Point-by-point response to Harrigan et al. GloFAS-ERA5

Dear David,

We thank again both Anonymous Referee's for their comments and constructive feedback. We believe their clarifications have sharpened the manuscript and made it clearer for the reader. Our point by point responses to each of their comments are provided below in blue together with their original review in black. Where the text is changed in the resubmitted manuscript is highlighted and a marked up version of the resubmitted manuscript is attached at the end of this document.

Response to Anonymous Referee #1

In this paper, the authors reported a newly developed river discharge dataset at the global scale using a meteorological reanalysis dataset and evaluated its performance. Since this river discharge dataset is very promising in terms of high resolution (0.1 degree) and feasibility for real-time update, it will benefit potential users among hydrology and related-field communities. The contents of this paper are also suited for this journal. This paper is well organized. But there is some room for improvement before publication. In particular, since this paper targets a new release of river discharge data and is intended to be published in the journal specialized for scientific data, methods and processes used in producing the dataset should be solidly and clearly written.

Thank you for your positive comments and constructive feedback. We believe your clarifications have sharpened the manuscript and made it clearer for the reader.

MAJOR COMMENTS

Figure 1: Since the spatial resolution of LISFLOOD (0.1deg) is finer than that of ERA5 (0.28125deg), I guess a kind of downscaling techniques was used to produce the LISFLOOD dataset. However, there is no information (except "been resampled" in L138) on this process in this paper. How did the authors produce runoff data at a finer resolution in this paper? Did the authors weight the ERA5 runoff value (by something) during the "resampling"? Did the authors consider terrain effects within an ERA5 cell in allocating surface/subsurface runoff to multiple 0.1deg land cells? Please provide the procedure in detail.

Response: This question was also asked by Anonymous Referee #2. In order to be consistent with the operational GloFAS procedure, the runoff fields from ERA5 were downscaled using the simple nearest neighbour method from the native ERA5 to the 0.1° GloFAS grid. The task was done using the open source 'pyg2p' module with interpolation 'grib_nearest' option in Python (https://pypi.org/project/pyg2p/). No weights were applied to runoff values and terrain effects within the ERA5 cell were not considered.

Change: We have added the following sentence into L151-153 in the resubmitted manuscript: "In order to be consistent with the operational GloFAS procedure, the runoff fields from ERA5 were downscaled using the simple nearest neighbour method from the native ERA5 to the 0.1° GloFAS grid."

Sect. 2.2 and Figure 1: The authors describe surface and subsurface runoff data originally generated from the HTESSEL land model. I think the runoff scheme directly affects the river discharge data, but less information about it is provided. To which depth of soil layer did the authors consider as the subsurface runoff? Regarding the description in L125-127, how much delays were considered before the subsurface water returns back to the river channel in the LISTFLOOD ground water module? Does it depend on the soil properties?

Response: The HTESSEL land surface model is used to calculate the water balance at the land surface. Excess precipitation and snowmelt are partitioned as surface runoff or infiltrated into a four-layer soil column (7 cm depth for top layer and then 21, 72, and 189 cm) at each ERA5 grid cell, before draining from the bottom of the soil column as sub-surface runoff. Water moving (vertically) through the soil column does depend on soil properties. There are six soil texture classes in HTESSEL (e.g. coarse or very fine) that determine hydraulic properties. Therefore, the soil properties will determine the amount of time it takes for water to exit at the bottom of the soil column as sub-surface runoff. Further information on the details is provided in Balsamo et al. (2009).

As mentioned in L125-127, the HTESSEL sub-surface runoff is used as input to the LISFLOOD groundwater module, which consists of two parallel linear reservoirs (upper zone for quick and lower zone for slower groundwater flow) that store and subsequently transport water to the river channel with a time delay. In Hirpa et al. (2018), the upper zone time constant was given a default value of 10 days with a lower (upper) bound of 3 days (40 days) during calibration. The upper zone time constant has a default value of 200 days with a lower (upper) bound of 40 days (500 days) during calibration.

Change: We have added the following sentence into L119-122 in the resubmitted manuscript: "Excess precipitation and snowmelt are partitioned as surface runoff or infiltrated into a four-layer soil column (7 cm depth for top layer and then 21, 72, and 189 cm) at each ERA5 grid cell, before draining from the bottom of the soil column as sub-surface runoff (Balsamo et al., 2009)".

We have added the following sentence into L139-141 in the resubmitted manuscript: "In Hirpa et al. (2018), the upper zone time constant was given a default value of 10 days with a lower (upper) bound of 3 days (40 days) during calibration. The upper zone time constant has a default value of 200 days with a lower (upper) bound of 40 days (500 days) during calibration".

L132-135: The authors describe flow alteration by lakes and reservoirs, but readers cannot figure out how much the flow is altered by them. Did the authors use a kind of algorithms of flow alteration or dam manipulation? The authors also discuss the limitation of this dataset as "While GloFAS-ERA5 reanalysis does represent major dams and reservoirs on the modelled river network, it does so in a simplified way and does not include operational operating schedules for individual structures. (L298-299)" in a later section, but due to the lack of description on dam operation schemes employed in this paper, it is very difficult to have a clear image on that. What does "a simplified way" mean? In addition, how the authors treat river water withdrawal from rivers for human activities (agriculture, industrial, etc.) in this dataset? Please provide information about it in detail.

Response: Reservoir outflow is calculated with a set of simplified rules depending on their filling level, and balances water recharge if storage is below normal or release if above normal. There is a minimum outflow to ensure the downstream river does not dry up, and a non-damaging release so the reservoir does not reach full capacity. Simplified reservoir operating parameters were used based on expert opinion (outlined in Zajac et al., 2017) given lack of availability of global operational release records.

As mentioned in our reply to Anonymous Reviewer #2, we propose to add a new table (Table A below) to accompany Fig. 1 in the resubmitted manuscript that makes it clearer for the reader to find the open access publications outlining the full methodological details of the key components of GloFAS-ERA5.

Change: We have added Table A (below), as the new Table 1 with the following sentence in L105-107 in the resubmitted manuscript: "The open access scientific publications and model documentation that describe the full methodological detail for each key component is provided in Table 1 and summarised below". This table includes reference to the full LISFLOOD model documentation (Burek et al., 2013).

Table A: Scientific papers and model documentation for the key components in the production of GloFAS-ERA5 v2.1 river discharge reanalysis dataset.

GloFAS-ERA5 component	Description	Reference
ERA5	Global reanalysis dataset using ECMWF Integrated Forecast System (IFS) model cycle 41r2 from 1979 to present	Hersbach et al. (2020)
ERA5 runoff	Surface and sub-surface runoff within ERA5 generated using the HTESSEL land surface model	Balsamo et al. (2009)
LISFLOOD river discharge	River discharge generated using LISFLOOD hydrological and channel routing model to route runoff into and through the river network and provide groundwater storage. LISFLOOD includes lake, reservoir and human water use routines	Burek et al. (2013)
Lakes and reservoirs used in GloFAS	Incorporated 463 lakes and 667 reservoirs into the GloFAS river network	Zajac et al. (2017)
Calibration of LISFLOOD used in GloFAS	LISFLOOD was calibrated against daily river discharge from 1287 observation stations worldwide	Hirpa et al. (2018)

Sect. 4.3: The authors provide monthly performance of this dataset. Such information is very useful, however, it is very difficult to interpret this seasonality, because the results are (probably) a mixture of contributions from both the northern and southern hemispheres. Have the authors made similar analysis for each hemisphere? The authors state "Attribution of such biases in the GloFAS-ERA5 reanalysis is outside the scope of this data paper (L293)", however, practical information on the seasonal performance of this dataset will be very beneficial for potential data users. In my view, the authors should add and show, at least, whether a larger bias ratio observed in the months of November to March than the other months (Fig 7c) is attributable to winter discharge from the northern hemisphere or summer discharge from the southern hemisphere (or a mixture of them; or from some specific regions).

Response: This is a very good suggestion. We have conducted your proposed analysis (Fig. A) and found that while the overall GloFAS-ERA5 monthly performance in each hemisphere does not change substantially from the global analysis (Fig. 7 in the original paper), there are some differences worth reporting.

Change: Fig. A is added to the resubmitted manuscript as a new Fig. 9 together with the following additional paragraph in Sect. 4.3:

“Results are grouped into northern (n=1268 stations) and southern (n=533 stations) hemispheres in Fig. 9. The overall GloFAS-ERA5 monthly performance in each hemisphere does not change substantially from the global analysis (Fig. 8). Nevertheless, there are some differences. The KGESS and bias ratio from the northern hemisphere (Fig. 9a and c, respectively) tend to follow the global analysis most strongly (i.e. Fig. 8a and c, respectively), which is not surprising given 70 % of all stations are located in the northern hemisphere. However, a higher proportion of southern hemisphere stations show large positive biases from April to June, compared to November to March in the northern hemisphere. The largest proportion of stations with negative KGESS in the southern hemisphere are found from August to October (Fig. 9a). These months correspond with lower southern hemisphere correlation (Fig. 9b) and a higher proportion of stations with large positive variability ratios (i.e. GloFAS-ERA5 has higher variability than observed river discharge).”

