method named GFD (Global Forcing Data) to combine different data sets in order to produce near real-time updated hydrological forcing data that are compatible with the products covering the climatological period. GFD resembles the already established WFDEI method (Weedon et al., 2014) closely, but uses updated climatological observations, and for the near real-time it uses interim products that apply similar methods. This allows GFD to produce updated forcing data including the previous calendar month around the 10^{th} of each month. We present the GFD method and different produced data sets, which are evaluated against the WFDEI data set, as well as with hydrological simulations with the HYPE model over Europe and the Arctic region. We show that GFD performs similarly to WFDEI and that the updated period significantly reduces the bias of the reanalysis data, although less well for the last two months of the updating cycle. For real-time updates until the current day, extending GFD with operational meteorological forecasts, a large drift is present in the hydrological simulations due to the bias of the meteorological forecasting model.

1 Introduction

Forcing data for large scale hydrological models are essentially not available in near real-time, and gridded observational data sets with near global coverage are generally only available at too coarse time steps. Current data sets that merge reanalysis and coarser observations are not available with regular updates, and often lack coverage of the recent years (Sheffield et al., 2006; Weedon et al., 2011, 2014; Beck et al., 2016).

The degree to which the skill of a hydrological forecast is sensitive to the initial hydrological conditions on one hand, and the meteorological forcing in the forecast period on the other hand, depends on factors such as the hydro-meteorological regime of the catchment and the memory of the hydrological system. The hydrological skill sensitivity to the initial state and/or the meteorological forecast varies as a function of the season, which have been shown for both seasonal and short term forecasts (Li et al., 2009; Shukla and Lettenmaier, 2011; Paiva et al., 2012; Demirel et al., 2013; Pechlivanidis et al., 2014). In most cases, however, hydrological forecast models are initialized by hindcast simulations covering some period before the forecast issue date, for which appropriate meteorological forcing data are needed.

Climatological hydrological simulations require consistent forcing data for a long period. Global observational data are often updated in discrete steps, and with several years delay. This can be an issue for impact modelling where up-to-date information is important, thus requiring a continuous updating of the forcing data, while retaining a consistent climatology.

Earlier methods (Sheffield et al., 2006; Weedon et al., 2011, 2014; Beck et al., 2016) have merged information from a re-analysis with temporally coarser observational data, to produce new data sets that inherit the temporal resolution of the re-analysis with the average properties of the observations. With these methods, long periods of daily or sub-daily resolution and global coverage become available for, e.g., large scale hydrological simulations. The various methods have applied different re-analysis data sets and observational records, and therefore differ in their final result. The more simple method is that of Weedon et al. (2014), where mainly single data sets are applied globally for the adjustment of each variable. Although this leaves the method highly dependent on the quality and availability of few data sets, it makes the method less affected by temporal and spatial inconsistencies between periods and regions.

Here, we present the GFD (Global Forcing Data) method for producing scaled meteorological forcing data sets for a near global domain. The novelty in the production of the data sets is the combination of reanalysis and operational global model input, as well as the combination of various observational data sources to fill the gap between the present and the end of the climatological products. We evaluate the updating procedure to the climatological data by direct comparison of the meteorological data, as well as by employing a hydrological model to evaluate the data sets. The main motivation for creating the data set is to update climatological simulations, but also to improve the initialisation for hydrological forecasting at large scales or in data sparse regions where dense observational data are not available for initialisation. We present evaluation of two such applications for the Arctic and European set-ups of the hydrological models E-HYPE and Arctic-HYPE.

2 Methods and Data

The GFD method is currently intended to be a substitute and extension of the WFDEI method (Weedon et al., 2011), which is currently used in many hydrological simulations with HYPE (Lindström et al., 2010) and other hydrological models. We are therefore mimicking the WFDEI set-up closely, however, with some necessary differences due to updates of the meteorological observations since the first appearance of WFDEI. GFD is adjusting precipitation and temperature at three and six hourly fields, respectively. The basic method is to, for each calendar month, construct monthly mean adjustment factors for each variable and to adjust every time step during the month with that factor. For temperature, the adjustment factor is produced by subtracting the monthly mean reanalysis from the observations, and adding this to every time step of the reanalysis. For precipitation, a first step of adjusting the number of wet days is performed. The underlying assumption is that the reanalysis model produces excessive light rainfall (drizzle). Days with the least amount of rainfall that are in excess to the observed rainy days are set to

Table 1. Table of model and data sources used in the analyses.

Data set	Variables	Resolution	Period	Reference
ERA-Interim (EI)	T, P	~0.8°	1979–(t-3 months)	Dee et al. (2011)
ECMWF-OD (OD)	T, P	~0.22°	2010–present	
CRUts3.22	T, P, wet-day*	0.5°	1901–2013	Harris and Jones (2014)
GPCC7	P	0.5°	1901–2013	Schneider et al. (2015b)
GPCC-Monitor (v5)	P	1.0°	1982–(t-2 months)	Schneider et al. (2015a)
GPCC first guess (FG)	P**, wet-day***	1.0°	2009–2013	Ziese et al. (2011); Schamm et al. (2013)
GHCN-CAMS	T	0.5°	1948–(t-1 month)	Fan and Van den Dool (2008)

* Gridded from SYNOP stations. ** Using the GPCC First guess monthly product

*** Derived from daily time-step information from the GPCC first guess daily product.

zero. In a second step, the ratio between the monthly mean observations and the reanalysis data is calculated and used to scale the reanalysis data.

The GFD system has been applied to produce the main climatological dataset called GFDCL, which is an equivalent to the WFDEI (Weedon et al., 2011) dataset except for updated climatological observations (see Tab. 2) and differences in the implementation. GFD, like WFDEI, is based on the ERA-Interim (EI) reanalysis but is coded so that EI can be interchanged with other reanalyses. Precipitation is corrected for wet day bias compared to CRUts3.22 wet day information, and scaled with monthly precipitation from GPCC7 (see Tab. 1). Temperature was corrected additively with CRUts3.22 monthly mean temperature. The GFD data set is restricted to the time period 1979–2013, due to the start of the EI reanalysis period, and by the end of the GPCC7 (Schneider et al., 2014) observational data set. The main difference of GFDCL and WFDEI arises from the treatment of under-catch, i.e. the rainfall likely not captured by the rain gauges due to turbulence around the gauge. WFDEI applied the Adam and Lettenmaier (2003) under-catch correction to the GPCC5 and GPCC6 data sets. With GPCC7, under-catch correction is already included in the data set, and need not be applied in the GFD methodology. However, for GPCC7, the under-catch correction was based on Legates and Willmott (1990), but reduced by 15% to better fit with their own estimates (Schneider et al., 2014). Adam and Lettenmaier (2003) compared their method with that of Legates and Willmott (1990) and found the latter to lead to too low precipitation amount by about 5–30%, and differences in the annual cycle of the correction factors. There is clearly a large controversy in how much under-catch to expect. We therefore expect differences between GFDCL and WFDEI in both annual totals and in the annual cycle.

