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A three-part bias correction of simulated European river runoff to force ocean models

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Abstract

In ocean or Earth system model applications, the riverine freshwater inflow is an important flux affecting salinity and marine stratification in coastal areas. However, in climate change studies, the river runoff based on climate model output often has large biases on local, regional or even basin-wide scales. If these biases are too large, the ocean model forced by the runoff will drift into a different climate state compared to the observed state, which is particularly relevant for semi-enclosed seas such as the Baltic Sea. In order to meet the requirements for low biases in river runoff, we have developed a three-part bias correction that includes different correction factors for low, medium and high percentile ranges of river runoff over Europe. Here, we present an experimental setup using the Hydrological Discharge (HD) model and its high-resolution (1/12°) grid. First, bias correction factors are derived at the locations of the downstream stations with available daily discharge observations for many European rivers. These factors are then transferred to the respective river mouths and mapped to neighbouring grid boxes belonging to ungauged catchments. The results show that the bias correction generally leads to an improved representation of river runoff. Especially over Northern Europe, where many rivers are regulated, the three-part bias correction provides an advantage compared to a bias correction that only corrects the mean bias of the river runoff. Evaluating two NEMO ocean model simulations in the German Bight indicated that the use of the bias corrected discharges as forcing leads to an improved simulation of sea surface salinity in coastal areas. Although in the present study, the bias correction is tailored to the high-resolution HD model grid over Europe, the methodology is suitable for any high-resolution model region with a sufficiently high coverage of river runoff observations. It is also noted that the methodology is applicable to river runoff based on climate hindcasts as well as on historical climate simulations where the sequence of weather events does not match the actual observed history. Therefore, it may also be applied in climate change simulations.

Keywords: Bias correction, river runoff, discharge, high resolution, Europe

1 Introduction

River runoff (or discharge/streamflow) is an important component of the global hydrological cycle, accounting for about one-third of precipitation over land areas. It closes the water cycle between land and ocean and influences various ocean properties, in particular the salinity of coastal and semi-enclosed seas (e.g. Väli et al., 2013), the ocean stratification in shelf areas (e.g. Hordoir and Meier, 2010) such as the German Bight (Becker et al., 1992), and the

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thermohaline circulation in different regions (e.g. Hordoir et al., 2008; Lehmann and Hinrichsen, 2000; Marzeion et al., 2007). In addition, river runoff and associated nutrient loads are important factors influencing marine ecosystem functioning (Daewel and Schrum, 2017).

Consequently, river runoff needs to be adequately represented in studies of the impacts of climate change on the marine environment or in coupled Earth system studies. In such studies, the atmospheric data used to force the respective ocean model are usually taken from climate models, reanalysis products or hydrological models. Here, it is desirable that the river runoff is consistent with the atmospheric forcing. In previous modelling studies, runoff was often taken from climatology or discharge observations, especially when hindcasts were used. However, this is not a recommended approach for climate change studies where consistently simulated river runoff should be used. Runoff from the driving climate, land surface or hydrological model will contain biases, e.g., due to biases in precipitation and/or uncertainties in the land surface representation of the model. Many simulations of historical daily river runoff show common biases in the tails of their distributions, with high discharges underestimated and low discharges overestimated (Farmer et al., 2018, and references therein). If the basin-wide biases are too large, a bias correction of the simulated discharge would be necessary to avoid the ocean model drifting into a different climate state compared to the observed state. This is particularly relevant for semi-enclosed seas such as the Baltic Sea. For example, for Baltic Sea ocean models, the mean long-term bias of river runoff must be less than 7% (Hagemann and Stacke, 2022).

The bias correction of river runoff is an approach that has been used particularly for short-term hydrological forecasts and ensemble predictions of up to six months. Here, Kim et al. (2021) provide examples of related studies. Recently, bias correction of river runoff has also been applied in the context of climate change. Quantile mapping based approaches are often used for such bias correction, as this usually leads to a large improvement in the representation of discharge of the considered river. For example, Budhathoki et al. (2022) used quantile mapping to correct discharge bias in the Chao Phraya River basin (Thailand), and Daraio (2020) used it for two basins in New Jersey (USA). However, Madadgar et al. (2014) noted that quantile mapping was not always successful in improving the initial forecast trajectory. In their application for the Sprague River (southern Oregon, USA), the skill of the forecast actually deteriorated when the quantile mapping technique was used. Similarly, Malek et al. (2022) used a quantile mapping based bias correction of discharge and showed that ex-post corrections of simulated discharge do not necessarily reduce biases in the simulation of key processes and in some cases can severely degrade system simulations.

Consequently, the aim of the present study was to develop a bias correction method sufficient to meet the requirements of ocean models in large-scale climate change studies. Note that we did not aim for the most accurate reproduction of observed discharge characteristics, as required for short-term hydrological predictions and flood forecasts used by water resource decision makers (e.g. Shi et al., 2008). In order to maintain a high degree of consistency of simulated runoff with the meteorological patterns in the driving (on- or offline) climate model (or data), a bias correction with as little modification of the daily runoff curves as possible is desired. Thus, our target is a simple bias correction that corrects the mean bias and the tail biases of the discharge distribution in climate change applications of ocean or coupled system models. The bias correction factors should be transferable from downstream stations to river mouths as well as to neighbouring ungauged catchments. Furthermore, it should be applicable to climate model or Earth system model data that lack the observed sequence of actual discharge events.

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The manuscript is organised as follows. Section 2 describes how the simulated discharges were generated and the newly developed bias correction methodology, as well as the data, models and metrics used in this study. Sections 3 and 4 evaluate the simulated and bias corrected discharges and present the effects of the bias correction for station locations and sea basin inflows, respectively. Finally, Section 5 concludes with a summary and conclusions.

2 Data and Methods

To generate the freshwater inflow from rivers to the ocean, we used an experimental setup analogous to Hagemann and Stacke (2022). Here we used two atmospheric forcing datasets (Sect. 2.1) and the same model chain of two large-scale hydrological models. The global hydrological model HydroPy (Sect. 2.2) was used to generate the input to the Hydrological Discharge (HD) model (Sect. 2.3) at the resolution of the atmospheric forcing data (0.5°). These input data of surface and sub-surface runoff were then interpolated onto the HD model grid and the HD model was used to simulate daily discharges from land to sea. Subsequently, we bias corrected these time series as described in Section 2.4 to generate bias corrected discharges at coastal ocean boxes of the European HD model domain from 1901-2019. Note that we combined the simulations based on two different atmospheric forcing datasets to cover the whole 20th century and to include the more recent years in the bias corrected discharge time series. Such an approach was also used in the second phase (ISIMIP, 2023) of the Inter-Sectoral Impact Model Inter-Comparison Project (ISIMIP; Warszawski et al., 2014). Figure 1 summarises the experimental setup. Section 2.5 refers to the observational data that are used in the evaluation of the model results. Finally, the evaluation metrics used in the analysis of the results are presented in Sect. 2.7.

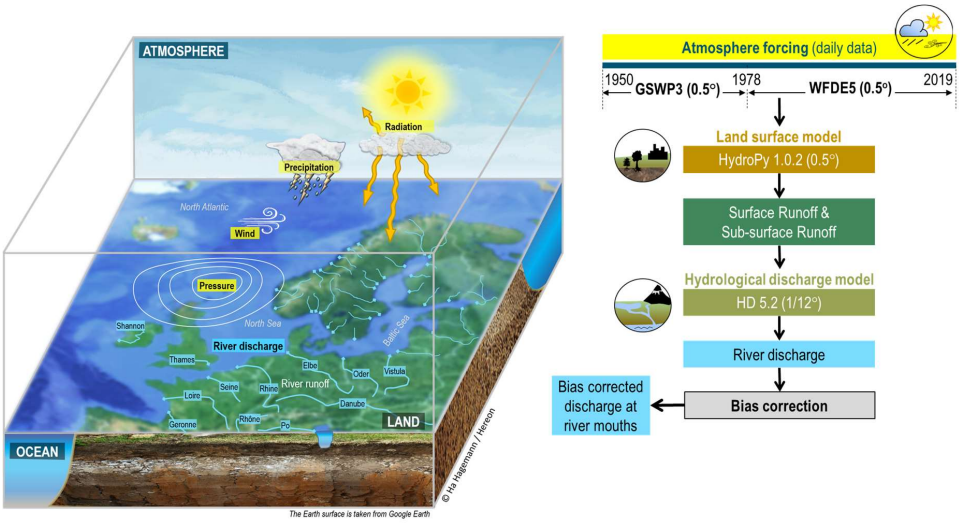

Figure 1. Overview on the main steps of generating bias corrected river discharge at HD river mouths.

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2.1 Atmospheric forcing

We used two atmospheric datasets specifically generated for forcing global hydrological models.

The Global Soil Wetness Project Phase 3 (GSWP3; Dirmeyer et al., 2006; Kim, 2017) dataset is available at 0.5° resolution from 1901-2014. To generate the GSWP3 dataset, the 20th Century Reanalysis (20CR; Compo et al., 2011) was first dynamically downscaled onto the T248 (~0.5°) grid using a spectral nudging technique (Yoshimura and Kanamitsu, 2008) in a Global Spectral Model (GSM). Observation-based bias correction procedures were then applied to the downscaled data to obtain daily time series.