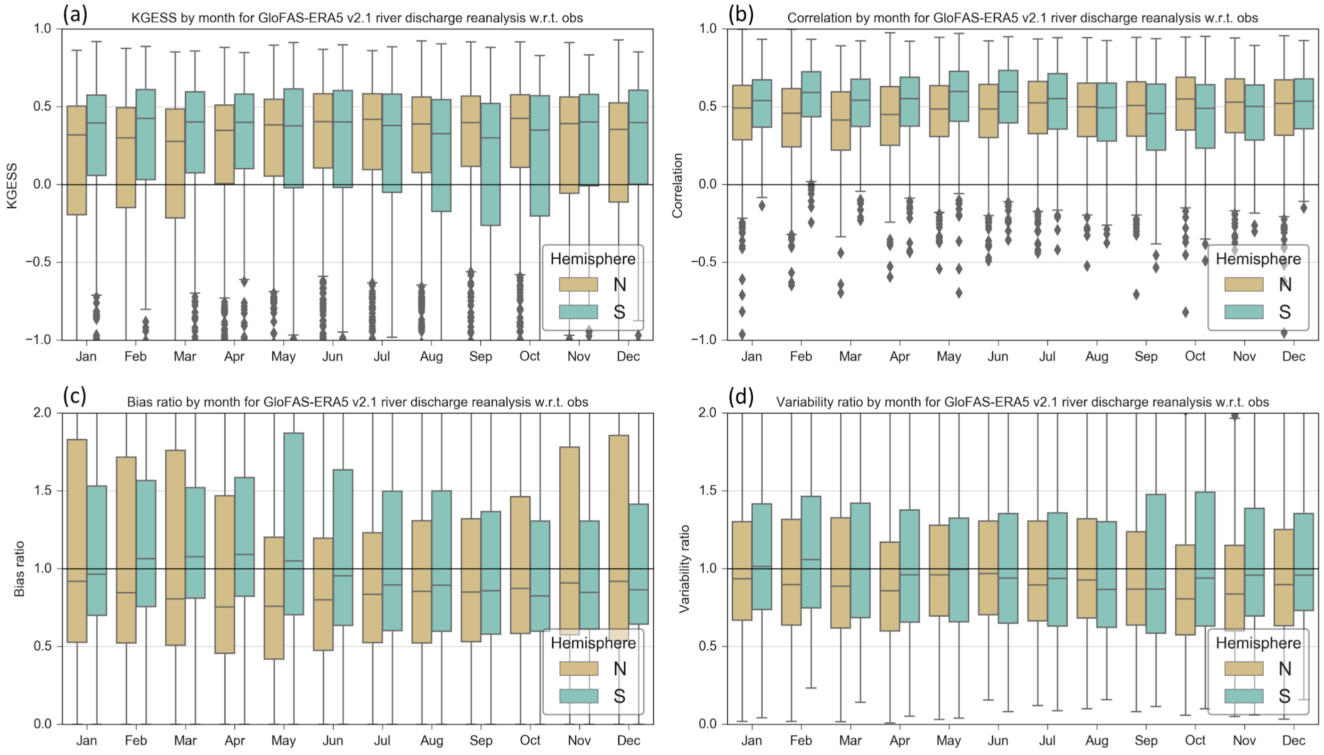

Figure A: Performance metrics for each month by hemisphere. Modified Kling-Gupta Efficiency Skill Score (KGESS) (a) with decomposition of KGE’ into Pearson correlation (b), bias ratio (c), and variability ratio (d). Brown (green) boxes represent the IQR and horizontal grey line the median for the northern (southern) hemisphere. Whiskers extend to the most extreme data point, unless the data point is more than 1.5 times the IQR from the box and is instead represented as an outlier (grey diamond).

MINOR COMMENTS L139:

Is a one-year spin-up enough for this simulation? Probably this depends on the groundwater module or dam operation schemes (the information is not clearly written in the current manuscript, though) used in this model.

Response: The initialisation routine within LISFLOOD has been designed so that one year is sufficient to estimate the initial state of all the state variables. For state variables that are fast responding and can reach equilibrium quickly (e.g. storage in the upper groundwater zone), a value of 0 can be used at start of the run and one year is more than long enough. However, for other state variables that are slowly responding it is correct that one year can be too short in some model calibration routines, especially for catchments with large groundwater stores. To avoid the need for very long spin up periods, LISFLOOD calculates a "steady-state" storage amount for the lower groundwater zone during a long-term pre-run, and thus reduces the lower zone's spin up time (Burek et al., 2013).

Change: We have added the following sentence into L153-155 in the resubmitted manuscript: "To avoid the need for very long spin up periods, LISFLOOD calculates a "steady-state" storage amount for the lower groundwater zone during a long-term "pre-run", and thus reduces the lower zone's spin up time (Burek et al., 2013)".

L191: The authors used "1801 catchments" here, but this expression might be confusing if there are multiple gauge stations in a large river system. I think dividing this sentence into two parts (and used "1801 stations" in the former one) will be clearer for understanding.

Change: We changed "1801 catchments" to "1801 stations" in L207 in the resubmitted manuscript.

Sect. 4.2: The authors discuss the results by using both the bias ratio (beta) and PBIAS, but this might be confusing. For example, "-9%" in L241 is PBIAS, due to its negative value, I guess.

Response: The bias term in the decomposition of the KGE' is the bias ratio β but can easily be converted to the more widely used percent bias (PBIAS) by $(\beta - 1) \times 100$ (as shown in L205-206 in the submitted manuscript). PBIAS was also used in Lin et al. (2019) when considering what we mean by a "very good" bias error in global hydrological modelling (i.e. ±20 %), mentioned on L235-236. Our original intention was to report the bias in the text in the more widely used PBIAS form. However, your point is valid that it might actually be more confusing to the reader.

Change: We now report bias errors as bias ratios and variability errors as variability ratios as per Equations 2 and 3 in the resubmitted manuscript.

Response to Anonymous Referee #2

The paper entitled "GloFAS-ERA5 operational global river discharge reanalysis 1979- present" presented by Harrigan et al., describes re-analysis driven global river discharge simulations that are updated in near real time and distributed through the Copernicus Climate Change Service Climate Data Store. Overall, the paper is well written and provides the reader with an overview on the methods used for data production, file formats and the performance of the data set.

Thank you for your positive comments and constructive feedback. Your clarifications have improved the manuscript and made it clearer for the reader.

Given, that this paper is a data-descriptor and neither a model documentation nor a research article there is little to criticize. Nonetheless, some aspects of the paper would benefit from additional information. My main points are summarized below:

1. Terminology: The data product presented is referred to as “reanalysis”. Although the runoff data used to drive lisflood stem from a reanalysis, the presented data product is not an integral part of ERA5. In addition, observational discharge data are only used for calibrating lisflood, but are (to my understanding) not assimilated through a state-updating procedure. Given that the term reanalysis is often associated with state updating, I would find a clarification of the chosen terminology helpful in order to avoid confusion about the nature of the presented data set.

Response: We use the term reanalysis to mean the optimal combining of in situ and satellite earth system observations together with models to provide consistent spatio-temporal “maps without gaps” of land, ocean and atmospheric variables of interest as per Hersbach et al. (2020) and is now common in Earth System Modelling.

Change: Our definition does not change from that reported in the original submitted manuscript on L42-45. However, Hersbach et al. (2020) ERA5 global reanalysis peer-reviewed paper has since been published, so the citation is updated.

2. Transparency of the data production process: Although the paper does a good job in summarizing the workflow resulting in the presented data set, the amount of information presented is not sufficient to replicate the data. While I acknowledge that a description of ERA5 or Lisflood are beyond the scope of the paper, there are a number of essential technical steps that are not described. Open questions include, but are not limited to, (i) how was ERA5 output disaggregated to the finer resolution, (ii) how was lisflood calibrated (are the data used for validation independent of the data used for calibration), (iii) what does it mean that reservoirs are included (e.g. is management also simulated), etc. I realize that some of these questions are also treated in other publications but for a user of the data set a comprehensive overview with more details would be essential to fully understand the capabilities (and limitations) of the data.

Response: Your overall point on the need for additional clarity, especially in regards to the hydrological modelling detail, was also raised Anonymous Referee #1. It is indeed a balance within this data paper to focus on the description of the GloFAS-ERA5 dataset and its evaluation, while providing sufficient detail on the modelling methodology to allow users to gain an understanding of the capabilities and limitations. Our intention is to provide only a summary of the modelling methodology that is already described in full detail in the published literature.

Change: We have added Table A (below), as the new Table 1 with the following sentence in L105-107 in the resubmitted manuscript: “The open access scientific publications and model documentation that describe the full methodological detail for each key component is provided in Table 1 and summarised below”. This table includes reference to the full LISFLOOD model documentation (Burek et al., 2013).

Responses and changes to your individual queries are given below:

i.) **Response:** This question was also asked by Anonymous Referee #1. In order to be consistent with the operational GloFAS procedure, the runoff fields from ERA5 were downscaled using the simple nearest neighbour method from the native resolution to the 0.1° LISFLOOD grid. The task was done using the open source 'pyg2p' module with interpolation 'grib_nearest' option in Python (https://pypi.org/project/pyg2p/). No weights were applied to runoff values and terrain effects within the ERA5 cell were not considered.

Change: We have added the following sentence into L151-153 in the resubmitted manuscript: "In order to be consistent with the operational GloFAS procedure, the runoff fields from ERA5 were downscaled using the simple nearest neighbour method from the native ERA5 to the 0.1° GloFAS grid."

ii.) **Response:** The LISFLOOD version used here for GloFAS-ERA5 v2.1 was calibrated by Hirpa et al. (2018) using an evolutionary optimisation algorithm against daily river discharge from 1287 stations worldwide. For each station, the record was split in two for calibration and validation. If the record was shorter than eight years, four years were used for calibration and the remainder for validation. If the record was equal to or longer than eight years, half was used for calibration and half for validation, with the most recent period used for calibration.

iii.) **Response:** Reservoir outflow is calculated with a set of simplified rules depending on their filling level, and balances water recharge if storage is below normal or release if above normal. There is a minimum outflow to ensure the downstream river does not dry up, and a non-damaging release so the reservoir does not reach full capacity.

Change: Added Table A as new Table 1 for clarity and added the following sentence to the limitations in L334-336: "simplified reservoir operating parameters were used based on expert opinion (outlined in Zajac et al. (2017)) due to lack of availability of global operational release records".

Table A: Scientific papers and model documentation for the key components in the production of GloFAS-ERA5 v2.1 river discharge reanalysis dataset.