Two flavours of GFD are produced to extend the period past year 2013 (see Tab. 2 for data sets and references):

1. GFDEI consists of the EI data set with precipitation scaled by the GPCC monitoring data set and wet day adjusted according to the GPCC first guess daily product. Temperature is adjusted with the GHCN-CAMS data set.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-326
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 17 August 2017

Table 2. Table of meteorological forcing data used in the analyses and hydrological simulations.

Abbreviation	Atm. model	Precipitation	Wet days	Temperature	Period
GFDCL	ERA-Interim	GPCC7	CRUts3.22	CRUts3.22	1979–2013
GFDEI	ERA-Interim	GPCC monitoringv5	GPCC first guess daily	GHCN-CAMS	2010–2013
GFDOD	ECMWF-OD	GPCC first guess monthly	GPCC first guess daily	GHCN-CAMS	2010–2013
OD	ECMWF-OD	NA	NA	NA	2010–2013

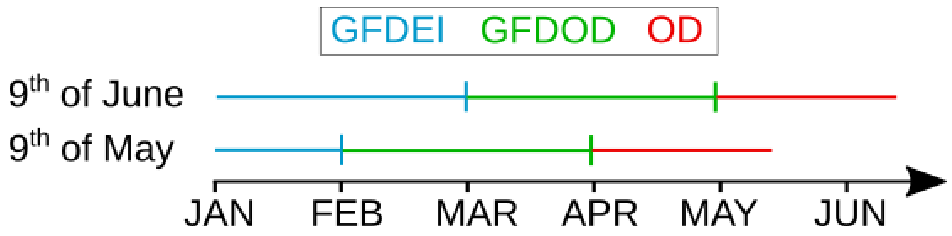

Figure 1. Schematic of the updating procedure. The GFD data are continuously updated with GFDEI as long as EI data are available. The intermediary data set GFDOD fills up the time series as long as GPCC data are available, and then continues with uncorrected OD data. Because the previous month becomes updated on the 10^{th} of each month, the 9^{th} is the day with the longest period of OD driving data. The next month, GFDEI is extended one month, and the GFDOD data are updated for the new month.

2. GFDOD consists of the ECMWF deterministic forecast, which differs from EI by mainly the model version and the assimilated data. Precipitation is scaled by the GPCC first guess monthly data set and wet day adjustments according to the GPCC first guess daily product. Temperature is adjusted with GHCN-CAMS data.

GFDEI fills the gap between the end of GFDCL in 2013 until the latest available EI data, i.e. until about three months ago. For the last two months, GFDOD is used to fill the gap. The necessary datasets are all available for download around the 10^{th} in each month. Fig. 1 shows a schematic for the update procedure. E.g., on the 9^{th} of May, the available GFDEI data extends until the end of January and the GFDOD data until the end of March. Thereafter, the ECMWF deterministic model, without adjustments, fills the gap until the present day. Therefore, the 9^{th} is the day of the month with the longest period of non-adjusted data. At the 10^{th} of May, new observational data arrive, and both GFDEI and GFDOD are extended by one month. The period of non-adjusted data then shrinks to ten days. In a hydrological forecasting context, the simulations are updated from the GFDEI data, which is the continuous extension of GFDCL, and the GFDOD and OD parts are re-run after each update to determine the new initial conditions.

Because the observational data sets only provide information over land areas, the GFD system only produces adjustments where data is available, and retains the original reanalysis, or deterministic forecast, when no data is available. On notable exception is Antarctica, which is not covered by the observational data sets, and is therefore not adjusted at any step of the updating procedure.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-326
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 17 August 2017

Hydrology and Earth System Sciences Open Access Discussions

2.1 HYPE model

The HYPE (Hydrological Predictions for the Environment) model is a processed based hydrological model developed for high-resolution multi-basin applications, which has been applied at various spatial scales (from tens to million square kilometres) and hydro-climatological conditions (Lindström et al., 2010; Strömqvist et al., 2012; Arheimer et al., 2012; Andersson et al., 2015; Gelfan et al., 2017). The model is based on a semi-distributed approach where the hydrological system is represented by a network of sub-basins, which are further divided into classes that can be selected to represent combinations of soil-type and land-cover or elevation zones. The water balance and runoff from each sub-class is calculated taking into account processes such as snow and glacier accumulation and melt, infiltration, evapotranspiration, surface runoff, tile drainage and groundwater recharge and runoff. The runoff from the land classes is further routed through the network of lakes and rivers represented by the sub-basin delineation. The model is used for research and operational purposes, to provide information for, for instance, flood and hydro power reservoir inflow forecasting, river discharge and nutrient loads to the ocean, as well as assessment of climate change impact on hydrological systems.

To evaluate the real usefulness of the GFD data in hydrological forecasting, the GFD data was tested in two continental scale applications of HYPE. For Europe, the E-HYPE v3.2 (Hundecha et al., 2016) hydrological model was calibrated with GFDCL and employed to evaluate the updating versions of GFD. The simulation domain ranges from wet Arctic, wet maritime to dry Mediterranean climatic conditions. The E-HYPE model has been shown to reproduce well the spatial and temporal variability in hydrological processes across Europe (Donnelly et al., 2016), and has been identified as a useful model for continental scale forecasting (Emerton et al., 2016). E-HYPE takes daily mean precipitation and temperature as input. Potential evapotranspiration is estimated from daily mean temperature and extraterrestrial radiation estimated separately for each sub-basin location and day of the year using the modified Jensen-Haise/McGuiness model following Oudin et al. (2005). For each sub-basin, air temperature and precipitation is taken from the nearest GFD grid point. Temperature is further corrected with a constant lapse rate (-0.65 $^{\circ}C/100\ m$) for the difference between the mean sub-basin elevation and the corresponding elevation of the GFD grid point. Elevation correction of precipitation is also possible in the HYPE model, but it is not used in E-HYPE.