To generate the WFDE5 dataset (Cucchi et al., 2020), the WATCH Forcing Data (WFD) methodology (Weedon et al., 2011) was applied to surface meteorological variables from the ERA5 reanalysis (Hersbach et al., 2020) to obtain bias corrected time series. ERA5 is the fifth generation of atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). WFDE5 is provided at 0.5 spatial resolution from 1979-2019.

2.2 HydroPy setup

HydroPy (Stacke and Hagemann, 2021) was driven by daily forcing data from 1901-2019. Daily input fields of surface and subsurface runoff were generated at a resolution of 0.5°. Analogous to the ERA5 forced simulation in Hagemann and Stacke (2022), precipitation, 2m temperature, downwelling shortwave and longwave radiation, 2m specific humidity, surface pressure and 10m wind are used as forcing from the respective forcing dataset. We performed a spin-up simulation over 50 iterations of the year 1901 with the GSWP3 forcing (cf. Stacke and Hagemann, 2021) to initialize the storages in the HydroPy model and to avoid any drift during the actual simulation period. We then forced HydroPy with the GSWP3 data from 1901-1978 and continued with the WFDE5 data from 1979-2019. We also conducted a GSWP3 forced simulation from 1979-2014 in order to derive bias correction parameters for the earlier period. For our analysis, we focus on the years from 1950 onwards so that we have an additional transient spin-up of 49 years.

2.3 HD model setup

To simulate discharge, the HD model (Hagemann et al., 2020) used the daily input fields of surface and subsurface runoff that were generated by HydroPy from the GSWP3 and WFDE5 data (see Sect. 2.2). As the time step of these runoff data is one day, the time step of the HD model was also set to one day. However, an internal time step of 0.5 hours is used for the flow within the river, as the minimum travel time through a grid box is limited by the chosen time step. The HD model v5.2.0 (Hagemann et al., 2023a) was applied over the European domain, which covers the land areas between -11°W to 69°E and 27°N to 72°N. The domain, along with a number of rivers specifically noted in this study, is shown in Figure 2. In the following, we refer to the WFDE5-based discharges as HD5-WFDE5 and to the GSWP3-based discharges as HD5-GSWP3.

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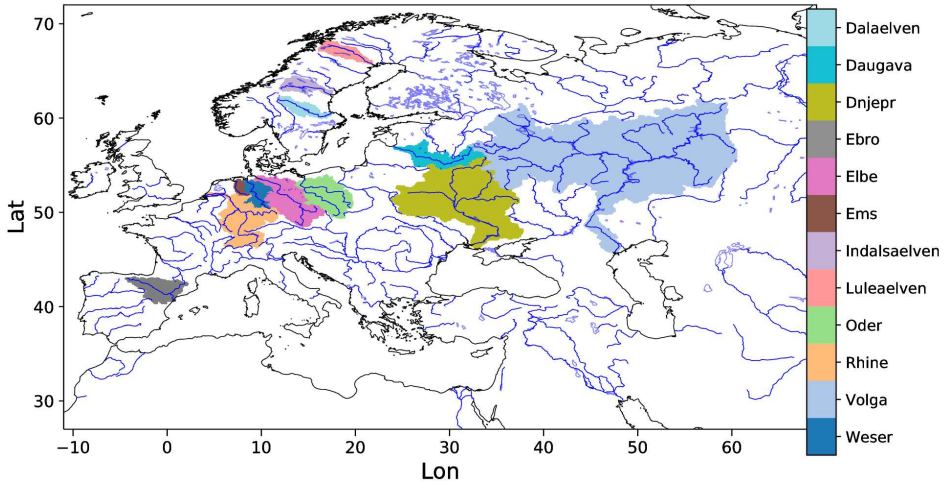

Figure 2. European HD model domain and catchment areas for selected rivers

2.4 Bias correction of river runoff

We have developed a three-part bias correction method for river runoff with different correction factors for low, medium and high percentiles. These are first calculated at the station locations and then applied to the respective river mouths. Finally, an interpolation is performed to neighbouring coastal mouth points for which no downstream observations are available in the respective catchment. This procedure is summarised in Figure 3. The three percentile ranges for daily discharge q_i are classified by

- Low (L): $q_i \leq Q_p$
- Medium (M): $Q_p < q_i < Q_{100-p}$
- High (H): $q_i \geq Q_{100-p}$

Here, Q_p denotes the p^{th} percentile of the daily discharge and p was set to 20. The percentiles Q_p and $Q_{100\text{-}p}$ were determined separately for the observed and the simulated discharges at the downstream station locations and then the mean discharges $\overline{q_R}$ were calculated for the three percentile ranges $R \in \{L, M, H\}$. Note that for these calculations only those days were considered for which an observed discharge was available. Then, the mean bias b_R (in %) was calculated for each percentile range and a correction factor f_R to remove the bias was derived as

$$f_R = \frac{100}{b_R + 100}$$

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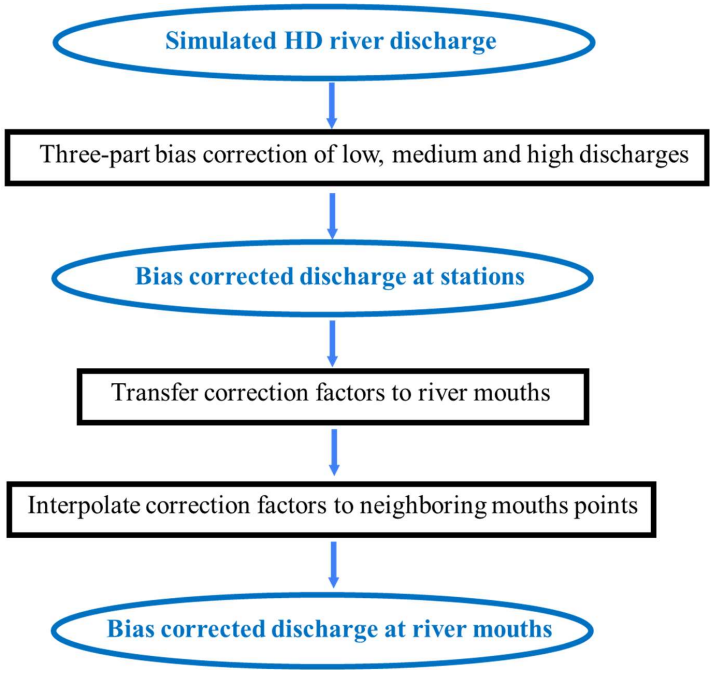

Figure 3. Steps to derive bias corrected discharge at river mouths from simulated discharges.

For the evaluation of the bias correction in Sect. 3, these correction factors were applied to the simulated discharges at the station locations. As the correction factors are independent of the absolute amount of discharge, they could be applied to the respective river mouths. For each river mouth with more than one inflow ($j > 1$) for which a correction factor $f_{R,j}$ is determined, a combined correction factor is obtained by calculating an average weighted by the respective mean inflows Q_j.

$$\bar{f_R} = \frac{\sum_j f_{R,j} * Q_j}{\sum_j Q_j}$$

From these river mouths, an interpolation is performed to neighbouring coastal mouth points for which no downstream observations are available in the respective catchment. This interpolation was motivated by the fact that the general pattern of bias of neighbouring rivers is often similar (cf. Sect. 3.1). The interpolation is performed by inverse distance weighting from the four closest (or fewer) river mouths within a search radius of 200 km. If no river mouth with a correction factor was found within the search radius, the correction factor was set to one (i.e. no correction).

Note that the bias correction can lead to spurious daily jumps in discharge when the percentile boundary is crossed and the bias correction factors differ between the percentile ranges. In order to reduce this effect, a smoothing radius of $\Delta s = 0.05$ was introduced around the percentile boundaries, which was applied at both station locations and river mouths.

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For $(1 - \Delta s) * q_p < q_i < (1 + \Delta s) * q_p$:

$$\widetilde{q_i} = q_i * (f_L + (f_M - f_L) * \frac{(q_i - (1 - \Delta s) * q_p)}{2 * \Delta s * q_p}$$

For $(1 - \Delta s) * q_{100-p} < q_i < (1 + \Delta s) * q_{100-p}$:

$$\widetilde{q_i} = q_i * (f_M + (f_H - f_M) * \frac{(q_i - (1 - \Delta s) * q_{100-p})}{2 * \Delta s * q_{100-p}}$$

The bias correction procedure corrects the days that fall into the different percentile ranges. However, this does not necessarily mean that it also corrects the whole distribution into the three percentile ranges. Particularly, if the biases in these ranges are quite different, the days may change their class and order within the distribution.

In order to apply the three-part bias correction to the simulated discharge time series from 1901-2019, two sets of bias correction factors were derived. The first set uses HD5-WFDE5 and discharge station observations for the period 1979-2014. This set was used to bias correct the simulated discharge at HD river mouths from 1979-2019. The second set uses a further discharge simulation where we continued HD5-GSWP3 utilizing the GSWP3 forcing up to 2014. Again, the set of bias correction factors was derived for the period 1979-2014 using discharge station observations. This set was then used to bias correct the simulated discharge at the HD river mouths from 1901-1978.