GloFAS-ERA5 component	Description	Reference
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Calibration of LISFLOOD used in GloFAS	LISFLOOD was calibrated against daily river discharge from 1287 observation stations worldwide	Hirpa et al. (2018)

3. The output variable (discharge) is “Volume rate of water flow, including sediments, . . .”. While I acknowledge that this is likely the variable of interest for flood forecasting, I would appreciate if the volume (or mass) of pure H2O could also be made available (if this does not differ significantly, then a statement explaining this might be useful).

Response: The definition given in Table 2 is the generic definition of discharge from rivers and streams by the World Meteorological Organisation (WMO) for hydrological products (https://community.wmo.int/activity-areas/wmo-codes/manual-codes/latest-version). It is used across all river discharge products at ECMWF and on the Copernicus Climate Change Service (C3S) Climate Data Store (https://apps.ecmwf.int/codes/grib/param-db?id=240013). Virtually all hydrological models, including GloFAS-ERA5, simulate the volume rate of water only due to inherent simplifications of reality.

4. What is the time resolution of the observations used for validation? I assume daily, but this was not stated explicitly.

Response: Yes, the observations are daily, and the evaluation carried out at the daily scale.

Change: Now clarified as daily in the abstract (L28), and in Sect. 4 (L194, L198 and L212) in the resubmitted manuscript.

5. Stations used for evaluation come “predominantly” from the GRDC. This is not transparent at all and hinders reproducibility of the study. I assume that some of the data cannot be re-distributed, but an overview (e.g. supplementary table) on the considered stations including some key properties (geolocation, river and station names, data-provider, catchment area, . . .) foster reproducibility of the results.

Response: Observations cannot be redistributed by the authors due to licencing agreements but to foster reproducibility of the results we have now included Supplementary Table S1 with the resubmitted manuscript with the following metadata for each of the 1801 stations: *GloFAS_ID, Provider, Provider_ID, Station_Name, River_Name, River_Basin, Country_Name, Catchment_Area_Provider_km2, Catchment_Area_GloFAS_km2, Latitude_Provider, Longitude_Provider, Latitude_GloFAS, Longitude_GloFAS.*

In addition, we include in the Supplementary Table S1 the corresponding performance metrics for each station to allow users to explore the results in more detail: *KGE’, KGESS, correlation, bias_ratio, variability_ratio, MAE_mm_per_day.*

Change: Supplementary Table S1 included in the resubmission.

6. If there is more than one station per grid-cell only one station is selected. This is OK. However, what is the criterion to select a particular station (random, expert judgment, catchment size,. . .)?

Response: When multiple observation stations were matched to the same GloFAS river cell, the station with the longest record was retained. This criterion removed 27 stations from the initial list.

Change: Now clarified on L205-205 with bullet point reading: “When multiple observation stations were matched to the same GloFAS river cell, the station with the longest record was retained [27 stations removed]”.

7. I personally would find extended global summaries (in addition to medians and IQRs) of the performance metrics useful (e.g. tables with percentiles, or empirical cumulative distribution functions).

Response: We have taken your suggestion on board.

Change: We now present the performance metrics for all 1801 stations as a cumulative distribution function in the resubmitted manuscript (Fig. A) (inserted as Fig. 4 in the resubmitted manuscript). We also include the performance metrics for each station along with the metadata in a Supplementary Table S1 you suggested in your point number 5. The text in Sect. 4.1 has been modified slightly to incorporate the new Figure.

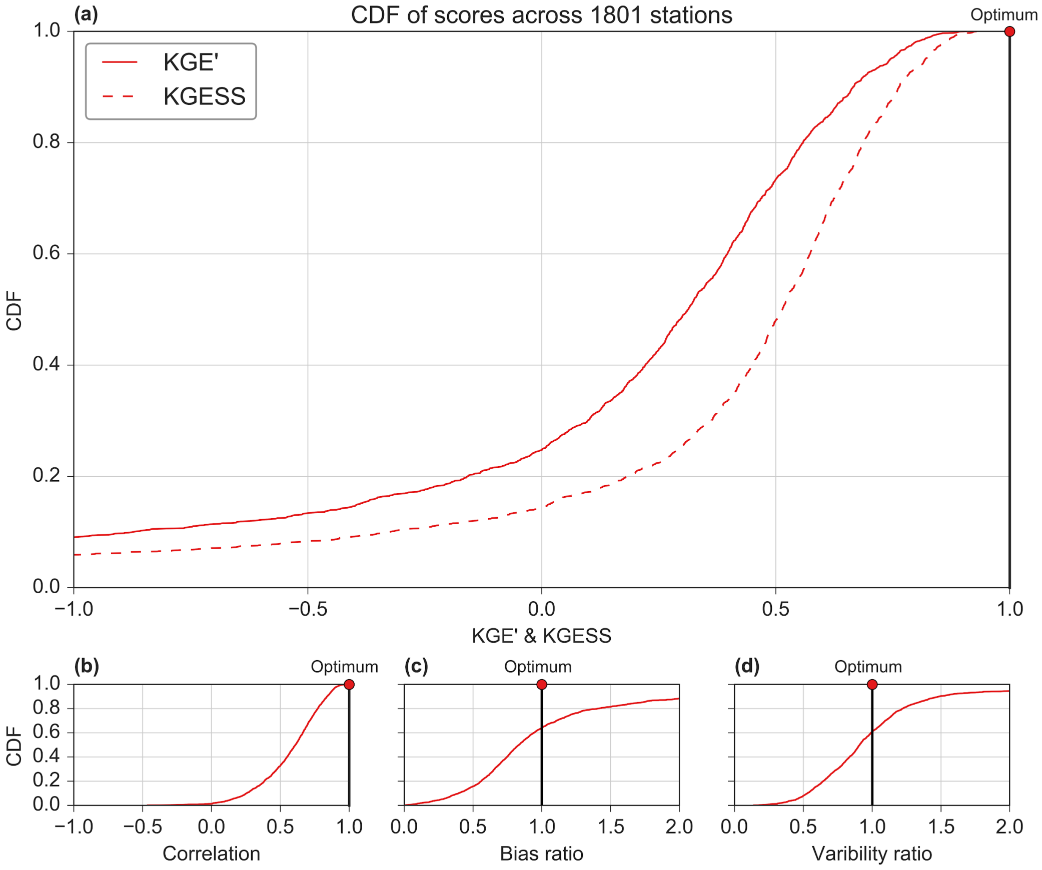

Figure A. Cumulative distribution function of performance metrics across all 1801 stations. Modified Kling-Gupta Efficiency (KGE’) and Skill Score (KGESS) (a) with decomposition of KGE’ into Pearson correlation (b), bias ratio (c), and variability ratio (d). The red dot marks the optimum value for each metric.

8. The performance assessment focuses predominantly on the skill of the full time series at daily resolution. For some users information focussing on different modes of variability (e.g. seasonal cycle, anomalies of the seasonal cycle, year-to-year fluctuations) would be also of great interest.

Response: Thank you for your suggestion. We agree that there are many other exciting potential applications of GloFAS-ERA5 that would be interested in an aggregation of the dataset. But here, focusing on the daily time-step will provide the performance of the dataset at the highest temporal resolution that is of most interest for the vast majority of hydrological applications. We expect and encourage users to undertake their own local evaluation for their specific application as the use of the dataset grows.

9. Accessibility of the data product. I am aware of and support the effort of the Copernicus Climate Change Service but I don't have an account for this at the time being. I am also reluctant to create "random" accounts that I need to keep track of if not really needed. Given the fact that the data are produced by one of the world leading institutions for global weather data (ECMWF) and hare hosted on the Copernicus platform, I assume that the data format will be state of the art.

Response: Thank you for your positive comment. A requirement for the GloFAS-ERA5 data to be hosted by the C3S Climate Data Store (CDS) is that state-of-the-art cataloguing, data format (i.e. NetCDF), and standardised metadata and documentation are adhered to: https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-glofas-historical?tab=overview. This allows GloFAS-ERA5 data to be found through the CDS search catalogue, work with the CDS "Toolbox", and follows the protocol that provides programmatic access to the data via the CDS Application Programming Interface (API). These are valuable tools to allow users to work more easily with large global datasets. More general information on the CDS and how data are delivered can be found here: https://climate.copernicus.eu/climate-data-store.

Other minor changes to the manuscript during the revision

1. Alfieri et al. (2019) updated to final published paper, Alfieri et al. (2020)

2. Hersbach et al. (2018) updated to the final published paper, Hersbach et al. (2020)

3. L340-341: Some additional detail on the 'rain bomb' issue in the ERA5 dataset was given in the final Hersbach et al. (2020) paper, and so additional detail on how rare they are (~10 episodes per year) and where they occur (mostly in isolated grid points over orographic areas in Africa) was added to the resubmitted manuscript for the benefit of readers.

We really appreciate the time and insight of both referees in reviewing our manuscript,

Kind regards,
Shaun (on behalf of all co-authors)

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GloFAS-ERA5 operational global river discharge reanalysis 1979-present

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Abstract. Estimating how much water is flowing through rivers at the global scale is challenging due to a lack of observations in space and time. A way forward is to optimally combine the global network of earth system observations with advanced numerical weather prediction (NWP) models to generate consistent spatio-temporal maps of land, ocean, and atmospheric variables of interest, known as a reanalysis. While the current generation of NWP output runoff at each grid cell, they currently do not produce river discharge at catchment scales directly, and thus have limited utility in hydrological applications such as flood and drought monitoring and forecasting. This is overcome in the Global Flood Awareness System (GloFAS; http://www.globalfloods.eu/) by coupling surface and sub-surface runoff from the HTESSEL land surface model used within ECMWF's latest global atmospheric reanalysis (ERA5) with the LISFLOOD hydrological and channel routing model. The aim of this paper is to describe and evaluate the GloFAS-ERA5 global river discharge reanalysis dataset launched on 5 November 2019 (version 2.1 release). The river discharge reanalysis is a global gridded dataset with a horizontal resolution of 0.1° at a daily time step. An innovative feature is that it is produced in an operational environment so is available to users from 1 January 1979 until near real time (2 to 5 days behind real time). The reanalysis was evaluated against a global network of 1801 daily river discharge observation stations. Results found that the GloFAS-ERA5 reanalysis was skilful against a mean flow benchmark in 86 % of catchments according to the modified Kling-Gupta Efficiency Skill Score, although the strength of skill varied considerably with location. The global median Pearson correlation coefficient was 0.61 with an interquartile range of 0.44 to 0.74. The long-term and operational nature of the GloFAS-ERA5 reanalysis dataset provides a valuable dataset to the user community for applications ranging from monitoring global flood and drought conditions, identification of hydroclimatic variability and change, and as raw input to post-processing and machine learning methods that can add further value. The dataset is openly available from the Copernicus Climate Change Service Climate Data Store:

https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-glofas-historical?tab=overview with the following DOI: 10.24381/cds.a4fdd6b9 (C3S, 2019).