For the Arctic, we use the Arctic-HYPE model v3.0 (Andersson et al., 2015; Gelfan et al., 2017) that covers the land area draining into the Arctic Ocean (excluding Greenland). The model domain is 23 million km^2 divided into 32599 sub-basins with an average size of 715 km^2. The Arctic region is characterized by numerous lakes of various size (5% areal fraction) and glaciers (about 50% of the glaciated area outside the Greenland and Antarctica Ice sheets, mainly on islands in the Canadian Arctic archipelago, Svalbard, and Russian Arctic islands) (Dyurgerov and Meier, 1997; Meier and Bahr, 1996). To take into account the long turnover times of larger lakes in the domain (for instance Lake Baikal) and the on-going decline in glacier volume, the Arctic-HYPE model was initialized using an initial spin-up period for the period 1961–2010 using the WFD data (Weedon et al., 2011) with a simplified correction of precipitation versus GPCC7 on a monthly basis, to be consistent with the GFDCL data, and extended using GFDCL for the period 1979-2013. As for E-HYPE, Arctic-HYPE is forced by daily mean precipitation and temperature, but in contrast to E-HYPE, potential evapotranspiration is calculated using the Priestly-Taylor equation assuming it to be more representative for the wide range of climatic conditions in the Arctic-HYPE domain. The

Priestly-Taylor equation requires solar radiation and relative humidity, which was estimated using the minimum and maximum daily temperatures as additional input variables, following the recommended procedures by Allen et al. (1998).

Both E-HYPE and Arctic-HYPE models have been parametrized and calibrated with similar step-wise approaches involving first of all sub-basin delineation based on globally available digital elevation data (USGS HydroSHEDS and Hydro1K). Secondly, classification into selected land-use and soil type classes based on land cover and soil data such as the ESA CCI Land cover or CORINE, and HWSD respectively. Thirdly, model parameters governing water balance processes in ice/snow, soil, lakes and rivers were thereafter calibrated in an iterative procedure using river discharge data from the Global Runoff Data Center (GRDC), as well as data on internal water balance components such as snow (ESA GlobSnow and Former Soviet Union Snow course data), glaciers (glacier area and mass balance data from ESA CCI Glacier and the World Global Monitoring Service), and evapotranspiration (fluxtower data from FluxNet and MODIS Evaporation products).

For the evaluation simulations with GFD products, the models are run once per month from 9^{th} of May 2010 to 9^{th} of December 2013, to recreate a 130 day initialization simulation for each run, ending on the given date. This is the longest possible initialization step, as the meteorological forcing data are updated at the 10^{th}, for which the initializations would advance one calendar month (Fig. 1). The first simulation starts from a saved state of the GFDCL simulation in January 2010, and each subsequent run is initialised from a starting state saved from the GFDEI portion of the previous simulation; making the GFDEI simulation continuous in time. A total of 44 simulations are made with each hydrological model. The simulations are then compared with a climatology simulated using GFDCL forcing for each region for the same period 2010–2013.

3 Results

We begin with evaluating the GFDCL data set, as well as comparing differences between the various GFD versions. Thereafter, we present analysis of hydrological simulations for Europe and the Arctic.

3.1 Meteorological evaluation

Climatology 1979–2013: GFDCL is directly comparable to the WFDEI data set due to the very similar method. Because WFDEI was on several occasions evaluated against flux tower measurements across the globe (Weedon et al., 2011, 2014; Beck et al., 2016), we do not repeat such evaluation for GFDCL here, and focus instead on comparisons to the WFDEI data set.

The baseline reanalysis data set EI has both wetter and drier regions compared to GPCC7, with biases towards $\pm 100\%$ that cover large regions (Fig. 2b). Overall, the wetter regions are dominating. Here, we note especially the wet bias throughout the Arctic (excluding Greenland), and mainly slightly wet bias in continental Europe. Corrections with GFD reproduces GPCC7 well (Fig. 2c), as practically per definition of the method. There are some isolated patches with underestimated precipitation, mainly in the dry regions of the Sahara desert and southern Arabic Peninsula, which appears because no scaling is possible for single months with a complete lack of precipitation in EI at these locations. In contrast to GFDCL, WFDEI has a general wet

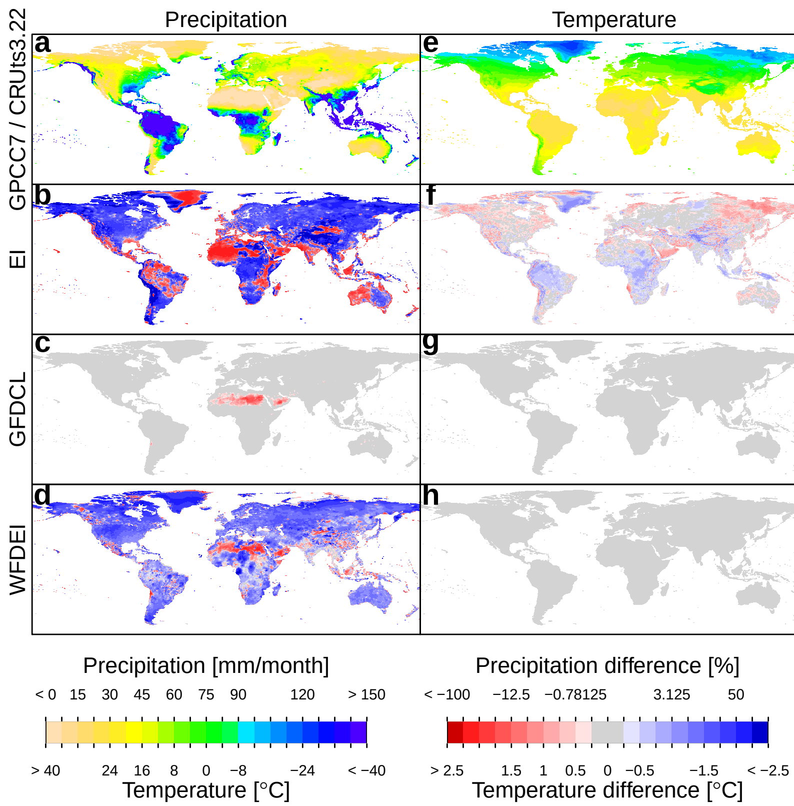

Figure 2. Climatological mean (top) precipitation and (bottom) temperature for the years 1979–2013 for (a) GPCC7, and (e) CRUts3.22, as well as the relative difference EI, GFDCL, and WFDEI. Note the non-linear colour scale for the relative differences, and the reversed scales for temperature for a more intuitive colour scale..

bias when compared to GPCC7 (Fig. 2d). The wet bias is explained mainly by stronger under-catch corrections included in WFDEI, as explained in Section 2.