2.5 Observed discharge data

We used available daily discharge data from downstream gauges for many rivers across Europe with a catchment area of about 1000 km² or more. These station data were obtained from Global Runoff Data Centre (GRDC) and various agencies and institutions listed in table 2 of Hagemann and Stacke (2022). In addition, French discharge data were accessed from the E.U. Copernicus Marine Service Information. In order to allow an assessment of the discharge at the river mouths, we considered basin-wide estimates from three different sources.

For the Baltic Marine Environment Protection Commission – also known as the Helsinki Commission (HELCOM), Svendsen and Gustafsson (2022) provided annual waterborne inflows into the seven main sub-basins of the Baltic Sea (Figure 4 – upper panel) from 1995 to 2020. Waterborne inflows comprise the sum of river runoff and direct inflows, i.e. flows from point sources discharging directly into the Baltic Sea. These point sources are not included in our experimental setup or in the bias correction. However, their contribution to the total waterborne inflow to the Baltic Sea is only about 1% (HELCOM, 1998).

Under the umbrella of the OSPAR Convention (Convention for the Protection of the Marine Environment of the North-East Atlantic), the IGC-EMO (Intersessional Correspondence Group for Eutrophication Modelling) database (Lenhart et al., 2010) of daily riverine freshwater inflows and nutrient loads was compiled by Van Leeuwen and Lenhart (2021), covering the major rivers discharging into the Baltic Sea, the North Sea and the Northeast Atlantic. An updated database covering a total of 370 rivers was mapped onto the flow grid of the European 1/12° domain of the HD model by Van Leeuwen and Hagemann (2023). The associated catchment areas of these rivers, which flow into a particular specific sea basin, do not cover the

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entire catchment area of the respective basin (see Table 1) so that the total inflow of the sea basin is underrepresented by the IGC-EMO data. To generate basin-wide estimates, we have up-scaled these values by dividing the integrated IGC-EMO river discharges in a basin by the fractional coverage of the entire basin catchment on the HD grid. Basin estimates for which the fractional coverage is less than 75% are considered to be highly uncertain and are therefore provided for completeness only, but are not included in the assessment of simulated inflows.

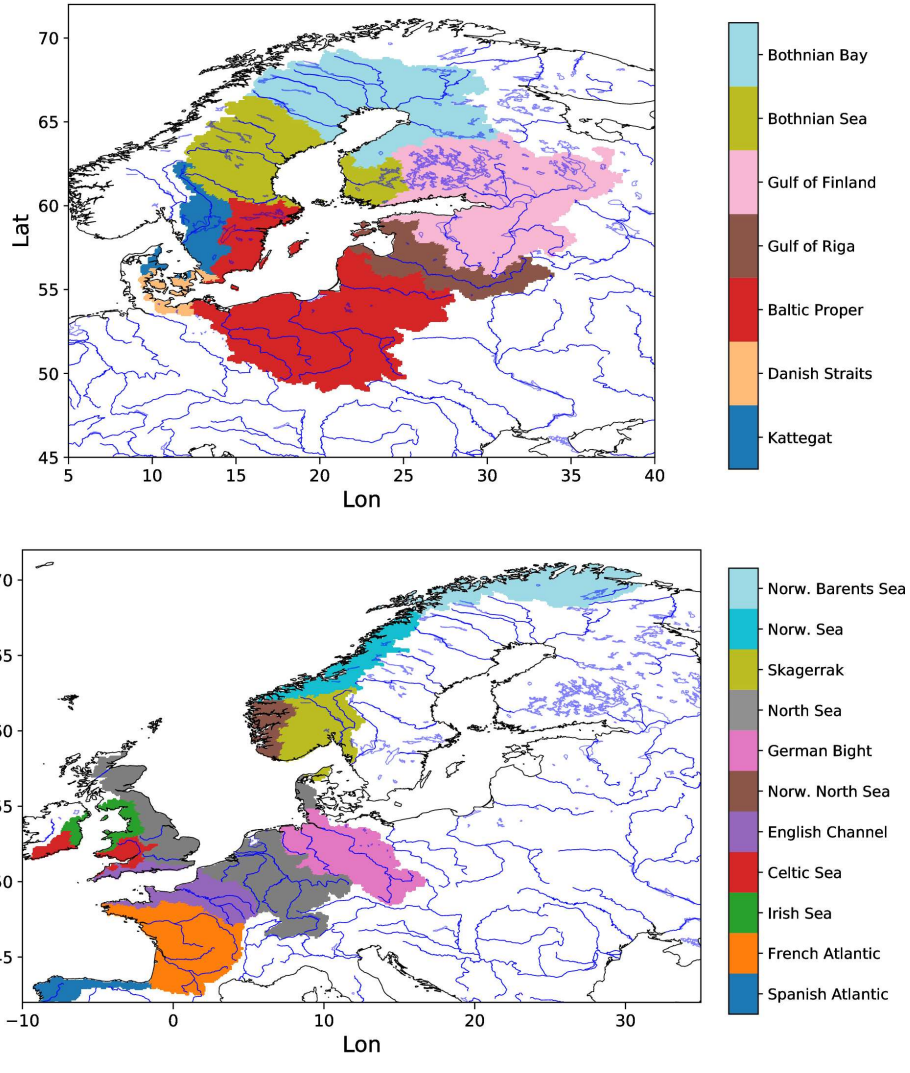

Figure 4. Selected HELCOM (upper panel) and OSPAR (lower panel) basins for which inflows are considered. For OSPAR, the Spanish Atlantic basin is limited to the coast of Northern Spain.

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Table 1. Sea basin catchment areas on the HD model grid and the fractional catchment coverage of the associated IGC-EMO rivers.

	HD Area [km²]		
Sea basin	**IGC-EMO**	**Total**	**Coverage**
Baltic Sea	1513967	1671823	90.6%
Bothnian Bay	238898	258420	92.4%
Bothnian Sea	199908	219375	91.1%
Gulf of Finland	379628	412412	92.1%
Gulf of Riga	124386	134025	92.8%
Baltic Proper	494929	551295	89.8%
Danish Straits	6731	19417	*34.7%*
Kattegat	69487	76876	90.4%
Norwegian Barents Sea	0	81004	0.0%
Norwegian Sea	0	58408	0.0%
Skagerrak	89060	101787	87.5%
North Sea	514334	599755	85.8%
German Bight	201233	208807	96.4%
Norwegian North Sea	4590	31327	*14.7%*
English Channel	94327	122235	77.2%
Celtic Sea	41122	44845	91.7%
Irish Sea	29748	35584	83.6%
French Atlantic	207657	257981	80.5%
Northern Spanish Atlantic	17692	46574	*38.0%*

In addition, we used estimates of long-term mean sub-basin-wide inflows to the North Sea and Northeast Atlantic, published directly by OSPAR (Farkas and Skarbøvik, 2021). Figure 4 (lower panel) shows the selected OSPAR basins for which the inflows are considered. It should be noted that the sea basin inflows provided by the different OSPAR countries are not consistent. Some countries include discharge estimates for unmonitored areas, while others do not (Table 2). In addition, the sea basin catchment coverage of the monitored areas varies between the countries. Note also that we have excluded the Spanish Atlantic from our comparisons for the following reason. Here, we limited the Spanish Atlantic basin to the coast of northern Spain (see Figure 4 – lower panel) to allow a comparison with the IGC-EMO data as the IGC-EMO data only cover rivers in this region, hereafter referred to as NSpA. These rivers cover about 38% of the total NSpA area on the HD model grid (Table 1), while the OSPAR data for NSpA cover about 50% (23201 km²; Farkas and Skarbøvik, 2021). However, the associated IGC-EMO discharge from 1961-1990 (629 m³/s) is 75 % larger than the OSPAR long-term mean average (359 m³/s). Therefore, both inflow values are unlikely to be representative for the NSpA region and this region is not considered in the following.

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Table 2. Country catchment coverage of OSPAR data and inclusion of estimates for unmonitored areas (Borgvang et al., 2008). NI means that no information on the coverage was provided.

Country	Coverage	Unmonitored
Belgium	> 90%	No
Denmark	NI	Yes[3]
France	84%	Yes
Germany	>90%	No[1]
Ireland	NI	Yes
Netherlands	>90%	No
Norway	ca. 50%	Yes
Portugal	NI	No
Spain	NI	No
Sweden	88.7%	Yes
United Kingdom	ca. 80%[2]	No

[1] Only for Eider river
[2] 10% in direct discharge
[3] e.g. Farkas and Skarbøvik (2021)

2.6 Ocean model experiments

To assess the effect of using bias corrected river discharge on simulated salinity in the German Bight, we used version 3.6 of the Nucleus for European Modelling of the Ocean (NEMO; Madec et al., 2017) and adopted a domain setup used by Ho-Hagemann et al. (2020). This domain covers the region of the north-west European shelf, the North Sea and the Baltic Sea between 19.89 E to 30.16 E and 40.07 N to 65.93 N with a resolution of two nautical miles (ca 3.6 km). We used the atmospheric forcing from ERA5 and the ocean boundary forcing from the ECMWF Ocean Reanalysis System 5 (ORAS5; Zuo et al., 2019) to conduct two simulations from 2010 to 2018. In these two simulations, the daily riverine inflow into the ocean was taken from the uncorrected and bias corrected discharges of HD5-WFDE5, which were converted to the NEMO grid using a procedure of Nguyen et al. (2024). For each HD model river mouth box, we associated the nearest coastal ocean box on the NEMO grid if such a box was found within a search radius of 200 km. Such a large radius is necessary because the NEMO coastline is very smooth, so many estuaries and bays in the HD model grid are not resolved by NEMO. If no ocean box was found, the corresponding HD model box was not linked. Consequently, the simulated discharge data at the river mouths were placed as freshwater inflow into the corresponding NEMO grid boxes.