1 Introduction

A key challenge in hydrology is estimating past, present, and future hydrological conditions in rivers around the world. This is largely due to severe temporal and spatial gaps in the global river discharge observing network. In many parts of the world there is simply not enough long-term river discharge observations at high enough spatial density, and in the vast majority of countries hydrometric data are not available in real time (Lavers et al., 2019). The lack of observations is therefore a major barrier in our ability to provide monitoring and early warning of hydrological extremes such as floods and droughts, which has for example implications for progressing international disaster risk reduction (UNDRR, 2015). A way forward pioneered in the field of meteorology and climate has been to optimally combine in situ and satellite earth system observations together with advanced numerical weather prediction (NWP) models to generate a ‘reanalysis’ of land, ocean, and atmospheric variables of interest, thus providing consistent spatio-temporal “maps without gaps” (Hersbach et al., ~~2018~~2020). Several global hydrological products have been developed that provide estimates of runoff or river discharge, with a wide range of forcing and methodological approaches (e.g. Fekete et al., 2002; Döll et al., 2003; Qian et al., 2006; Sperna Weiland et al., 2010; Reichle et al., 2011; Yamazaki et al., 2011; Beck et al., 2017; Ghiggi et al., 2019; Lin et al., 2019). While these datasets can be used to understand past variability and change in the terrestrial hydrological cycle, they are currently not produced in an operational environment in near real time, so cannot be used for monitoring current global river conditions or provide initial conditions to hydrometeorological forecasting systems.

A long term and near real time river discharge reanalysis is produced operationally as part of the Global Flood Awareness System (GloFAS; http://www.globalfloods.eu/) which bridges this gap. GloFAS is the global flood service of the European Commission’s Copernicus Emergency Management Service (CEMS), an operational system for monitoring and forecasting floods across the world with over 4000 registered users. GloFAS was developed together by the Joint Research Centre (JRC) of the European Commission, the University of Reading, and the European Centre for Medium-Range Weather Forecasts (ECMWF). The system went pre-operational in July 2011 (Alfieri et al., 2013), becoming a fully operational 24/7 supported service in April 2018 (version 1.0, upgraded to version 2.0 in November 2018). GloFAS is provided through a free and open licence and is designed for decision makers and forecasters in national and international water authorities, water resources management, hydropower companies, civil protection authorities, and international humanitarian aid organisations. A recent example of the use of GloFAS was for supporting the humanitarian response to the devastating floods that affected large parts of Mozambique, Malawi, and Zimbabwe in the wake of tropical cyclone Idai in March 2019 (Magnusson et al., 2019). Given the large amount of openly available data that is generated by GloFAS, including a long-term near real time river discharge reanalysis, a large set of reforecasts, and real time flood and seasonal forecasts, it is also used by researchers and commercial industries for a wide range of projects and for developing value-added products.

In GloFAS, ensemble river discharge forecasts are produced each day at a daily time step and provide probabilities of exceeding flood thresholds for a given river section with a lead time out to 30 days ahead (GloFAS 30-day; Alfieri et al., 2013). There is also a seasonal component, GloFAS-Seasonal (Emerton et al., 2018), that provides forecasts once per month at a weekly time step with a lead time out to four months ahead. The river discharge reanalysis is used for two core tasks within GloFAS. First, flood thresholds at 2-, 5-, and 20-year return periods for each river cell are derived from the long-term reanalysis series. This allows for the magnitude of the real time ensemble river discharge forecasts to be directly compared to the magnitude of the long-term flood thresholds, and thus awareness of a flood signal if the threshold is exceeded. Second, it provides the basis to derive initial hydrometeorological conditions for both GloFAS 30-day and GloFAS-Seasonal real time forecasts. Estimating initial conditions is a key step to determine current status of soil moisture, groundwater, snow cover, and initial state of water within rivers and other waterbodies and has been identified as one of the major challenges in continental and global scale flood forecasting given the limited availability of observational data at these scales (Emerton et al., 2016).

The aim of this data paper is to describe the newly produced operational river discharge reanalysis dataset as part of the launch of GloFAS v2.1 on 5 November 2019 (see GloFAS technical documentation for details on upgrades: https://confluence.ecmwf.int/display/COPSRV/GloFAS). GloFAS river discharge reanalysis is based on ERA5 (Hersbach et al., 2020~~18~~), ECMWF's latest global atmospheric reanalysis which extends back to 1979, officially released in January 2019. An innovation of ERA5 is that it is produced in near real time in an operational environment, allowing for the production of GloFAS-ERA5 reanalysis with a latency of 2 to 5 days behind real time. This has the major advantage for GloFAS that the initial hydrometeorological conditions can now be derived from the same product as the long-term flood thresholds are derived, so will ensure much better consistency with real time forecasts compared to previous GloFAS model configurations. Uniquely, the global river discharge product is over 40 years long, produced in near real time, and is freely available to download for the community through the Copernicus Climate Change Service (C3S) Copernicus Climate Data Store (CDS): https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-glofas-historical?tab=overview (C3S, 2019), opening multitudes of hydroclimate applications across the world.

Section 2 outlines the production of the dataset and Sect. 3 describes its main attributes including available variables and file format. An evaluation of the dataset against a global network of observations is conducted in Sect. 4. The dissemination of the data through the CDS is shown in Sect. 5 before key conclusions and future work are offered in Sect. 6.

2 Data production

Pappenberger et al. (2010) first demonstrated that it was possible to achieve useful river discharge predictions by coupling a river routing scheme with the land surface model of the ECMWF global numerical weather prediction (NWP) system. The GloFAS-ERA5 river discharge reanalysis uses this concept and is produced by coupling the land surface model runoff component of the ECMWF ERA5 global reanalysis (Hersbach et al., 2020~~18~~) with the LISFLOOD hydrological and channel routing model (van der Knijff et al., 2010). In ERA5 the runoff (m d^{-1}) from one cell is not connected to neighbouring cells, hence it is not possible to estimate river discharge (m^3 s^{-1}) at the catchment scale. Coupling ERA5 runoff with LISFLOOD allows for lateral connectivity of grid cells with runoff routed through the river channel to produce river discharge. A schematic of the key components in the production of the GloFAS-ERA5 reanalysis is provided in Fig. 1~~ and described below~~. The open access scientific publications and model documentation that describe the full methodological detail for each key component is provided in Table 1 and summarised below.

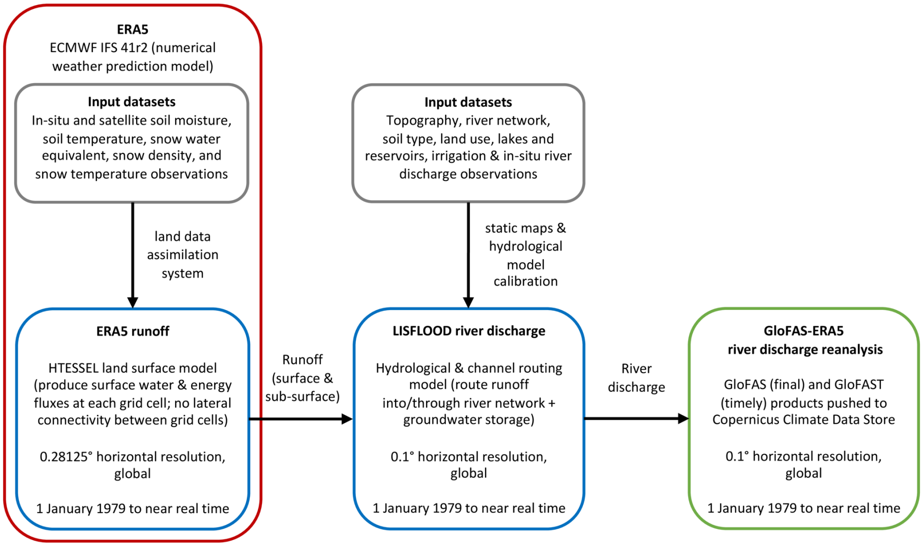

Figure 1: A schematic of the key components in the production of GloFAS-ERA5 v2.1 river discharge reanalysis dataset.

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Table 1: Scientific papers and model documentation for the key components in the production of GloFAS-ERA5 v2.1 river discharge reanalysis dataset.

GloFAS-ERA5 component	Description	Reference
ERA5	Global reanalysis dataset using ECMWF Integrated Forecast System (IFS) model cycle 41r2 from 1979 to present	Hersbach et al. (2020)
ERA5 runoff	Surface and sub-surface runoff within ERA5 generated using the HTESSEL land surface model	Balsamo et al. (2009)
LISFLOOD river discharge	River discharge generated using LISFLOOD hydrological and channel routing model to route runoff into and through the river network and provide groundwater storage. LISFLOOD includes lake, reservoir and human water use routines	Burek et al. (2013)
Lakes and reservoirs used in GloFAS	Incorporated 463 lakes and 667 reservoirs into the GloFAS river network	Zajac et al. (2017)
Calibration of LISFLOOD used in GloFAS	LISFLOOD was calibrated against daily river discharge from 1287 observation stations worldwide	Hirpa et al. (2018)

2.1 ERA5 runoff

ERA5 runoff is produced from the HTESSEL land surface model (Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land; Balsamo et al., 2009) as used within the ECMWF Integrated Forecasting System (IFS). HTESSEL computes the surface water and energy fluxes, and the temporal evolution of soil temperature, soil moisture, and snowpack. Excess precipitation and snowmelt are partitioned as surface runoff or infiltrated into a four-layer soil column (7 cm depth for top layer and then 21, 72, and 189 cm) at each ERA5 grid cell, before draining from the bottom of the soil column as sub-surface runoff (Balsamo et al., 2009). ERA5 uses an advanced land data assimilation system to assimilate conventional in-situ and satellite observations for land surface variables such as soil moisture, soil temperature, snow water equivalent, snow density, and snow temperature as outlined in de Rosnay et al., (2014).