Temperature bias in EI is low ($<0.5\ ^{\circ}C$) for most land areas (Fig. 2f), but there are regions with considerable bias. There is a mostly warm bias of partly several degrees Celsius in the Arctic regions. Europe has a low bias, except for Scandinavia, which shows a warm bias. Both GFDCL (Fig. 2g) and WFDEI (Fig. 2h) correct the bias per definition, and are both indistinguishable at $0.25\ ^{\circ}C$ accuracy, even though different versions of CRU were employed (GFDCL: CRUts3.22; and WFDEI:CRUts3.1 for 1979–2009, CRUts3.21 for 2010–2012, and CRUts3.23 for 2013).

In summary, GFDCL is methodologically similar to WFDEI and differences in the results are mainly due to the different precipitation source used.

Evaluation of updating method (2010–2013): To evaluate the updating method of the GFDEI and GFDOD datasets, we investigate differences in bias for the period 2010–2013 when all data sources are available (see Tab. 1). The only methodological difference between GFDEI/OD and GFDCL is the calculation of the number of wet days in a month. Whereas the latter

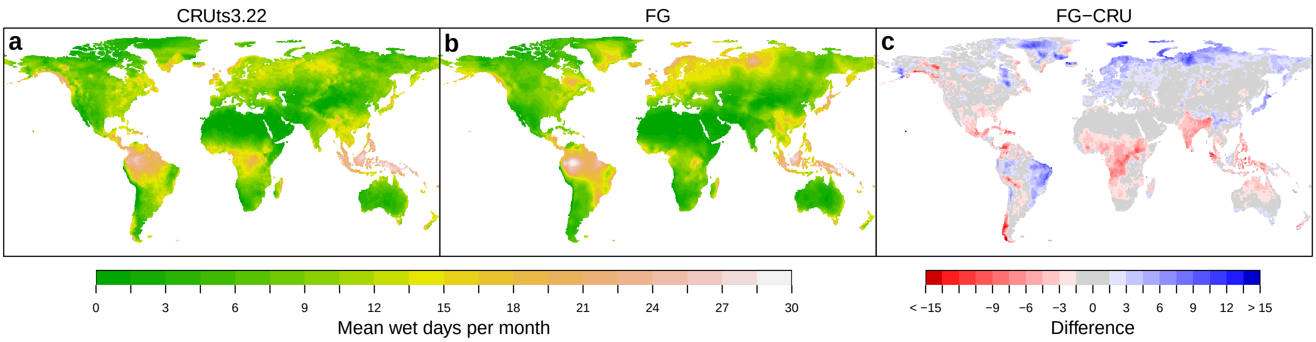

Figure 3. Comparison of the number of wet days provided by (a) the CRUts3.22 data set, compared to those derived from (b) GPCC-FG, and (c) the difference between the two for the period 2010–2013.

uses gridded station measurements of the number of wet days from CRUts3.22, the former data sets have the number of wet days calculated from the GPCC-FG daily product as the number of days in a month with precipitation larger than or equal to 1 mm/day. Fig. 3 presents the period average number of wet days in a month for CRUts3.22 and GPCC-FG. The two methods to calculate wet days differ significantly for Europe and especially the Arctic part of Scandinavia and western Russia, where the updating method overestimate the number of wet days. The updating method also produce underestimations in Africa, Latin America and the Andes. An interesting difference is markedly confined within the political borders of India, which implies a difference already in the observations entering either CRUts3.22 or GPCC-FG, and could be an artefact of a higher station density in that region compared to surrounding regions.

Fig. 4 shows the bias between the different data sets used here, such that the data set given at the top of the plot is compared with that named to the left of each row. In the first row (Fig. 4a–d), all data sets are compared to GPCC7. Clearly, GPCC-Monitor and GPCC-FG both underestimate precipitation for most parts of the globe compared to GPCC7. This is partly due to the lack of under-catch correction, but differences may also result from lower station density, as not all stations are available in real-time. The latter effect can be seen in the different bias patterns for GPCC-Monitor and GPCC-FG (Fig. 4a and b, respectively), and also in the difference between GPCC-Monitor and GPCC-FG (Fig. 4e). The extension of the GFDCL data set is mainly through the GFDEI product, which is adjusted by GPCC-Monitor, and the GFDOD product is mainly used interim to bridge the data gap for initializations of forecasts. GFDEI has a similar spatial structure as GPCC7, with some marked regional differences, but a general reduction of a few percent in total precipitation is seen. EI has a similar bias as for the climatological period (compare Fig. 4c and Fig. 2b). The bias of GPCC-Monitor shrinks in significance when compared to that of EI, which means that the extension of GFDCL with GFDEI is indeed relevant when extending the climatological data set for, e.g., hydrological applications.

OD has a similar bias as EI when compared to GPCC7 (Fig. 4d), however, also clear differences although of lower magnitude appear in a direct comparison of OD and EI (Fig. 4j). The main differences are confined to the tropical regions, however, the