2.7 Evaluation metrics

The evaluation of the simulated discharge was performed for the grid boxes corresponding to the discharge station locations within the river network. For the evaluation at these station locations, we used the mean bias and the Kling-Gupta efficiency (KGE; Gupta et al., 2009; Kling et al., 2012). Both metrics were calculated with simulated and observed daily discharge time series for the period considered, using only those days for which observed data are available. The KGE is a quality metric combining bias, correlation and coefficient of variation. If a simulated discharge time series has a KGE > -0.41, then it is a better representation of the observations than the use of the observed long-term mean discharge (Knoben et al., 2019). Note that many ocean model applications still use the latter method.

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3 Evaluation of the bias correction

Below, various metrics have been calculated at the station locations and at the river mouths. However, these measures have been assigned to the respective catchment areas for the purpose of graphical presentation.

3.1 Evaluation of simulated discharge

The distribution of bias and KGE for HD5-GSWP3 and HD5-WFDE5 during 1979-2014 (Figure 5) is quite similar to the pattern shown by Hagemann and Stacke (2022) for the ERA5-based discharge. For both simulations, the general discharge behaviour is well captured (KGE > 0.4) for many European rivers, especially in Northern Iberia, Western and Central Europe, and over Northern Russia (Figure 5, lower row). As expected (cf. Hagemann et al., 2020), larger deviations of the simulated from observed discharges occur for rivers that are heavily influenced by human activities such as water abstraction, e.g. for irrigation, and regulation, e.g. by dams. This is the case for many Scandinavian and Turkish rivers as well as the Volga and Don.

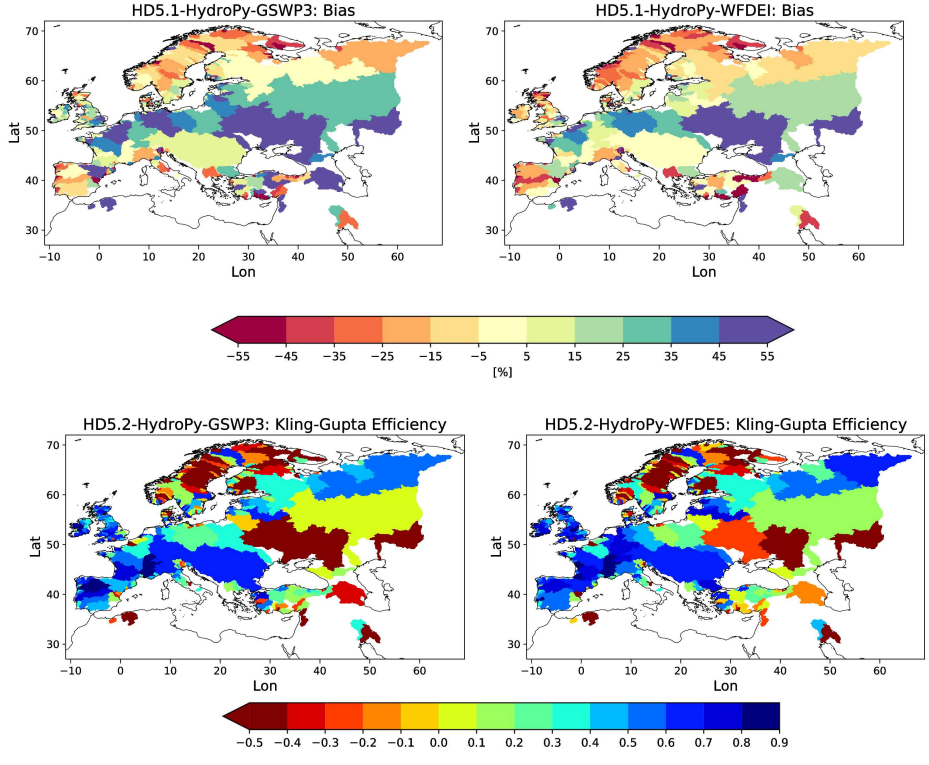

Figure 5. Mean discharge bias [%] (upper row) and Kling Gupta efficiencies (lower row) for HD5-GSWP3 (left) and HD5-WFDE5 (right) during 1979-2014.

In general, the HD5-WFDE5 discharges are slightly drier than the HD5-GSWP3 discharges, as indicated by larger dry biases in Northern Europe and smaller wet biases in Central Europe.

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Despite the differences in bias distribution, the KGEs of HD5-WFDE5 are similar to or slightly better than those of HD5-GSWP3. Compared to the ERA5-based discharge of Hagemann and Stacke (2022), HD5-WFDE5 tends to have smaller discharge biases and better KGEs. This is an expected behaviour caused by the application of a bias correction methodology to the ERA5 data in the generation of the WFDE5 data (cf. Sect. 2.1). An exception to this general improvement occurs over Northern Europe, where the dry bias of HD5-WFDE5 tends to be slightly larger and the KGEs lower. Note that Hagemann and Stacke (2022) attributed the dry bias over Northern Europe to an overestimation of the evapotranspiration simulated by HydroPy.

3.2 Added value of the three-part bias correction

In this section, we consider the effect of the bias correction at the station locations and investigate whether the three-part bias correction adds value compared to using only the mean bias correction. For this purpose, we use HD5-WFDE5 and the period 1979-2014.

Table 3. Mean bias and KGE of simulated (HD5-WFDE5) and bias corrected discharge for selected rivers during 1979-2014.

	HD5-WFDE5		Mean Bias corr.		3-part Bias corr.	
River	**Bias**	**KGE**	**Bias**	**KGE**	**Bias**	**KGE**
Dalaelven	-32.02 %	-0.32	0 %	-0.28	0.01 %	0.48
Elbe	36.44 %	0.46	0 %	0.60	-0.06 %	0.85
Indalsaelven	-19.32 %	-0.79	0 %	-0.78	-0.02 %	0.38
Odra	41.30 %	0.14	0 %	0.25	0.01 %	0.75
Rhine	14.60 %	0.74	0 %	0.78	-0.02 %	0.85
Weser	33.15 %	0.55	0 %	0.70	-0.01 %	0.90

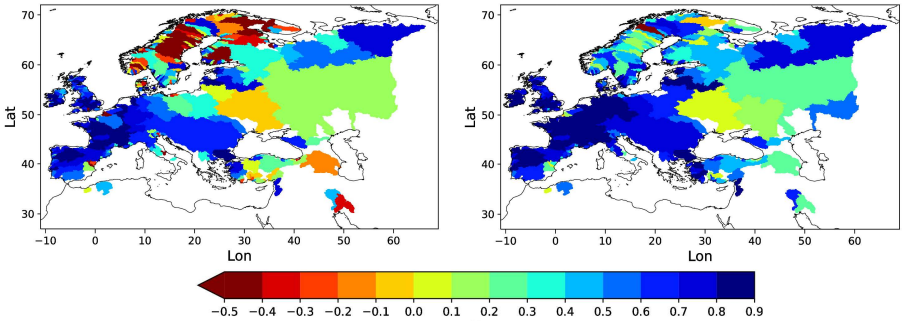

Figure 6. Kling Gupta efficiencies for bias corrected HD5-WFDE5 discharges using the mean bias correction (left) and the three-part bias correction (right) during 1979-2014.

Both bias correction methods reduce the mean discharge bias to zero or close to zero in the case of the three-part bias correction due to the smoothing around the percentile range thresholds (see Table 3 for selected rivers). When the mean bias correction is applied, the KGEs (Figure 6 – left panel) are noticeably improved over Western and Central Europe. However, with a few exceptions, the KGE pattern over Northern Europe and other areas remains largely unchanged. This indicates that a correction of the long-term bias in the annual mean discharge over these areas is not sufficient. Only with the three-part bias correction does the KGE (Figure

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6 – right panel, Table 3 for selected rivers) improve considerably over these areas, with the largest improvements occurring over Scandinavia. The three-part bias correction also leads to some further improvements over Western and Central Europe, where the bias corrected discharge with the mean bias correction already shows relatively high KGE values, e.g. for the rivers Elbe, Rhine and Weser.

To visualise the effect of the three-part bias correction on the simulated daily discharges, we consider the corresponding discharge curves for the period 2000-2009 for selected large rivers. The respective biases and KGE are shown in Table 3 for the period 1979-2014. For the rivers, Elbe, Weser and Oder, the peak discharges are generally overestimated, while the low flows are close to the observed values (Figure 7). The correction of the high percentiles leads to a considerable improvement in the representation of the peak discharges, while the change in the low flows is rather small. The discharge of the Rhine (Figure 7) is well represented by HD5-WFDE5. However, the small downward correction of the peak discharges and the slight increase in the low flows still lead to an improved discharge curve, which is also indicated by the increased KGE (Table 3).