ERA5 benefits from a decade worth of numerical weather prediction (NWP) developments in model physics, numerics, and data assimilation by using ECMWF IFS model cycle 41r2 (2016) compared to model cycle 31r2 (2006) as used in its predecessor, ERA-Interim (Dee et al., 2011). ERA5 has a horizontal resolution of approximately 31 km at the equator (native

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octahedral grid) and since January 2019 is openly available from 1979 to present. A key novelty of ERA5 is its operational production that makes available an intermediate timely product, ERA5T in near real time, allowing the production the GloFAS-ERA5 river discharge reanalysis operationally with a latency of between 2 and 5 days behind real time.

2.2 LISFLOOD river discharge

River discharge is currently not calculated by HTESSEL. Instead, surface and sub-surface runoff from the HTESSEL land surface model are coupled with a simplified global version of LISFLOOD, a spatially distributed grid-based hydrological and channel routing model. The details of the global version of LISFLOOD used within GloFAS v2.1 and its calibration can be found in Hirpa et al. (2018) but are briefly summarised here for context. The sub-surface runoff from HTESSEL is used as input to the LISFLOOD groundwater module, which consists of two parallel linear reservoirs that store and subsequently transport water to the river channel with a time delay. The upper zone represents quick groundwater and sub-surface flow while the lower zone represents slow groundwater flow that generates base flow. In Hirpa et al. (2018), the upper zone time constant was given a default value of 10 days with a lower (upper) bound of 3 days (40 days) during calibration. The upper zone time constant has a default value of 200 days with a lower (upper) bound of 40 days (500 days) during calibration. The surface runoff from HTESSEL is used as input to the LISFLOOD river channel routing module. This is a two-stage process whereby the surface runoff for each cell is first routed to the nearest downstream river channel cell, then the water in the channel is routed through the river network using the kinematic wave approach. Groundwater and river routing parameters in GloFAS were calibrated against daily river discharge observations for 1287 catchments globally by Hirpa et al. (2018). A key feature of LISFLOOD is the ability to represent features ~~such as lakes and reservoirs~~ that can severely alter the timing and magnitude of river discharge, such as lakes, reservoirs and human water use (Burek et al., 2013). A total of 463 of the largest lakes (surface area > 100 km^2) and 667 largest reservoirs ~~have~~ were ~~been~~ incorporated into the GloFAS river network by Zajac et al. (2017).

To generate the GloFAS-ERA5 river discharge reanalysis, the ~~global~~ LISFLOOD model is forced with daily HTESSEL surface and sub-surface runoff from ERA5 ~~that has been resampled to the 0.1° GloFAS gridded river network~~ starting from 1 January 1979 (Fig. 1). In order to be consistent with the operational GloFAS procedure, the runoff fields from ERA5 were downscaled using the simple nearest neighbour method from the native ERA5 to the 0.1° GloFAS grid. To avoid the need for very long spin up periods, LISFLOOD calculates a "steady-state" storage amount for the lower groundwater zone during a long-term "pre-run", and thus reduces the lower zone's spin up time (Burek et al., 2013). LISFLOOD was therefore given a one-year model spin up using preliminary ERA5 output for 1978. To produce GloFAS-ERA5 reanalysis in near real time operationally, the latest available ERA5T data is used.

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3 Data description

The key attributes of the current operational version (v2.1) of the GloFAS-ERA5 river discharge reanalysis dataset are shown in Table 1. The daily reanalysis is global in coverage, except for Antarctica, with a horizontal grid resolution of 0.1° (approximately 11 km at the equator). The dataset is over 40 years long starting 1 January 1979. An innovative aspect of the dataset is its operational production allowing it to be available 2 to 5 days behind real time, shortly after ERA5T becomes available. The intermediate ERA5T data is not quality assured due to its timely nature. Consequently, there will be two reanalysis streams available: GloFAS (consolidated) is the final product based on the consolidated ERA5 from 1 January 1979 until 2 to 3 months behind real time, updated on the CDS on a monthly basis; and GloFAST (intermediate) is the timely product based on the intermediate ERA5T from 1 August 2019 until 2 to 5 days behind real time, updated on the CDS on a daily basis whenever ERA5T becomes available.

The GloFAS-ERA5 reanalysis dataset includes the variables river discharge and the upstream area for each GloFAS grid cell (Table 2). Data are stored in NetCDF format with one file per day containing the 24 h mean river discharge (00 UTC to 00 UTC). Each daily filename follows the convention 'CEMS_ECMWF_dis24_<YYYYMMDD>_glofas<T>_v2.1.nc' whereby the date stamp represents the end of the 24 h averaging period. So, for example the file 'CEMS_ECMWF_dis24_20190101_glofas_v2.1.nc' contains the daily mean flow for the 24 h period 00 UTC 2018-12-31 to 00 UTC 2019-01-01. Appendix A shows the header metadata information contained within the example NetCDF file. Each daily NetCDF file for the whole globe has an uncompressed size of ~21.7 MB, therefore the estimated size of the dataset from January 1979 to October 2019 is ~320 GB.

Figure 2 maps the mean daily river discharge over 1979 to 2018 for each GloFAS river with an upstream area greater than 1000 km^2, revealing the main river arteries of the world. An example hydrograph of the long-term near real time reanalysis against available river discharge observations is shown in Fig. 3 for the Teles Pires River in the Amazon basin, Brazil.

Table 1: Summary of GloFAS-ERA5 dataset attributes on the C3S Climate Data Store

Dataset attribute	**Details**
Horizontal coverage	Global except for Antarctica (90° N-60° S, 180° W-180° E)
Horizontal resolution	0.1° x 0.1°
Spatial reference system	Latitude/Longitude (WGS 84, EPSG:4326)
Vertical resolution	Surface level for river discharge

Temporal resolution	Daily data
Temporal coverage	1979-01-01 to near real time
Availability behind real time	i.) GloFAS (consolidated): 2 to 3 months, updated on CDS monthly (final product following availability of officially released quality assured ERA5 data) ii.) GloFAST (intermediate): 2 to 5 days, updated on CDS daily (timely product following availability of non-quality assured ERA5T data)
Update frequency	A new river discharge reanalysis will be published with every major update of the GloFAS system. The latest version will always be the version used in operations
File format	NetCDF
Data type	Grid
Data size on disk	Approximately 21.7 MB uncompressed per global NetCDF file for one day (full dataset currently ~320 GB uncompressed)
Version	GloFAS-ERA5 v2.1
File naming convention	'CEMS_ECMWF_dis24_<YYYYMMDD>_glofas<T>_v2.1.nc' where YYYY is year, MM is month, DD is day, and T is for timely (i.e. GloFAST). The date stamp, <YYYYMMDD>, represents the end of the 24 h averaging period

Table 2: Variables available within GloFAS-ERA5 dataset on the C3S Climate Data Store

Variable type	**Name**	**Units**	**Description**
Primary variable	River discharge	$m^3 s^{-1}$	Volume rate of water flow, including sediments, chemical and biological material, in the river channel averaged over a time step through a cross-section. The value is an average over a 24 h period
Related variable	Upstream area	m^2	Static file ('upArea.nc'), Upstream area for the point in the river network

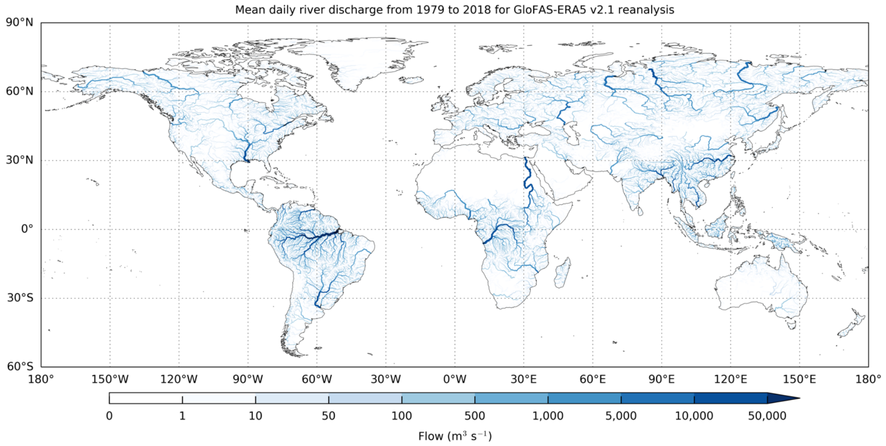

Figure 2: Mean GloFAS-ERA5 daily river discharge over 1979 to 2018 for each GloFAS river grid cell with an upstream area greater than 1000 km^2. Darker blue river sections have larger river discharge.