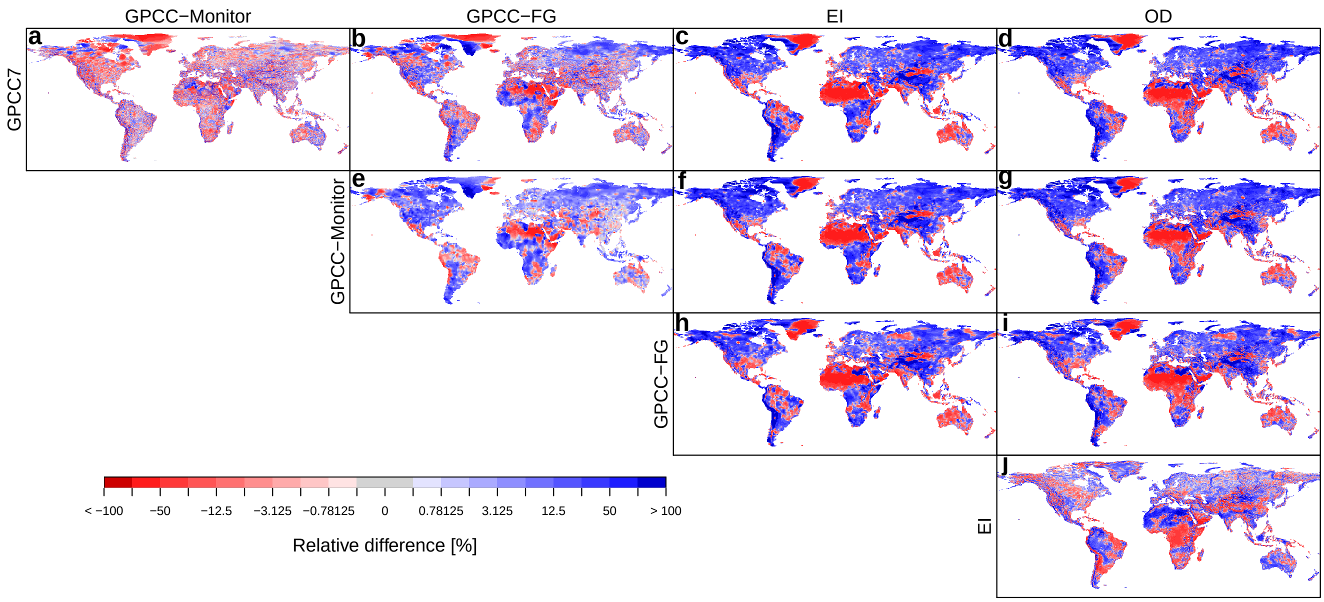

Figure 4. Relative difference of mean monthly precipitation between different data sources and (a–d) GPCC7, (e–g) GPCC-Monitor, (h–i) GPCC-FG, and (j) EI. Note the non-linear colorscale for the biases.

bias of OD is much more prevalent than that of GPCC-FG, which indicates value in the interim GFDOD product. GFDEI and GFDOD retains the average bias of the GPCC-Monitor and GPCC-FG products, per definition (not shown).

Temperatures are compared between the data sets GHCN-CAMS, EI and OD toward CRUts3.22 (not shown). The main differences are in the Arctic, especially for Greenland, and for various mountain ranges and coastal areas, with magnitudes of several degrees Celsius. EI and OD have similar bias for most of the globe, although OD has a larger warm bias in the Arctic and northern Europe.

3.2 Hydrological evaluation

Evaluation simulations are performed both for E-HYPE and Arctic-HYPE in the following procedure. First, a climatological simulation driven by GFDCL is carried out for the years 2010–2013, starting from a saved model state the $10^{t}h$ of January 2010. Second, a set of simulations separated by one calendar month was carried out for the period 10^{th} of May 2010 until 10^{th} of November 2013. Each of the simulations start from GFDEI for the first month, continue with GFDOD for two months, and then OD for one month and ten days (see Fig. 1). The model state of the last day of the GFDEI simulation is saved and used for the initial state of the next month's GFDEI simulation. When nothing else is stated, the evaluation is performed with day one at the first day of the GFDEI until the last day of the simulation, which is approximately day 130. In the figures we mark with colours as in Fig. 1 the different forcing data periods approximated by 30 day months to indicate which data set was used.

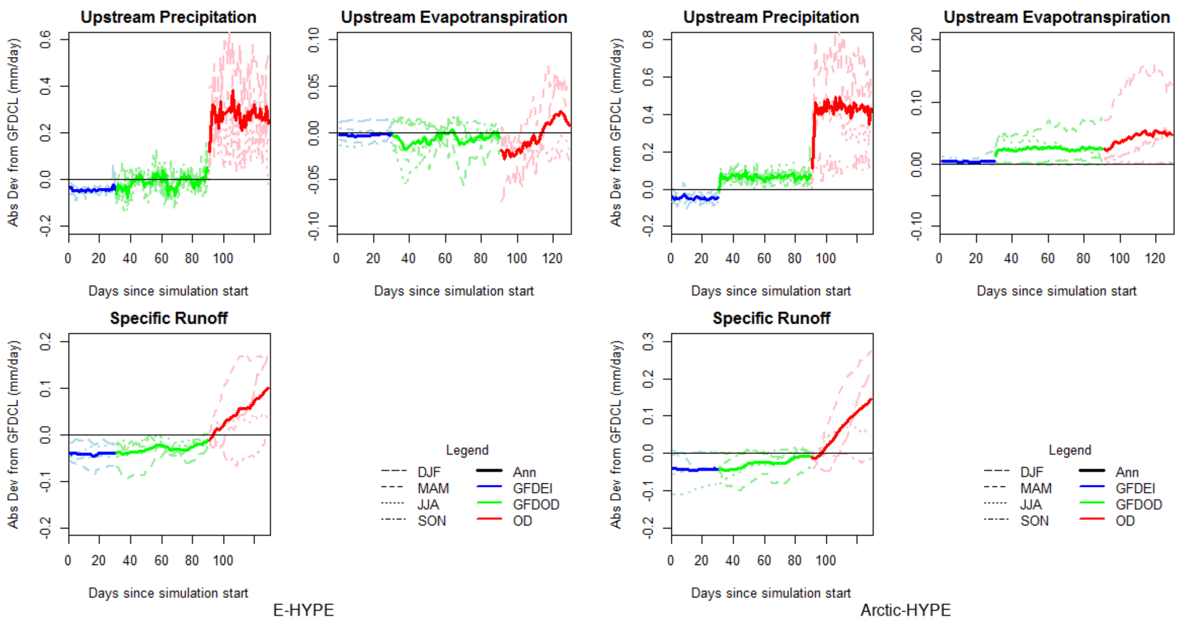

Figure 5. Upstream precipitation, evapotranspiration and specific runoff averaged over all catchments and shown for all forecast times as well as per season. All runs are presented as deviations from the GFDCL forced simulation.

The impact of the differences in the GFDEI, GFDOD and OD data sets compared to the reference GFDCL simulation are shown as an average across the respective simulation domains in Fig. 5. The specific runoff shows lower values for GFDEI and GFDOD for both domains. Clearly, the main determining factor for the differences arise from the differences in upstream precipitation from the first 30 days with GFDEI. Even though GFDOD has less of an offset from GFDCL, and for the Arctic even a positive difference, the GFDEI offset causes a slow drift toward the new conditions of GFDOD, and therefore a remaining negative offset for the first about 90–100 days. Upstream evapotranspiration shows a low offset from GFDCL for GFDEI, which shows that the GHCN-CAMS and CRUts3.22 data sets are similar for these two domains. However, although the same data set is used for GFDOD, there is a larger offset for this period. The difference in upstream evapotranspiration offsets between the two model domains is most likely a result of the larger (and positive) offset in upstream precipitation for the GFDOD and OD periods in the Arctic-HYPE domain, rather than the smaller differences in temperature. OD has a strong wet precipitation bias (Fig. 4d), which is on a much larger magnitude than that of GFDEI. The bias causes the slow drift of the specific runoff to accelerate around day 90–100, as the model adjusts to the new precipitation average. The case is similar for both domains. Another striking feature from Fig. 5 is the larger variability for GFDOD and OD, compared to GFDEI, which is due to differences between EI and OD. This affects the dynamics of the simulations, but not the water balance.