As mentioned above, the greatest improvements from the three-part bias correction compared to the application of the mean bias correction occur over Scandinavia. Here many rivers are highly regulated. For this reason, the discharge curves of the Daleaelven and Indalsaelven rivers are examined in more detail in Figure 8. The observed discharges clearly show the effect of the human regulation, where regulation leads to the elimination of peak discharges, while maintaining certain flows during low flow periods. Figure 8 shows that, on the one hand, peak discharges are often suppressed or reduced, especially during the spring, and that, on the other hand, low-flow periods are either almost absent (especially for the Indalsaelven) or show a rather noisy, unnatural daily variability. Here, the bias correction partially mimics these regulation effects by reducing the peak discharges and increasing the low flows.

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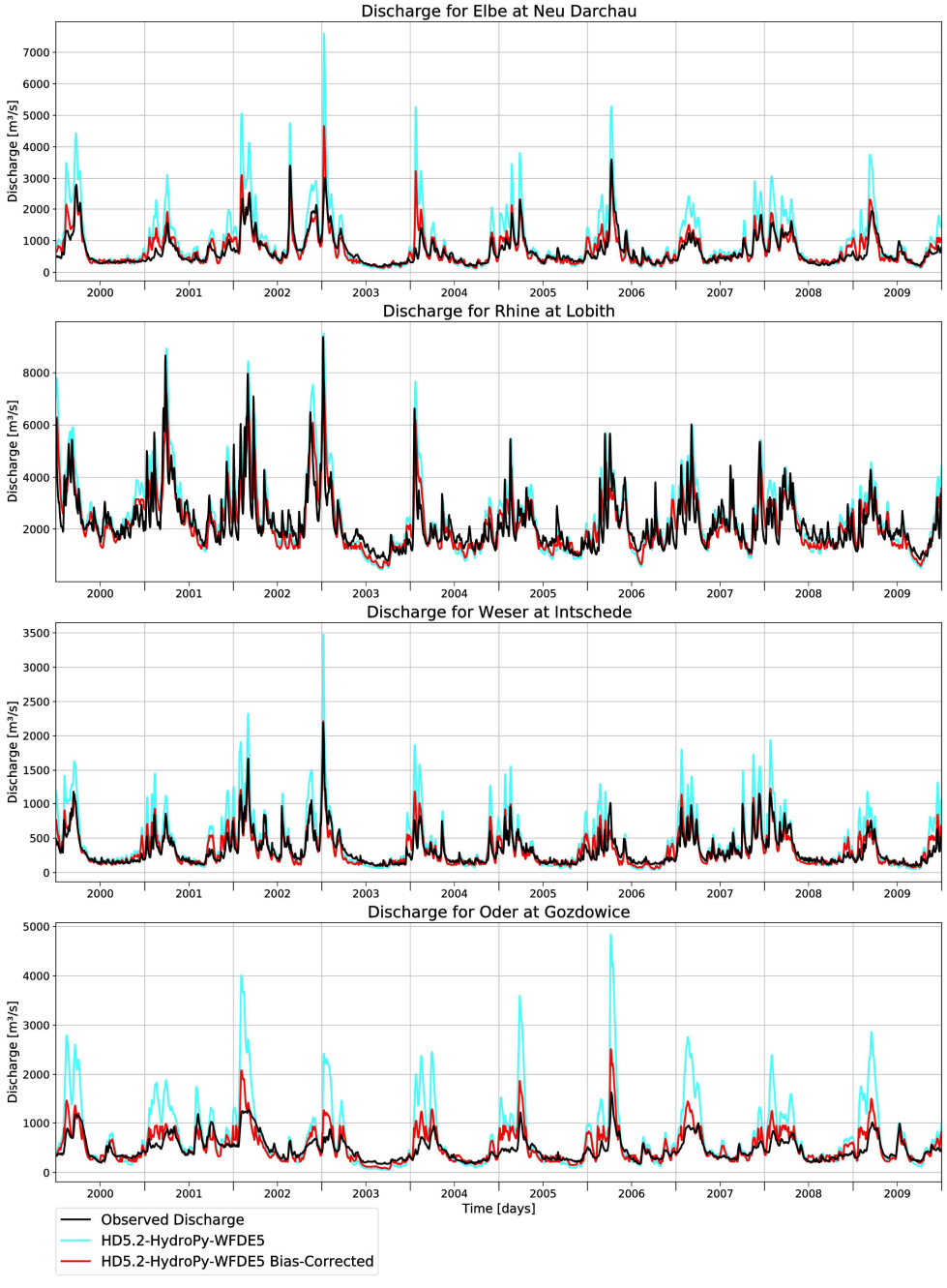

Figure 7. Observed and simulated daily discharges for the rivers Elbe (1st panel), Rhine (2nd panel), Weser (3rd panel) and Odra (4th panel) during 2000-2009.

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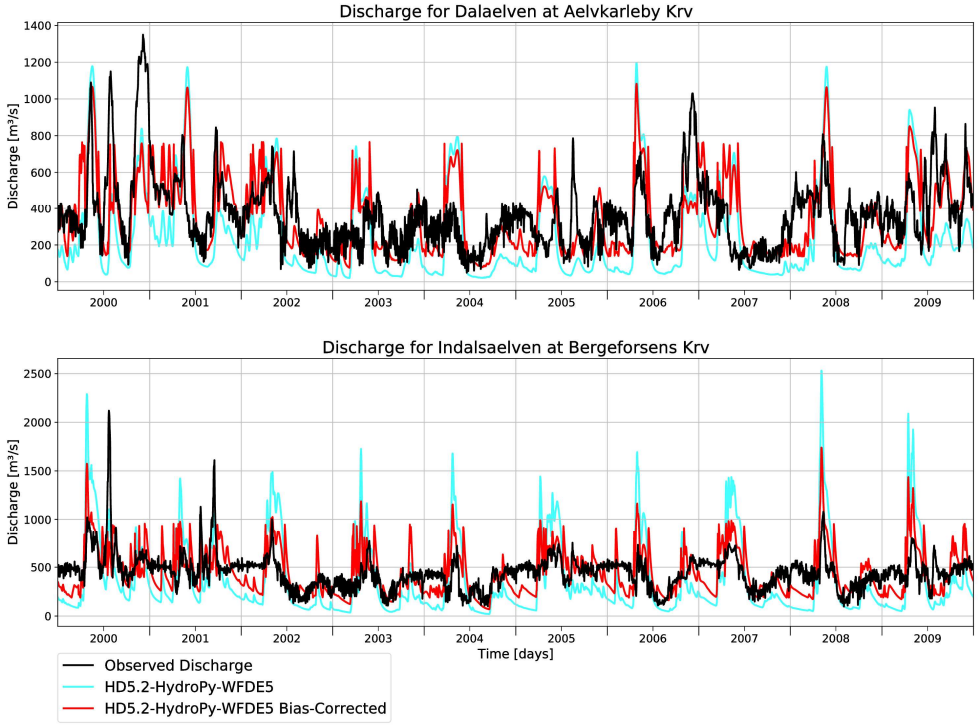

Figure 8. Observed and simulated daily discharges for the rivers Dalaelven (1st panel) and Indalsaelven (2nd panel) during 2000-2009.

3.3 Application of the bias correction for a different time period

To consider the effect of the bias correction for the applications over different time periods, we derived bias correction factors for HD5-GSWP3 during 1979-2014 and applied the factors for the period 1950-1978.

For HD5-GSWP3, the distributions of bias and Kling-Gupta efficiencies are quite similar between the two periods 1950-1978 (Figure 9 – left column) and 1979-2014 (Figure 5 – left column). Consequently, the bias correction leads to similar improvements in the KGE (Figure 9) as for the most recent period (not shown). The bias also becomes small for most of the rivers. Noticeable exceptions are the Dnjepr, Volga and some rivers in Southern Europe. This may be related to differences in the anthropogenic influence on the discharge between the two periods, as is the case for the river Ebro. Here, the large wet bias (51.65 %) in the more recent period is contrasted with a small wet bias (12.05%) in the earlier period (Figure 10). Since large anthropogenic water abstractions occur in the Ebro River (Merchán et al., 2013), this seems to be related to the different irrigation activities in the two periods, which are much more pronounced in the more recent years. The latter can be seen by looking at the observed daily discharges between 1960-1969 and 2000-2009 (Figure 10). In the earlier period, the Ebro discharge still shows some variations according to the sequence of weather events in the dry season. However, in the later period, the observed discharge includes only very small variations during the dry season, indicating more intense human water abstraction than in the earlier

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period. Consequently, the bias correction based on the recent wet bias leads to a dry bias (-25.78 %) in the corrected Ebro discharge in the earlier period. However, the KGE decreases only slightly from 0.68 to 0.63, so that the deterioration of the mean bias seems to be largely compensated by the correction of the different percentile ranges.