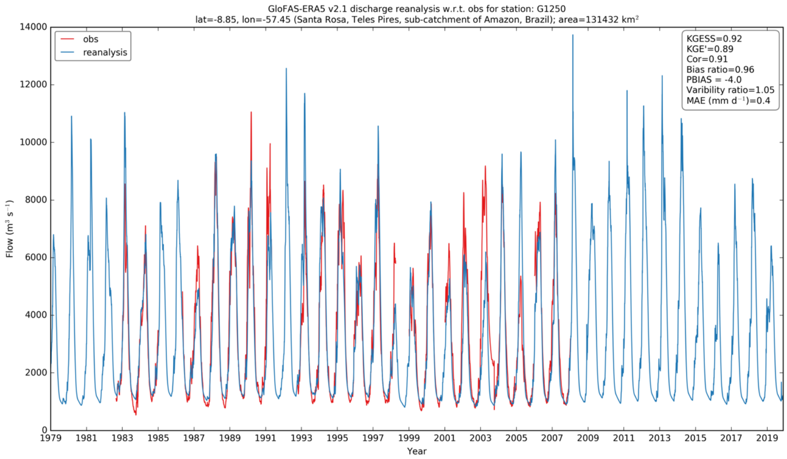

Figure 3: Hydrograph for GloFAS-ERA5 river discharge reanalysis (blue line) from 1 January 1979 to 12 November 2019 and observations (red line), when available, for the Santa Rosa gauging station on the Teles Pires River, a sub-catchment of the Amazon, Brazil (GloFAS ID=1250; GRDC ID=3629770). Summary statistics from evaluation of the reanalysis against observations in top right box as used in Sect. 4.

4 Evaluation and limitations

GloFAS-ERA5 v2.1 river discharge reanalysis was evaluated against a global network of daily river discharge observations. As part of GloFAS a database of global hydrological observations for 2042 stations is held, consisting predominantly (i.e. ~75 %) from the Global Runoff Data Centre (GRDC) and supplemented by data collected through collaboration with GloFAS partners worldwide to improve spatial coverage. A number of criteria were used to select ~~the~~ stations for the evaluation ~~list~~:

- At least 4 years of daily data available between 1979 and 2018 (not necessarily contiguous) [78 stations removed]
- Minimum upstream area of 500 km^2 [4 stations removed]
- Error in catchment area supplied by data provider and upstream area for corresponding cell on the GloFAS river network within 20 % [93 stations removed]
- ~~When multiple observation stations were matched to the same GloFAS river cell, only one was selected [27 stations removed]~~
- First order visual quality check on observed river discharge time-series to remove stations with erroneous data (for example, time series truncated above a threshold, severe inhomogeneities, or series monitoring an artificial canal instead of a river) [39 stations removed]
- When multiple observation stations were matched to the same GloFAS river cell, the station with the longest record was retained [27 stations removed]

This filtering procedure resulted in the selection of 1801 ~~catchments~~ stations with drainage areas ranging between 575 km^2 to 4,664,200 km^2, and a median of 30,046 km^2. Individual metadata of all 1801 stations are given in Supplementary Table S1. Care must be taken in spatial representativeness of the following evaluation results as the observation network is sparse in some regions of the world, particularly in large parts of Africa and Asia.

Performance at the daily scale was assessed using the modified Kling-Gupta Efficiency metric (KGE'; Gupta et al., 2009; Kling et al., 2012). The KGE' is gaining popularity as the standard performance metric in hydrology (e.g. Beck et al., 2017; Harrigan et al., 2018; Lin et al., 2019) and can be decomposed into three components important for assessing hydrological dynamics: temporal errors through correlation, bias errors, and variability errors:

$$KGE' = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2} \tag{1}$$

$$\beta = \frac{\mu_s}{\mu_o} \tag{2}$$

$$\gamma = \frac{\sigma_s/\mu_s}{\sigma_o/\mu_o} \tag{3}$$

Formatted: Outline numbered + Level: 1 + Numbering Style: Bullet + Aligned at: 0.63 cm + Tab after: 1.27 cm + Indent at: 1.27 cm where r is the Pearson correlation coefficient between reanalysis simulations (s) and observations (o), β is the bias ratio, γ is the variability ratio, μ the mean discharge, and σ the discharge standard deviation. The KGE' and its three decomposed components (correlation, bias ratio, and variability ratio) are all dimensionless with an optimum value of 1. ~~The bias ratio β can be easily converted into the more commonly used percent bias (PBIAS (%)) by (β - 1) × 100.~~ In order to evaluate the hydrological simulation *skill* of GloFAS-ERA5 reanalysis, its performance is compared against a simpler benchmark. Here the observed mean flow is used as a benchmark as proposed by Knoben et al. (2019). This is not a difficult benchmark to beat but should arguably be the minimum reference for any hydrological system to be compared against. Here we represent KGE' as a skill score, KGESS, to evaluate the performance of GloFAS-ERA5 river discharge reanalysis against the mean flow benchmark simulation, given as:

$$KGESS = \frac{KGE'_{reanalysis} - KGE'_{bench}}{KGE'_{perf} - KGE'_{bench}} \tag{4}$$

where $KGE'_{reanalysis}$ is the KGE' value for the GloFAS-ERA5 reanalysis against observations, KGE'_{bench} is the KGE' value for the observed mean flow benchmark against observations (i.e. $KGE'(\overline{Q_{obs}}) = 1 - \sqrt{2} \approx -0.41$ from Knoben et al. (2019)), and KGE'_{perf} is the value of KGE' for a perfect simulation which is 1. A KGESS = 0 means the GloFAS-ERA5 reanalysis is no better than the mean flow benchmark so has no skill, KGESS > 0 for when the reanalysis is considered skilful, and KGESS < 0 for when performance is worse than the benchmark so has negative skill. Performance metrics for all 1801 stations are included in Supplementary Table S1.

4.1 Overall performance

Results for overall performance show that the GloFAS-ERA5 river discharge reanalysis is skilful in 86 % of catchments (Fig. 4a). The global median KGESS (KGE') is 0.51 (0.31) with an Interquartile range (IQR) of 0.30 (0.00) to 0.66 (0.52). Performance is best in Brazil (particularly the Amazon basin), central Europe, and eastern and western regions of the US (Fig. 5). GloFAS-ERA5 reanalysis performance is poor (i.e. KGESS < 0) in many catchments in Africa, the North American Great Plains extending into Mexico, with notable patches in eastern Brazil, Thailand, and southern Spain. Results will be biased towards regions with a larger number of stations, especially when good performing large basins contain many sub-catchments (e.g. Amazon and Rhine basins).

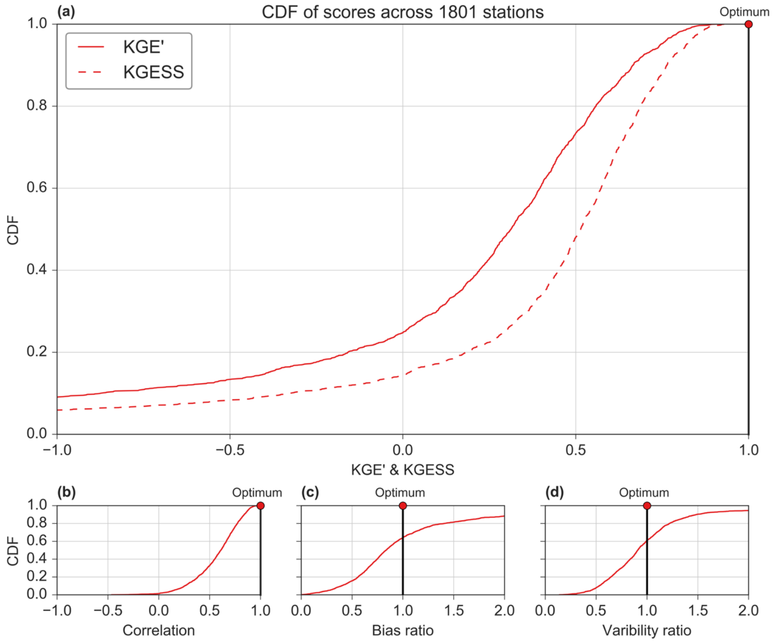

Figure 4: Cumulative distribution function of performance metrics across all 1801 stations. Modified Kling-Gupta Efficiency (KGE') and Skill Score (KGESS) (a) with decomposition of KGE' into Pearson correlation (b), bias ratio (c), and variability ratio (d). The red dot marks the optimum value for each metric.

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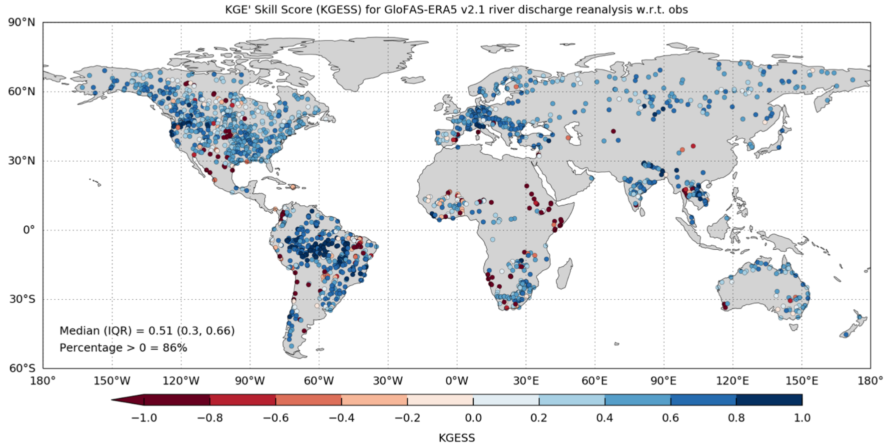

Figure 5~~4~~: Modified Kling-Gupta Efficiency Skill Score (KGESS) for GloFAS-ERA5 river discharge reanalysis against 1801 observation stations. Optimum value of KGESS is 1. Blue (red) dots show catchments with positive (negative) skill.