Fig. 5 shows also results per season. For both Europe and the Arctic, precipitation and runoff biases are largest for the OD forced period in DJF and MAM, and relatively minor in JJA and SON. Seen as a continental mean, there is little variation in the biases between individual years, meaning that the results are robust in time (not shown).

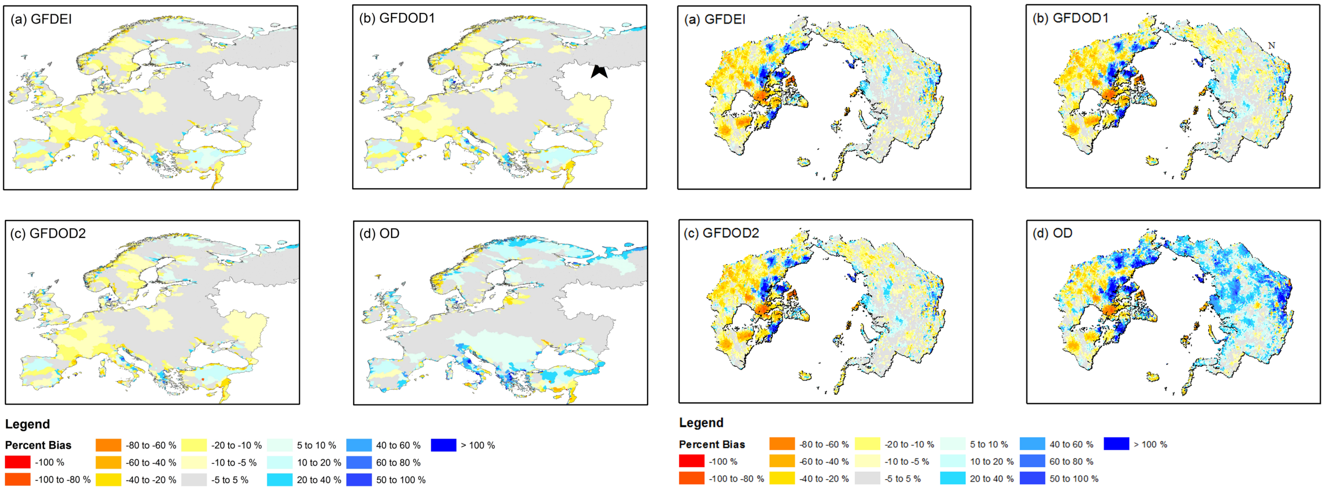

Figure 6. Relative upstream specific runoff difference from GFDCL for each catchment of (left) E-HYPE and (right) Arctic-HYPE.

Fig. 6 shows a spatial view the average upstream runoff difference from the GFDCL simulation for each domain. The two months with GFDOD were here divided into two separate maps to see if there is any difference dependent on the time elapsed since the GFDEI simulation. In the resolution of the colour scales, there is only small differences between GFDEI and GFDOD1, and even less between GFDOD1 and GFDOD2. The offsets from GFDCL are mainly within ±20% for Europe, but much stronger local offsets are seen in the Arctic domain. The Arctic is a more sensitive region to differences in the station density behind the gridded observational data sets, as there are fewer stations to begin with. This fact plays a large role in shaping the offsets seen here. The OD period is, as expected, wetter for most of the domains, but more clearly so for the Arctic domain.

A selection of in-situ observations from gauging stations with available data from at least two of the four simulated years was used for the analysis. Performance criteria of the models for each of the gauges are presented for each data set in comparison to GFDCL in Fig. 7. Since GFDCL is always the reference, the results for each gauge lines up vertically in the figure. The two domains show similar results, and we therefore describe the results in a general sense. The bias follows the patterns described above, with lower values for GFDEI and GFDOD, while OD has higher values. Whether there is a positive of negative bias is determined by the initial bias of the GFDCL simulation. NSE and correlation (r) are not showing any clear structure, but remain reasonable for most of the simulations. The variability is consistently higher for the OD simulation as also noted above.

In summary, the domain average deviations from GFDCL shows that the updating procedure adds value to the simulations by keeping the precipitation and temperature climate closer to the GFDCL data set. The extension of GFDCL with GFDEI has therefore only minor effects on the long term hydrology. However, for forecast initializations, the inevitable switch to OD data closer to the "current" date, i.e. the day to issue a forecast, there is a strong drift due to the wet bias of OD. The drift continues