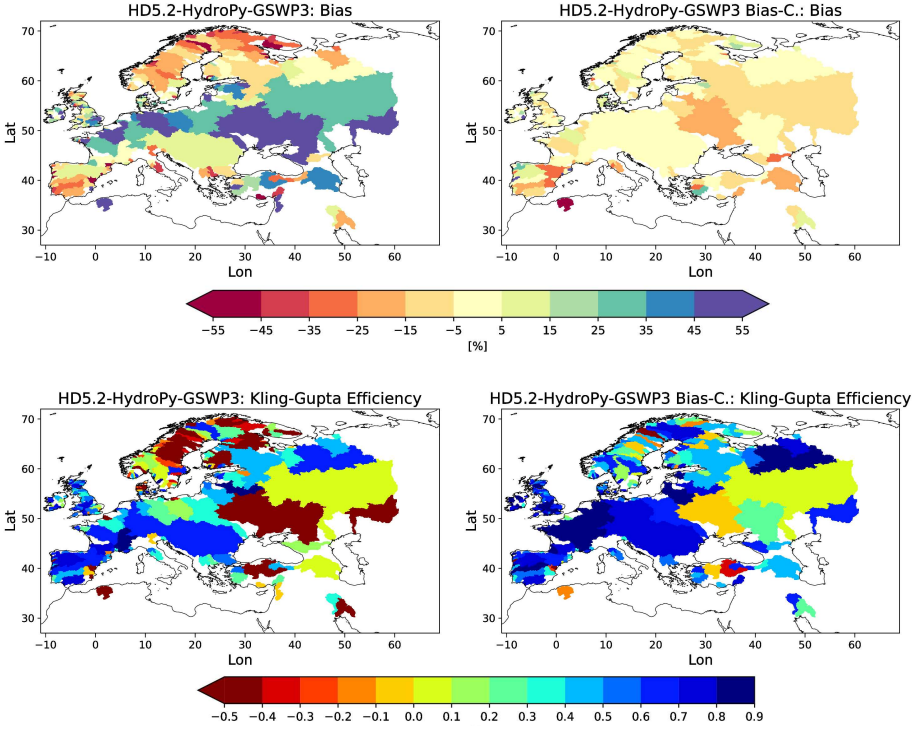

Figure 9. Mean discharge bias [%] (upper row) and Kling Gupta efficiencies (lower row) for HD5-GSWP3 (left) and bias corrected HD5-GSWP3 data (right) during 1950-1978.

4 Evaluation of the inflow into sea basins

To evaluate the simulated and bias corrected discharges at the river mouths, we considered the integrated inflow into different sea basins. First, we evaluated the discharges into the Baltic Sea using HELCOM and IGC-EMO data in Section 4.1. We then compared the discharges to the North Sea and the Northeast Atlantic with OSPAR and up-scaled (see Section 2.5) IGC-EMO data in Section 4.2.

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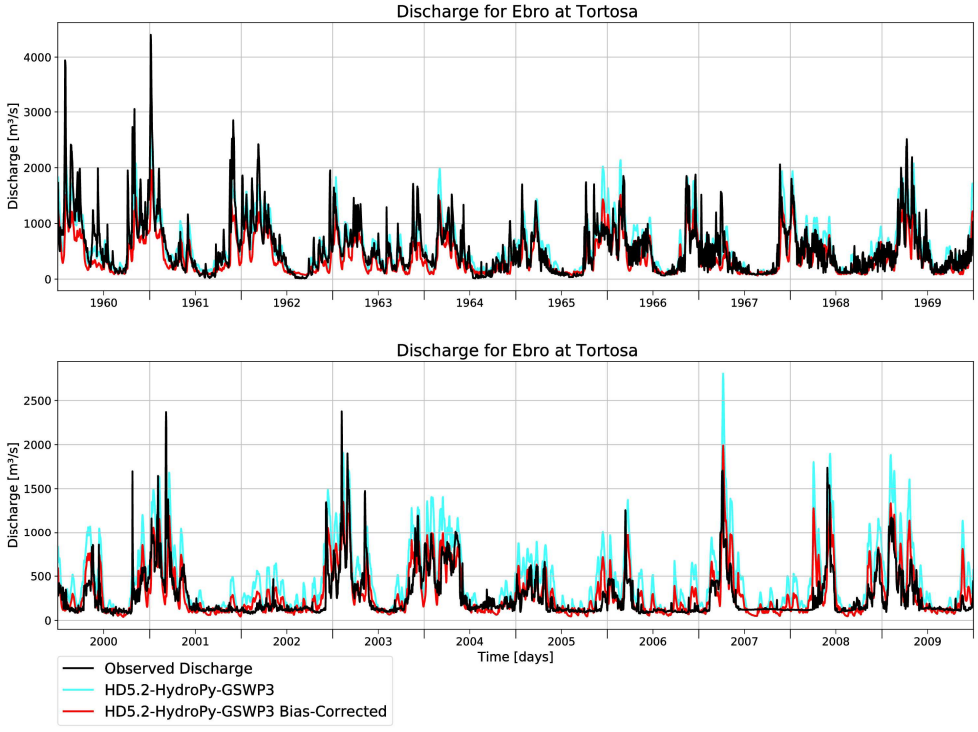

Figure 10. Observed and simulated daily discharge of HD5-GSWP3 for the Ebro river during 1960-1969 (1st panel) and 2000-2009 (2nd panel).

4.1 Baltic Sea

In order to achieve a maximum overlap of the simulated discharge time series data with the HELCOM data (cf. Section 2.5), we considered 1995-2019 as the evaluation period for the Baltic Sea and its seven sub-basins (Figure 4 – upper panel). For the whole Baltic Sea and most of its sub-basins, the bias correction improves the basin inflows if compared to the HELCOM estimates (Table 4, Figure 11). Only for the Gulf of Finland and the Gulf of Riga, the bias correction leads to a slightly larger bias while the biases of HD5-WFDE5 in these basins are relatively small. When the simulated inflows are compared with the IGC-EMO estimates, similar results are obtained, except for the Gulf of Riga. Here, the IGC-EMO estimates are about 32% larger than the HELCOM estimates, indicating a larger uncertainty in at least one of these two estimates. For the Gulf of Riga basin, the major part of the inflow is contributed by the Daugava river. In IGC-EMO, the discharge from the Daugava is based on observed time series from 1970-1990. These data were extended to earlier and later periods, e.g. by climatological values and trend preservation (Van Leeuwen and Hagemann, 2023). For 1970-1990, the mean IGC-EMO discharge comprises 623 m³/s at the Daugava mouth, while this has increased by ca. 45% in 1995-2019 (902 m³/s). However, this strong increase cannot be seen in the observed discharge time series at the station Daugavpils that covers about three quarter of the Daugava catchment. Here, the discharge increases only slightly from 1970-1999 (439 m³/s; 95% temporal data coverage) to 1995-2019 (452 m³/s; 83% temporal data coverage). This

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indicates a large overestimation of the IGC-EMO Daugava discharge during 1995-2019 and, hence, also of the respective Gulf of Riga inflow.

Table 4. Estimated and simulated inflows (unit: m³/s) into the Baltic Sea and its major sub-basins during 1995-2019. Note that for the Danish Straits no IGC-EMO estimate is provided as the respective catchment area coverage of the rivers in IGC-EMO is too low.

Sea basin	HELCOM	IGC-EMO c.	HD5-WFDE5	HD5 Bias C.
Baltic Sea	15676	15286	14764	15995
Bothnian Bay	3444	3420	2642	3369
Bothnian Sea	2913	3038	2347	3391
Gulf of Finland	3519	3448	3520	3612
Gulf of Riga	1071	1411	1114	1017
Baltic Proper	3436	2901	4070	3377
Danish Straits	217	0	198	222
Kattegat	1077	949	873	1008

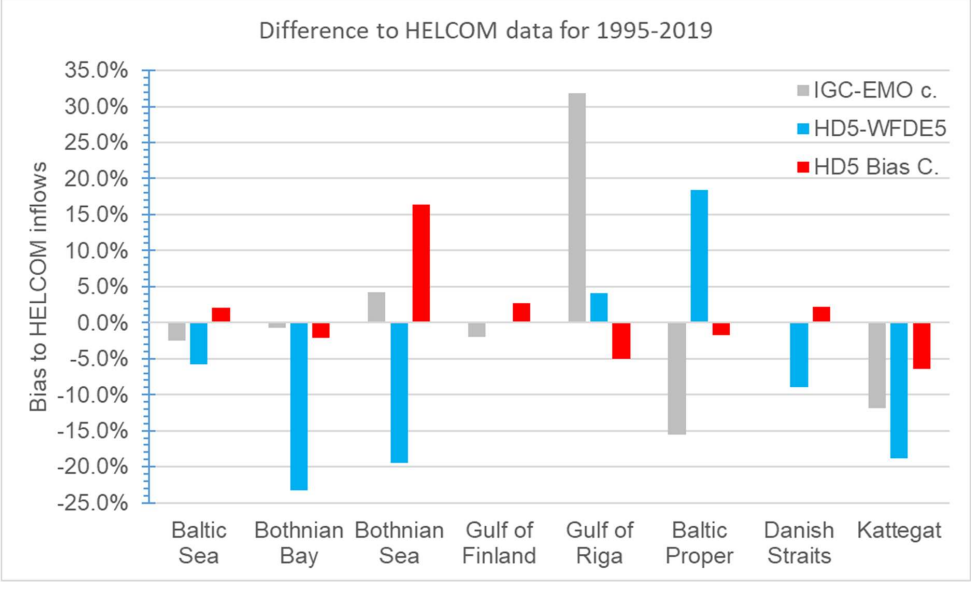

Figure 11. Relative difference in basin inflows compared to HELCOM data for 1995-2019. Note that no IGC-EMO estimate is provided for the Danish Straits as the respective river catchment coverage in IGC-EMO is too small.