4.2 Decomposition into correlation, bias, and variability

An advantage with the KGE’ is that it can be decomposed into three constituent components so that greater insights can be gained into which aspects of the GloFAS-ERA5 reanalysis are driving poor and good skill. Almost all (99%) catchments show positive correlation (Fig.~~ure~~ ~~5~~4b~~a~~ and Fig. 6a) with a global median Pearson correlation coefficient of 0.61 (IQR = 0.44, 0.74). Figure 4~~5~~c~~b~~ shows that river discharge reanalysis is negatively biased in 64 % of catchments (i.e. bias ratio < 1) with global median bias ratio ~~(expressed as PBIAS)~~ of ~~-16 %~~0.84 (IQR = ~~-38 %~~0.62, ~~21 %~~1.21). In the evaluation of their global river simulation, Lin et al. (2019) consider a ~~PBIAS~~ percentage bias within ±20 % (equivalent to a bias ratio within 0.8 to 1.2) to be very good. Whilst only 28 % of stations meet this criterion for the GloFAS-ERA5 reanalysis, results are in line with simulations in Lin et al. (2019). Worst performing catchments (dark red KGESS dots in ~~Figure~~ Fig. 5~~4~~) are predominantly driven by very large positive biases (dark blue dots in ~~Figure~~ Fig. 6~~5~~b) in dryer rivers of Central US, Africa, eastern Brazil, as well as the western coast of South America; in total 12 % of catchments have a bias ratio > 2 (equivalent to a percent bias > 100 %)~~positive PBIAS > 100 % (i.e. bias ratio > 2)~~. Figure 4d (shown spatially in Fig. ~~5~~6c) shows lower variability in GloFAS-ERA5 reanalysis than observations in 61 % of catchments (i.e. variability ratio < 1) but errors in variability are less severe than bias errors with global median ~~values~~ variability ratio of ~~-9 %~~0.91 (IQR = ~~-31 %~~0.69, ~~15 %~~1.15).

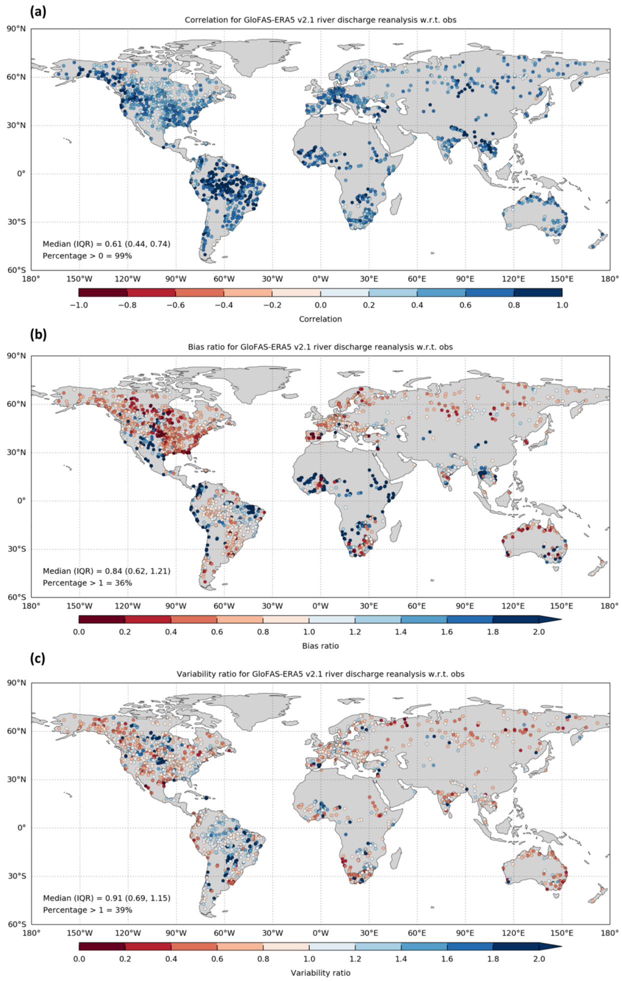

Figure 6~~5~~: Decomposition of the Modified Kling-Gupta Efficiency KGE' into its three components, Pearson correlation (a), bias ratio (b), and variability ratio (c) for GloFAS-ERA5 river discharge reanalysis against 1801 observation stations. Optimum values for each of the three KGE' components is 1. Blue (red) dots represent positive (negative) values.

It is important to also look at the average magnitude of errors as a small over/under estimation in dry rivers can produce large percentage biases (and hence bias ratios). This was done by converting the units of both the reanalysis and observation time-series from m^3 s^{-1} to runoff depth across the catchment area in mm d^{-1} to allow direct comparison between catchments of different sizes, then compute the Mean Absolute Error (MAE) metric (Figure 7~~6~~). The global median MAE is 0.41 mm d^{-1} (IQR = 0.18 mm d^{-1}, 0.72 mm d^{-1}). Most areas with a ~~PBIAS~~ bias ratio > ~~100 %~~2 (in Fig. 6~~5~~b), namely much of Africa, central US, and eastern Brazil, have in fact a low absolute magnitude of errors given their dry locations. Other notable areas with low absolute magnitude of errors include large parts of India, South East Asia, and Australia. There are however catchments in the western coast of South America, Sudan and Ethiopia, and tributaries of the River Ganges with a large MAE.

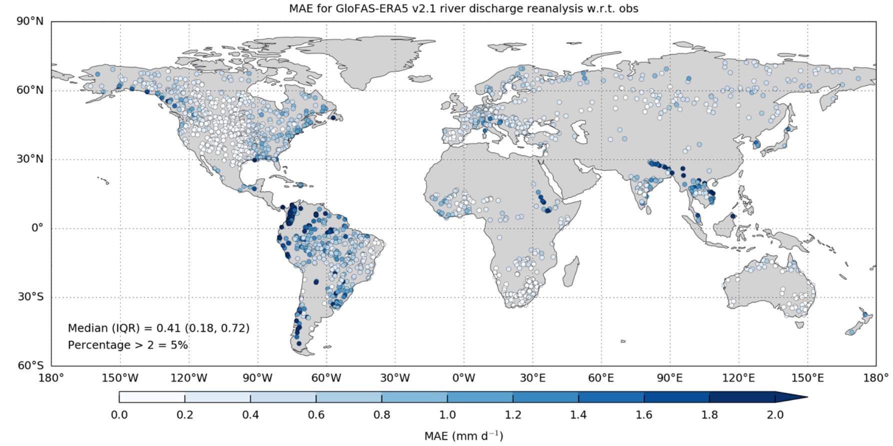

Figure 7~~6~~: Mean Absolute Error (MAE) for GloFAS-ERA5 reanalysis against 1801 observation stations. Units for both reanalysis and observations have been converted from m^3 s^{-1} to runoff depth across the catchment area (mm d^{-1}) to allow direct comparison of the magnitude of errors. Optimum value of MAE is 0, catchments with larger magnitude of errors are darker shades of blue dots.

4.3 Performance by month

Figure 8~~7~~ shows the global performance of GloFAS-ERA5 reanalysis for each month across all 1801 stations. Hydrological simulation skill is relatively consistent across each month with median KGESS ranging between 0.32 to 0.41 (Figure 8~~7~~a). The April to October months have highest skill, with November to March ~~January, February, March, November, and December~~ having a higher proportion of catchments with negative skill. When the KGE' is decomposed into correlation, bias, and variability components at the monthly scale (Figure 8~~7~~b-d, respectively) it shows that the months with higher incidence of negative KGESS are driven by a higher proportion of catchments with large positive biases in those months. Correlation and variability error metrics do not vary much from one month to the next, in comparison to bias errors.

Results are grouped into northern (n=1268 stations) and southern (n=533 stations) hemispheres in Fig. 9. The overall GloFAS-ERA5 monthly performance in each hemisphere does not change substantially from the global analysis (Fig. 8). Nevertheless, there are some differences. The KGESS and bias ratio from the northern hemisphere (Fig. 9a and c, respectively) tend to follow the global analysis most strongly (i.e. Fig. 8a and c, respectively), which is not surprising given 70 % of all stations are located in the northern hemisphere. However, a higher proportion of southern hemisphere stations show large positive biases from April to June, compared to November to March in the northern hemisphere. The largest proportion of stations with negative KGESS in the southern hemisphere are found from August to October (Fig. 9a). These months correspond with lower southern hemisphere correlation (Fig. 9b) and a higher proportion of stations with large positive variability ratios (i.e. GloFAS-ERA5 has higher variability than observed river discharge).

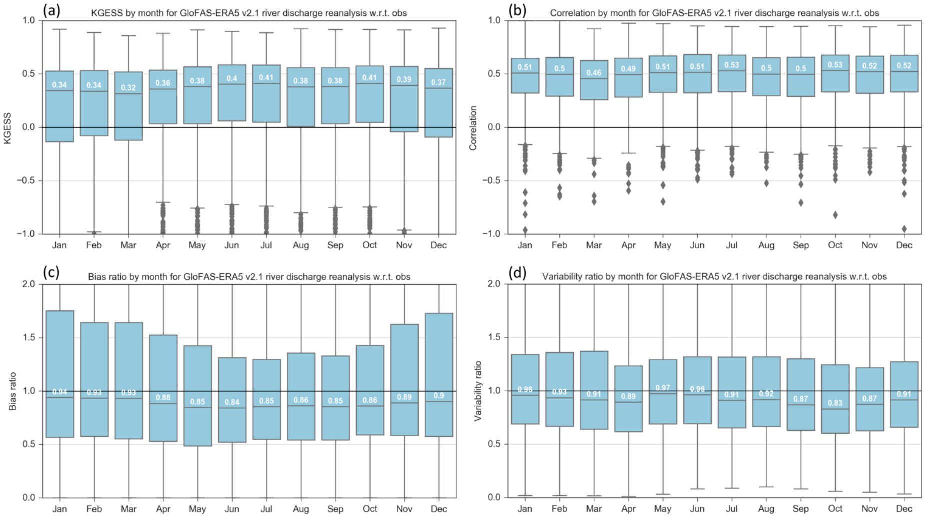

Figure 8~~7~~: Performance metrics for each month for all 1801 stations. Modified Kling-Gupta Efficiency Skill Score (KGESS) (a) with decomposition of KGE' into Pearson correlation (b), bias ratio (c), and variability ratio (d). Boxes represent the IQR and horizontal grey line the median. Whiskers extend to the most extreme data point, unless the data point is more than 1.5 times the IQR from the box and is instead represented as an outlier (grey diamond).