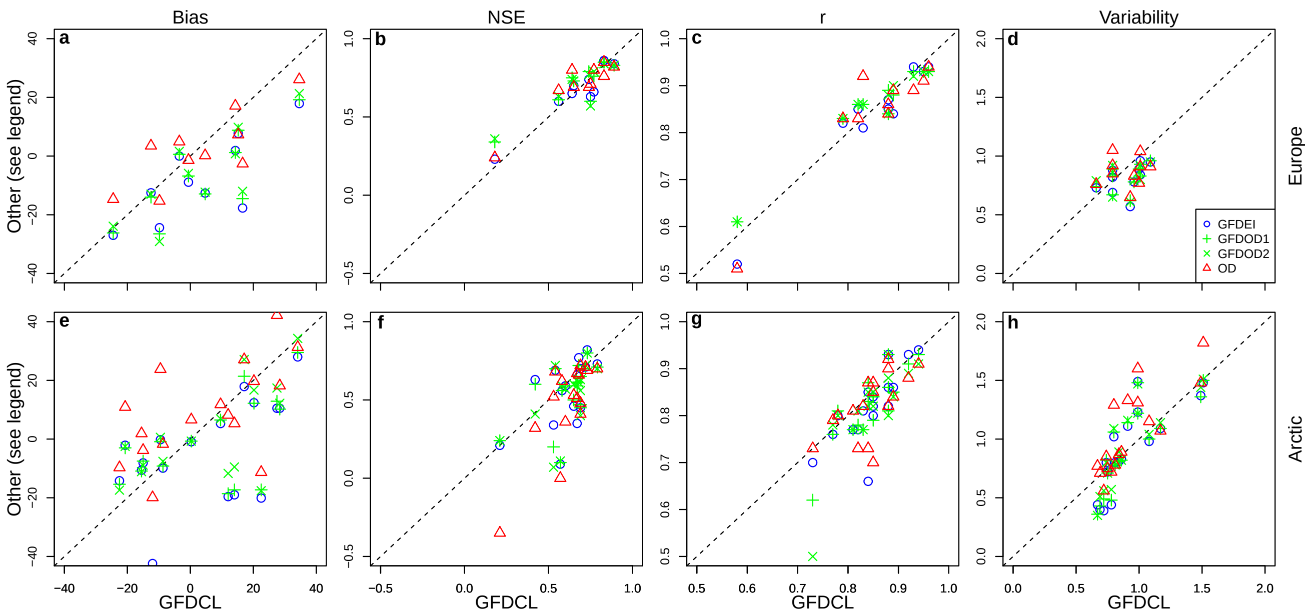

Figure 7. River discharge model performance measures: bias (relative volume error in %), Nash-Suthcliff Efficiency (NSE), Pearson correlation (r), and ratio of simulated and observed variance for a selection of grid points in the (top) Europe, and (bottom) Arctic, with GFDCL on the x-axis and the other evaluated simulations (GFDEI, GFDOD1, GFDOD2, and OD) on the y-axis.

throughout the OD period, which means that the initial drift a forecast is subjected to is dependent on the day of the forecast. The drift is largest for forecasts issued just before the 10^{th} and lowest just after.

4 Conclusions

We present a new data set called GFD, which consists of several products. The main product, GFDCL, is the equivalent to the already well established WFDEI (Weedon et al., 2014), although with updated observational data sets. To extend the data set beyond year 2013, when e.g. the GPCC7 data set ends, adjustments are performed with regularly updated data sets. This is performed with the GFDEI product until the latest update of EI, which is with about a three month delay. For near real-time updates, GFDOD makes use of the ECMWF deterministic model with similar data sets for adjustments as for GFDEI. GFDOD is available until the end of the previous month from around the 10^{th} of the current month.

GFDCL is found to be a much similar product as WFDEI, but with a more consistent data set. The introduced under-catch corrections in the precipitation data set GPCC7 differ from that assumed in WFDEI, which leads to generally lower amounts in GFD. Temperature is very similar.

The updates in GFDEI beyond 2013, are evaluated for an overlapping period (2010–2013). GFDEI is found to have slightly lower precipitation amounts, and spatially somewhat different temperatures. However, the differences to GFDCL shrinks in comparison to the bias of EI which has bias of often an order of magnitude higher.

When EI is not available, the OD model is employed and the precipitation data source changes from GPCC-Monitor to GPCC-FG. The change in data source has the largest impact, with several geographical differences which impact on the GFDOD product. As an interim product until the next update, GFDOD reduces the bias of OD (which is similar to that of EI) to levels similar to GFDEI.

Initializations of hydrological simulations for forecasting purposes are investigated for GFDOD, extended by the non-corrected OD until the day before the next update of GFDOD. It is found that the strong bias of OD, especially for precipitation, causes a severe drift of the hydrological model away from the GFDOD climatology. The results are similar for both the domains investigated, i.e. Europe and the Arctic region. Some measure to reduce the induced drift due to bias of OD would be necessary for reliable forecasts.

The GFD data sets are planned for public release via a web interface on http://hypeweb.smhi.se/. Besides the climatological data set GFDCL, the website will feature monthly updates of the GFDEI and GFDOD data sets.

5 Data availability

The GFD method relies mainly on open data sets, as referenced within the article. ECMWF reanalysis can be accessed via the web portal https://www.ecmwf.int/en/research/climate-reanalysis/era-interim/. The forecasts from ECMWF (here referred to as "OD"), are restricted to member institutes (or other special circumstances, see https://www.ecmwf.int/en/forecasts/accessing-forecasts), and are therefore not available for public download. However, the GFDCL, GFDEI and GFDOD data sets, with regular updates, will shortly appear online on http://hypeweb.smhi.se/. Hydrological simulations were performed with the open source model HYPE, which can be accessed at http://hypecode.smhi.se/.

Acknowledgements. We acknowledge the hard work of building the data sets used within the presented work. This includes the data from the ERA-Interim, CRU, GPCC and WFDEI as referenced within the paper, as well as GHCN-CAMS (National Center for Atmospheric Research Staff (Eds). Last modified 08 May 2014. "The Climate Data Guide: GHCN (Global Historical Climatology Network) Related Gridded Products." Retrieved from https://climatedataguide.ucar.edu/climate-data/ghcn-global-historical-climatology-network-related-gridded-products.) and the ECMWF deterministic forecast system. Further, we acknowledge the inital work of implementing the GFD system at SMHI by Lisa Bengtsson, Magnus Lindskog and Heiner Körnich, and the work on operationalization by Fredrik Almén.

References

Adam, J. C. and Lettenmaier, D. P.: Adjustment of global gridded precipitation for systematic bias, J. of Geophys. Res. Atm., 108, 2003.

Allen, R. G., Pereira, L. S., Raes, D., Smith, M., et al.: Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, FAO, Rome, 300, D05 109, 1998.

Andersson, J., Pechlivanidis, I., Gustafsson, D., Donnelly, C., and Arheimer, B.: Key factors for improving large-scale hydrological model performance, European Water, 49, 77–88, 2015.

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

Beck, H. E., van Dijk, A. I. J. M., Levizzani, V., Schellekens, J., Miralles, D. G., Martens, B., and de Roo, A.: MSWEP: 3-hourly 0.25°global gridded precipitation (1979-2015) by merging gauge, satellite, and reanalysis data, Hydrol. Earth Syst. Sci. Discuss., pp. 1–38, doi:10.5194/hess-2016-236, 2016.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quart. J. Roy. Meteor. Soc., 137, 553–597, doi:10.1002/qj.828, 2011.

Demirel, M. C., Booij, M. J., and Hoekstra, A. Y.: Effect of different uncertainty sources on the skill of 10 day ensemble low flow forecasts for two hydrological models, Water Resour. Res., 49(7), 4035–4053, doi:10.1002/wrcr.20294, 2013.