4.2 North Sea and Northeast Atlantic

Due to the different treatment of unmonitored regions by the OSPAR countries (cf. Section 2.5), and thus of the respective sea basin areas, we have not corrected the OSPAR inflows. Instead, we have also considered up-scaled IGC-EMO data as alternative estimates of basin

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inflow (as in Section 4.1). Table 5 shows simulated and estimated basin inflows for the considered OSPAR regions (cf. Figure 4 – lower panel). Note that IGC-EMO data for the Norwegian shares of the Barents Sea, Norwegian Sea and North Sea, and the North Spanish Atlantic are not included in the following comparisons due to their limited area coverage. When comparing the simulated sea basin inflows with the OSPAR and IGC-EMO data, we found that the bias correction improves the simulated inflows for most of the OSPAR regions (Figure 12). Exceptions are the values for the Celtic Sea and the Irish Sea. For the Celtic Sea, the bias corrected inflows are very close to the uncorrected inflows and the difference to the OSPAR data is rather small. For the Irish Sea, the bias corrected inflows are somewhat larger than the uncorrected ones, with both showing large differences (52.5% and 47.5%) to the OSPAR data. Here both inflows are closer to the IGC-EMO estimate, which exceeds the OSPAR estimate by about 40%.

Table 5. Estimated and simulated inflows (unit: m³/s) into major sub-basins of the North Sea and the Northwest Atlantic during 1961-1990. Note that the North Sea does not comprise Skagerrak and the English Channel. Up-scaled IGC-EMO basin estimates for which the fractional area coverage of IGC-EMO rivers is less than 75% are considered as highly uncertain and are therefore only given in brackets (cf. Sect. 2.5). The same applies to the OSPAR inflow into the Northern Spanish Atlantic.

Sea basin	OSPAR	IGC-EMO c.	HD5-WFDE5	HD5 BiasC.
North Sea	9190	6600	9798	9164
Norwegian North Sea	3534	(1499)	2038	2856
Norwegian Barents Sea	2294	-	1106	1723
Norwegian Sea	3663	-	2242	2922
Skagerrak	2544	2113	1956	2292
German Bight	1344	1505	2025	1419
English Channel	1250	1011	1498	1222
Celtic Sea	976	839	1016	1016
Irish Sea	672	939	992	1025
French Atlantic	2862	2391	3147	2684
Northern Spanish Atlantic	(359)	(1655)	1104	1550

While the OSPAR values from Ireland include estimates for unmonitored areas, this is not the case for the UK (Table 2). Farkas and Skarbøvik (2021) list the rivers contributing to the OSPAR value (560 m³/s) from the UK part of the Irish Sea catchment (35000 km²). Adding up the catchment areas of each river, obtained from various online resources, gives a coverage of about 70%. In order to account for this under-representation of the catchment area, an up-scaling can be performed, similar to the treatment of the IGC-EMO data. This would give an estimate of about 803 m³/s for the UK Irish Sea inflow and thus 915 m³/s for the whole Irish Sea. The respective IGC-EMO inflow is close to this value (+2.6%) and the overestimation of inflows is less pronounced for HD-WFDE5 and bias corrected discharges with +8.4% and +12% respectively.

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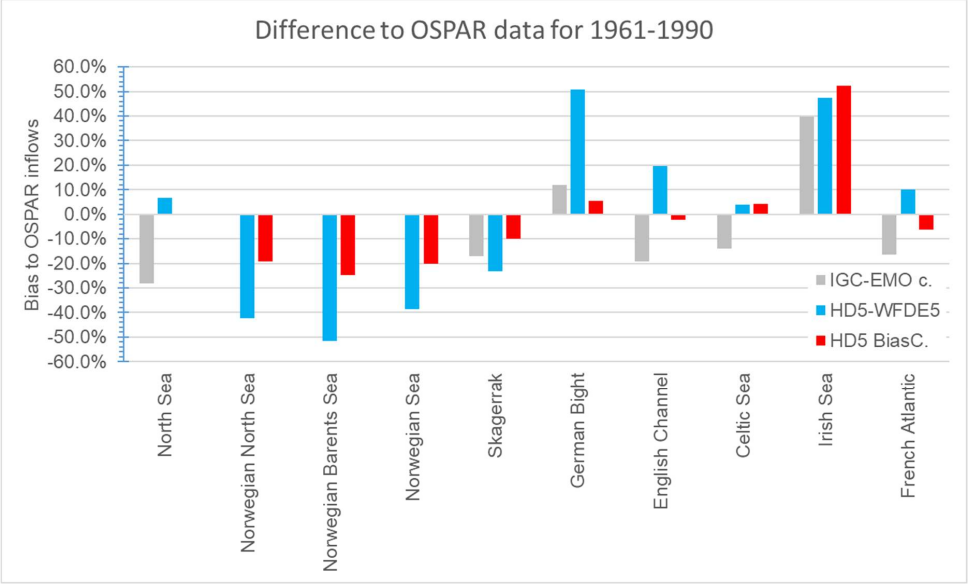

Figure 12. Relative difference in basin inflows compared to OSPAR data for 1961-1990. IGC-EMO basin estimates for which the fractional area coverage is less than 75% are not shown.

4.3 Simulated salinity in the German Bight

Using the two experiments described in Sect. 2.6, we evaluated the simulated sea surface salinity (SSS) with satellite-based analyses and in-situ observations for the period 2010 to 2018. The SSS analyses were derived using a multivariate optimal interpolation algorithm that combines sea surface salinity images from several satellite sources, such as the National Aeronautics and Space Administration (NASA) Soil Moisture Active Passive (SMAP) satellite and the European Space Agency (ESA) Soil Moisture Ocean Salinity (SMOS) satellite, with in-situ salinity measurements (Droghei et al., 2018). These SSS data are available with a spatial resolution of 0.125°.

Figure 13a shows the mean analysed SSS in the German Bight for the period 2010-2018, with lower salinities near the west coast of Germany and higher salinities towards the west. The NEMO simulation using the uncorrected discharges of HD5-WFDE5 (Figure 13c) has too low SSS in coastal areas, especially near the estuaries. This low bias is reduced using the bias corrected discharges (Figure 13d), as the general effect of the bias correction in the German Bight leads to reduced riverine inflows (cf. Figure 12) and hence increased SSS in coastal areas (Figure 13b).

In addition, we had access to salinity measurements at three stations in the German Bight operated by the BSH as part of the Marine Environmental Monitoring Network in the North and Baltic Seas (MARNET). These three stations are Deutsche Bucht (DB; located at 54.17ºN, 7.45ºE), EMS (54.17ºN, 6.35ºE) and Nordsee Boje II (NSB; 55ºN, 6.33ºE) and their locations are shown in Figure 13. In general, the bias corrected discharges lead to an improved simulation of the daily salinity at 6 m depth at the stations DB and EMS. Here the RSME decreases from

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1.70 to 1.45 and from 1.43 to 1.32, respectively. It seems that in NEMO the positive effect of using bias corrected discharges is limited to near-surface salinities, as there is no noticeable effect at 30 m depth (not shown). NSB is not considered in detail as it is located further offshore where no noticeable SSS changes were introduced by using bias corrected discharges (Figure 13b).

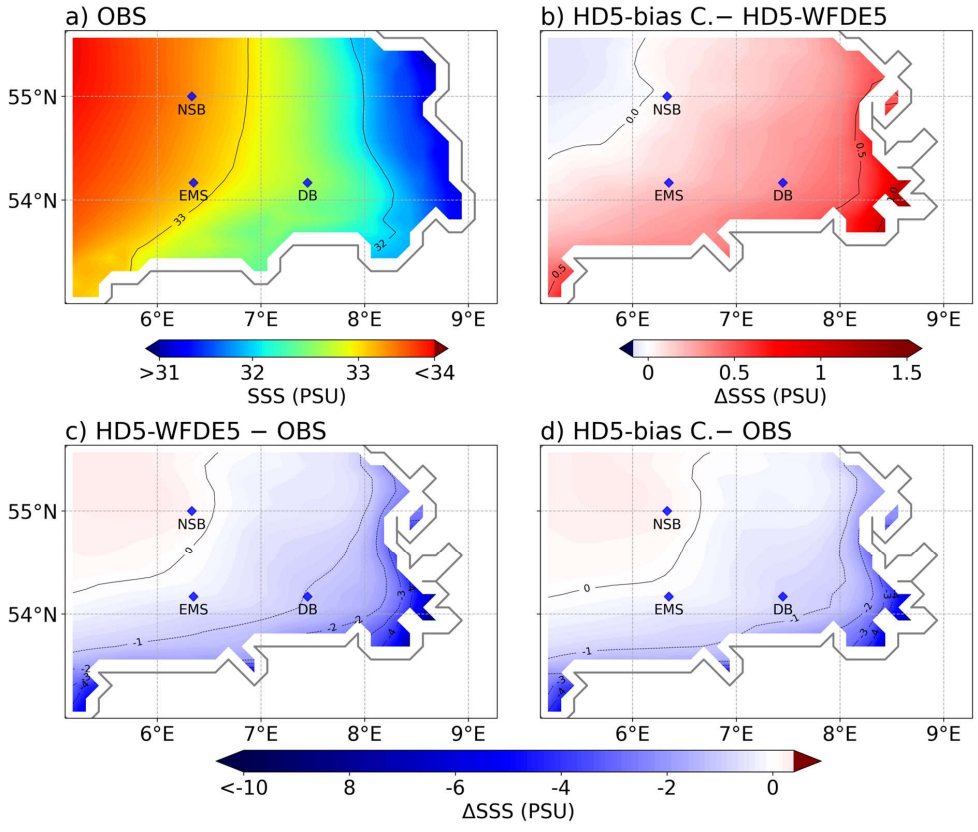

Figure 13. Mean analyzed SSS: a) OBS and various SSS differences of the NEMO experiments in the German Bight for the period from 2010 to 2018. The SSS differences comprise b) HD5-Bias C. minus HD5-WFDE5, c) HD5-WFDE5 minus OBS, and d) HD5-Bias C. minus OBS.

In summary, the results of the NEMO experiments indicate the beneficial effect of using bias corrected discharges on the simulated SSS in coastal areas. However, although the low SSS biases are reduced by using the bias corrected discharges, the simulated SSS is still underestimated in coastal areas, especially close to the estuaries of large rivers (Figure 13d). This may be attributed to the rather smooth coastline of the NEMO ocean grid. Here, most parts of the large estuaries of the rivers Elbe, Ems and Weser are not included. In reality, a major part of the mixing of the riverine freshwater inflow and the saline North Sea happens within these estuaries. In the NEMO model setup, the freshwater inflow is introduced at the respective river mouth points of the smooth NEMO coastline where it starts to mix with the saline North Sea water. Consequently, the simulated water at and near those points is much fresher than in reality,

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which leads to the low SSS bias. Note that on the one hand such a smooth coastline is necessary in NEMO to avoid numerical instabilities. On the other hand, the spatial resolution of the NEMO grid is not high enough to adequately resolve parts of the longer estuaries.

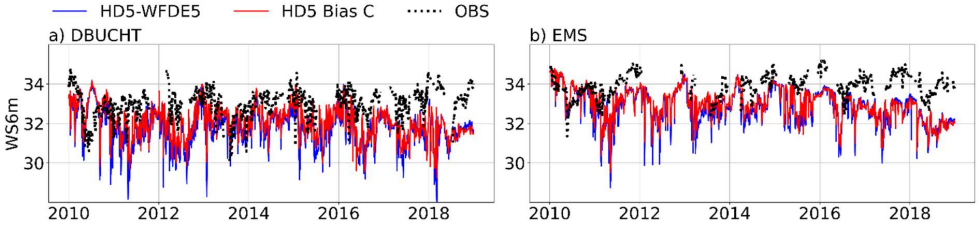

Figure 14. Observed and simulated daily time series of salinity in 6 m depth for the MARNET stations: a) DB and b) EMS. Unit: PSU

5 Summary and Conclusions

In the present study, we have introduced a methodology for the bias correction of European river runoff to provide corrected riverine inflows as forcing for ocean models in offline and coupled system model simulations. The central part of this methodology is a three-part bias correction, which can correct different biases for low, medium and high discharges. The bias correction parameters are derived in two steps. First, different correction factors for low, medium and high flows are derived for each river considered (cf. Sect. 2.5) at the location of the most downstream station for which daily discharge measurements were available. These factors were then transferred to the respective river mouth on the HD model grid and to adjacent coastal inflow points in its vicinity.

The evaluation of the bias corrected discharge at the station location showed that the bias correction greatly improved the simulated discharges. For the evaluation of the bias corrected discharge at the downstream station locations, we considered the mean bias and the KGE, which is a quality metric combining bias, correlation and coefficient of variation. Considering the same period as used to derive the bias correction factors, the mean bias is trivially close to zero. However, the bias is also substantially reduced for most rivers if a different period is considered. Irrespective of the period, the KGE pattern generally improves for the bias corrected discharges and shows high values for many rivers. Exceptions are those rivers with a very strong anthropogenic distortion of the natural flow, e.g. by many dams or large water withdrawals. Here, despite of some improvements, the KGE values are still rather low, such as for the rivers Dnjepr, Volga, Luleälven and a few Turkish rivers flowing into the Black Sea. The KGE also shows the beneficial effect of the three-part bias correction, as correcting only the long-term mean annual discharge bias is not sufficient in many areas, especially in northern Europe. We found that the three-part bias correction often improves the KGE in regulated rivers, so that it appears to mimic the effect of regulation, where regulation leads to the elimination of peak flows while maintaining certain flow levels during low flow periods.

The evaluation of riverine inflows to the sea at river mouths with observed daily discharge is rarely possible as there are usually no river gauges available. Even if there is a gauge at the mouth of a river, the measurements are often affected by tidal influences from the coast, so that the measured amounts may not represent the actual river discharge. For obvious reasons, it is also difficult to compare simulated inflows with observed discharges for unmonitored rivers.

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Therefore, we compared the simulated and bias corrected discharges with long-term mean inflow estimates into different sea basins from HELCOM, OSPAR and IGC-EMO. For most of the basins considered, the bias correction improves the simulated inflows. This indicates a reasonable performance of the approach to transfer the bias correction factors obtained at the downstream stations to the respective river mouths and adjacent coastal areas. Exceptions are the Gulf of Finland, the Gulf of Riga, the Celtic Sea and the Irish Sea. For the Gulf of Finland and the Celtic Sea, the deviations of the uncorrected and bias corrected inflows from the inflow estimates are rather small. For the Gulf of Riga, the deviations of the uncorrected and bias corrected inflows from the HELCOM estimates are also small, but they significantly underestimate the IGC-EMO estimates. However, this could be due to a large overestimation of the Daugava discharge during the period 1995-2019 in the IGC-EMO data and thus also of the corresponding Gulf of Riga inflow. For the Irish Sea, IGC-EMO seems to be closer to reality as the OSPAR inflow does not cover the unmonitored rivers in the British part of the catchment.

A caveat applies for rivers where the human influence on river flow has changed significantly over time. Applying bias correction factors derived for 1979-2014 to earlier periods may lead to errors for regulated rivers in years before these regulatory measures were implemented. This is the case for the Ebro, where irrigation activities have largely intensified during the period 1979-2014 compared to earlier periods (see Sect. 3.3). A detailed analysis of the rivers and periods concerned is beyond the scope of this study. However, at least for the period 1950-1978, the KGE distribution does not seem to be significantly affected, as there is no noticeable deterioration.

We have shown that our bias correction method works well for Europe at the station locations as well as for the riverine inflow into northern and western European sea basins. Using two NEMO simulations in the German Bight, we have also shown that the use of the bias corrected discharges as forcing leads to an improved simulation of sea surface salinity in coastal areas. However, for the potential transfer of the bias correction methodology to other regions, it has to be pointed out that the application of the three-part bias correction over a region only makes sense if a large part of the catchment area is covered by available daily discharge measurements. As the three-part bias correction is based on biases in three percentile ranges of daily flows, it is also suitable for the use in climate change applications. Here the bias correction factors can be derived from a historical discharge simulation and then applied to future projections or past reconstructions. In addition, the bias correction can also be applied in Regional Coupled System Model (RCSM) simulations, where the bias correction factors can be derived from an initial simulation and then applied during the run-time of the actual RCSM simulation. This capability has been implemented in the HD model v5.2.2 (Hagemann et al., 2023b) and is currently being applied in the GCOAST AHOI system (Ho-Hagemann et al., 2020). Finally, we note that the bias corrected discharges are available from the World Data Centre for Climate and are already used within the CoastalFutures project (https://www.coastalfutures.de).

Data Availability Statement

Many of the observed daily discharge data used can be obtained from the GRDC (https://grdc.bafg.de/GRDC/EN/02_srvcs/21_tmsrs/riverdischarge_node.html). Other data have been retrieved from public websites associated with the sources referred to in Sect. 2.5. GSWP3 data were retrieved from the ISIMIP data portal (https://data.isimip.org) and WFDE5 data were retrieved from the Copernicus Climate Data Store (https://cds.climate.copernicus.eu). OSPAR data were taken from an OSPAR report (Farkas and Skarbøvik, 2021) or its associated

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data available on the OSPAR webpage (https://odims.ospar.org/en/search/?dataset=rid-data-reports). This study has been conducted using E.U. Copernicus Marine Service Information data on SSS (https://doi.org/10.48670/moi-00051) and some French discharge measurements. The daily data of surface runoff and subsurface runoff as well as the simulated and bias corrected discharge data (Hagemann and Stacke, 2023) can be accessed via the World Data Centre for Climate (WDCC) at DKRZ.

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Author Contributions

SH developed and applied the three-part bias correction, conducted the discharge simulations and analysis of results, and wrote the manuscript. HH conducted the NEMO simulations, helped with the analysis of results and revised the manuscript. TN evaluated the SSS data of the NEMO simulations, helped with the analysis of results and revised the manuscript.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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