Donnelly, C., Andersson, J., and Arheimer, B.: Using flow signatures and catchment similarities to evaluate a multi-basin model (E-HYPE) across Europe, Hydr. Sciences Journal, 61(2), 255–273, doi:10.1080/02626667.2015.1027710, 2016.

Dyurgerov, M. and Meier, M.: Year-to-year fluctuations of global mass balance of small glaciers and their contribution to sea-level changes, Arct. Alp. Res., 29(4), 392–402, 1997.

Emerton, R. E., Stephens, E. M., Pappenberger, F., Pagano, T. C., Weerts, A. H., Wood, A. W., Salamon, P., Brown, J. D., Hjerdt, N., Donnelly, C., and Baugh, C. A.: Continental and global scale flood forecasting systems, Wiley Interdisciplinary Reviews: Water, 3(3), 391–418, 2016.

Fan, Y. and Van den Dool, H.: A global monthly land surface air temperature analysis for 1948–present, J. Geophys. Res. Atm., 113, D1, 2008.

Gelfan, A., Gustafsson, D., Motovilov, Y., Kalugin, A., Krylenko, I., and Lavrenov, A.: Climate change impact on the water regime of two great Arctic rivers: modeling and uncertainty issues, Clim. Chang., 141 (3), 1–17, doi:10.1007/s10584-016-1710-5, 2017.

Harris, I. and Jones, P.: CRU TS3.22: Climatic Research Unit (CRU) Time-Series (TS) Version 3.22 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901- Dec. 2013), doi:10.5285/18BE23F8-D252-482D-8AF9-5D6A2D40990C, 2014.

Hundecha, Y., Arheimer, B., Donnelly, C., and Pechlivanidis, I.: A regional parameter estimation scheme for a pan-European multi-basin model, J. Hydrol. Regional Studies, 6, 90–111, doi:10.1016/j.ejrh.2016.04.002, 2016.

Legates, D. and Willmott, C.: Mean seasonal and spatial variability in gaugecorrected, global precipitation, Int. J. Climatol., 10, 111–127, 1990.

Li, H., Luo, L., Wood, E. F., and Schaake, J.: The role of initial conditions and forcing uncertainties in seasonal hydrologic forecasting, J. Geophys. Res., 114(D4), D04 114, doi:10.1029/2008JD010969, 2009.

Lindström, G., Pers, C., Rosberg, R., Strömqvist, J., and Arheimer, B.: Development and test of the HYPE (Hydrological Predictions for the Environment) model - A water quality model for different spatial scales, Hydrol. Res., 41.3-4, 295–319, doi:10.2166/nh.2010.007, 2010.

Meier, M. F. and Bahr, D. B.: Counting glaciers: Use of scaling methods to estimate the number and size distribution of the glaciers of the world, in: Glaciers, Ice Sheets and Volcanoes: A Tribute to Mark F. Meier, vol. 96, pp. 89–94, DTIC Document, 1996.

Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andreassian, V., Anctil, F., and Loumagne, C.: Which potential evapotranspiration input for a lumped rainfall-runoff model?: Part 2 - Towards a simple and efficient potential evapotranspiration model for rainfall-runoff modelling, J. Hydrol., 303(1-4), 290–306, 2005.

Paiva, R. C. D., Collischonn, W., Bonnet, M. P., and De Goncalves, L. G. G.: On the sources of hydrological prediction uncertainty in the Amazon, Hydrol. Earth Syst. Sci., 16(9), 3127–3137, doi:10.5194/hess-16-3127-2012, 2012.

Pechlivanidis, I. G., Bosshard, T., Spångmyr, H., L. G., Gustafsson, D., and Arheimer, B.: Uncertainty in the Swedish operational hydrological forecasting systems, in: Vulnerability, Uncertainty, and Risk: Quantification, Mitigation and Management, edited by Beer, M., Au, S. K., and Hall, J. M., pp. 253–262, Liverpool, UK, doi:10.1061/9780784413609.026, 2014.

Schamm, K., Ziese, M., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., and Schneider, U.: GPCC First Guess Daily Product at 1.0°: Near Real-Time First Guess daily Land-Surface Precipitation from Rain-Gauges based on SYNOP Data, doi:10.5676/DWD_GPCC/FG_D_100, 2013.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Ziese, M., and Rudolf, B.: GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle, Theoretical and Applied Climatology, 115, 15–40, 2014.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., and Ziese, M.: GPCC Monitoring Product: Near Real-Time Monthly Land-Surface Precipitation from Rain-Gauges based on SYNOP and CLIMAT data, doi:10.5676/DWD_GPCC/MP_M_V5_100, 2015a.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., and Ziese, M.: GPCC Full Data Reanalysis Version 7.0 at 0.5°: Monthly Land-Surface Precipitation from Rain-Gauges built on GTS-based and Historic Data, doi:10.5676/DWD_GPCC/FD_M_V7_050, 2015b.

Sheffield, J., Goteti, G., and Wood, E. F.: Development of a 50-yr high-resolution global dataset of meteorological forcings for land surface modeling, J. Climate, 19, 3088–3111, 2006.

Shukla, S. and Lettenmaier, D. P.: Seasonal hydrologic prediction in the United States: Understanding the role of initial hydrologic conditions and seasonal climate forecast skill, Hydrology and Earth System Sciences, 15(11), 3529–3538, doi:10.5194/hess-15-3529-2011, 2011.

Strömqvist, J., Arheimer, B., Dahné, J., Donnelly, C., and Lindström, G.: Water and nutrient predictions in ungauged basins - Set-up and evaluation of a model at the national scale, Hydrol. Sci. J., 57(2), 229–247, 2012.

Weedon, G., Gomes, S., Viterbo, P., Shuttleworth, W., Blyth, E., Österle, H., Adam, C., Bellouin, N., Boucher, O., and Best, M.: Creation of the watch forcing data and its use to assess global and regional reference crop evaporation over land during the twentieth century, J. Hydrometeor, 12, 823–848, doi:10.1175/2011JHM1369.1, 2011.

Weedon, G. P., Balsamo, G., Bellouin, N., Gomes, S., Best, M. J., and Viterbo, P.: The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data, Water Resour. Res., 50, 7505–7514, 2014.

Ziese, M., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., and Schneider, U.: GPCC First Guess Product at 1.0°: Near Real-Time First Guess monthly Land-Surface Precipitation from Rain-Gauges based on SYNOP Data, doi:10.5676/DWD_GPCC/FG_M_100, 2011.