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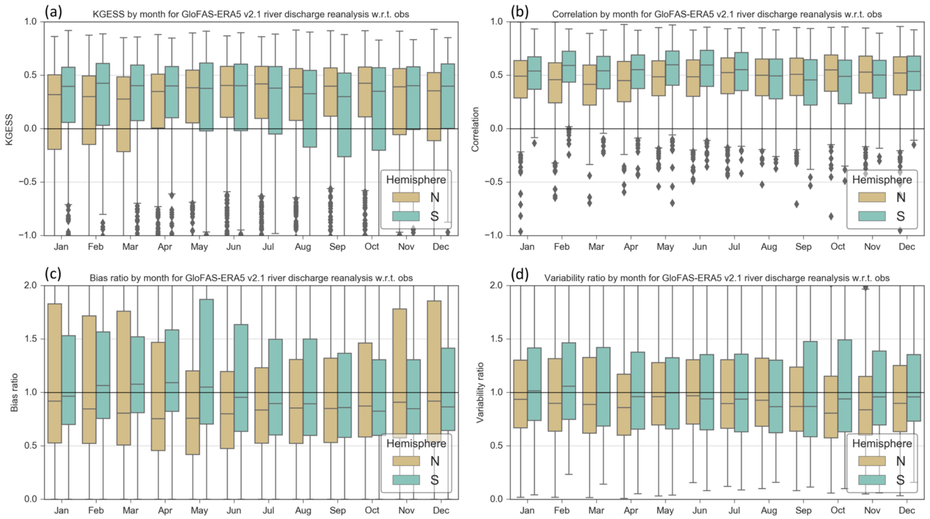

Figure 9: As in Fig. 8 but by hemisphere. Northern hemisphere (n=1268 stations) brown boxes and southern hemisphere (n=533 stations) as green boxes.

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4.4 Performance by catchment area

The skill of GloFAS-ERA5 river discharge reanalysis grouped into seven catchment area categories is shown in Fig. 10~~8~~. In general, skill is lowest for catchments in the three categories < 10,000 km^2 with median KGESS = 0.21 (n=39), 0.4 (n=41), and 0.42 (n=53), respectively. Performance improves as catchment size increases, with median KGESS = 0.56 for catchments > 50,000 km^2. It must be noted that results are affected by uneven samples of catchment sizes available within the GloFAS observations database, with catchments between 10,000 and 50,000 km^2 being dominant (n=1013) and smaller catchments being underrepresented.

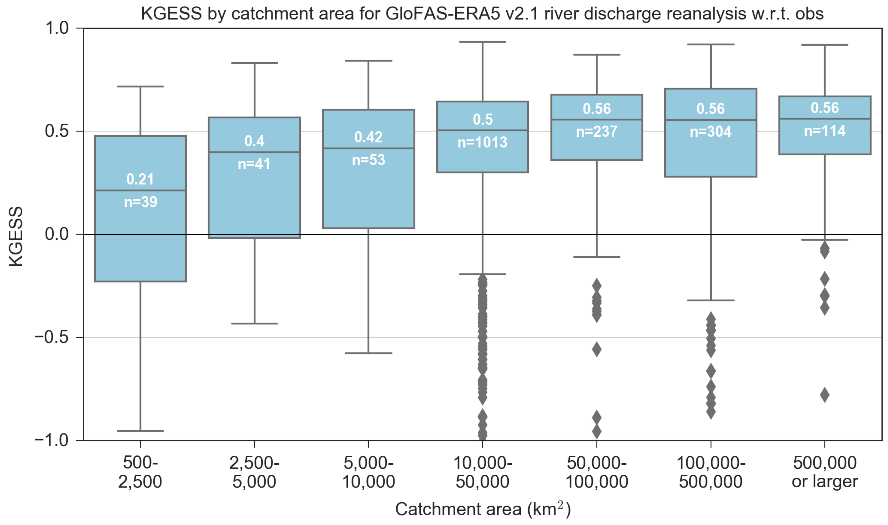

Figure 10~~8~~: Modified Kling-Gupta Efficiency Skill Score (KGESS) grouped into seven catchment area categories. Boxes and whiskers description as in Fig. 8~~7~~.

4.5 Limitations

This first evaluation has found the dataset to be hydrologically skilful in the vast majority of catchments tested, although the strength of skill can vary considerably depending on location. The degradation in skill, as defined using the KGESS, is the combination of (lower) correlation, (larger) bias errors, and (larger) variability errors. The evaluation provides users with an overview of the global scale quality of the dataset, although users are advised to undertake more in-depth evaluation of the dataset for their region of interest. A key limitation of the dataset is the large biases identified in several regions (see above). Attribution of such biases in the GloFAS-ERA5 reanalysis is outside the scope of this data paper, but ongoing investigations such as Zsoter et al. (2019) has shown biases can be introduced by the real time land data assimilation within the HTESSEL land surface model. Another expected cause of differences between river discharge reanalysis and observations is due to human modification within catchments and river channels (e.g. Harrigan et al., 2014). It is estimated that just 37 % of rivers remain free-flowing globally, with construction of reservoirs and dams the main contributor to loss of connectivity (Grill et al., 2019). While GloFAS-ERA5 reanalysis does represent major dams and reservoirs on the modelled river network, simplified reservoir operating parameters were used based on expert opinion (outlined in Zajac et al. (2017)), due to lack of availability of global operational release records~~it does so in a simplified way and does not include operational operating schedules for individual~~

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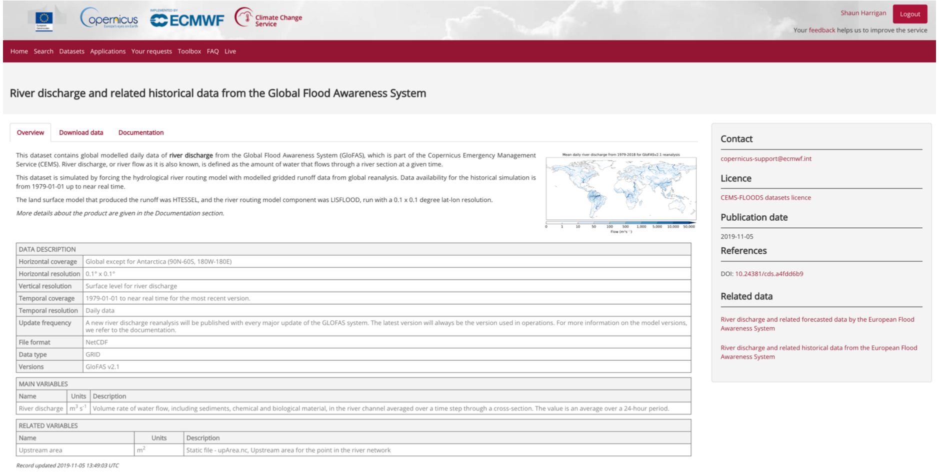
~~structures~~. Given the fundamental dependence of the dataset on ERA5, it would be pertinent for users to be aware of the known ERA5 issues, which can be found in the ERA5 documentation: https://confluence.ecmwf.int/display/CKB/ERA5. In particular, 'rain bombs' are known to occur from time to time in the numerical weather prediction (NWP) model used by ERA5 whereby extremely large rainfall totals are generated, although these are rare (~10 episodes per year) and happen ~~over very small areas~~mostly in isolated grid points over orographic areas in Africa (Hersbach et al., 2020). However, their impact on hydrology has not been assessed. As with any reanalysis product, care must be taken when calculating long-term trends in river discharge as discontinuities may be present in the record due to changes in the global observing system entering ERA5.

5. Data availability

The GloFAS-ERA5 river discharge reanalysis is provided through the European Commission Copernicus Emergency Management Service (CEMS) and follows the Copernicus open data policy that users shall have free, full, and open access to Copernicus Service Information. With the drive for open data, comes challenges. In the era of 'big data' it is clear that traditional ways of hosting and disseminating large earth system datasets is no longer fit-for-purpose. An exciting development in the way large climate datasets are discovered, accessed, and used is the Copernicus Climate Change Service (C3S) Climate Data Store (CDS; https://cds.climate.copernicus.eu/cdsapp#!/home). The CDS hosts various global and regional reanalysis products, gridded records for Essential Climate Variables (ECVs), in which river discharge is included as a key terrestrial ECV, and much more. The CDS requires standardisation of data and metadata so that datasets are more useable and discoverable through the CDS metadata pages. The CDS website provides easy access to data through user-friendly download forms. There is also a CDS Python Application Programming Interface (API) to allow programmatic access to data. An innovative feature of the CDS is the Toolbox, which makes it easier to handle large volumes of data by allowing users to make custom applications, filter data by geographical region and date range, and finally present the data using maps and charts directly through the CDS cloud infrastructure.

The GloFAS-ERA5 river discharge reanalysis product is available on the CDS: https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-glofas-historical?tab=overview with the following DOI: 10.24381/cds.a4fdd6b9 (C3S, 2019). The CDS landing page for the GloFAS-ERA5 reanalysis dataset is shown in Fig. 11~~9~~. Both the long-term consolidated and the near real time intermediate reanalysis data are available in two ways. First, through the '~~Data~~ Download data' tab whereby users can manually select options in a form for which data they would like to download. Second, data can be retrieved through the dedicated Python CDS API; an example API retrieval script is shown in Appendix B. Note that users must register for a CDS account (for free) before gaining access.



River discharge and related historical data from the Global Flood Awareness System

This dataset contains global modelled daily data of **river discharge** from the Global Flood Awareness System (GloFAS), which is part of the Copernicus Emergency Management Service (CEMS). River discharge, or river flow as it is also known, is defined as the amount of water that flows through a river section at a given time.

This dataset is simulated by forcing the hydrological river routing model with modelled gridded runoff data from global reanalysis. Data availability for the historical simulation is from 1979-01-01 up to near real time.

The land surface model that produced the runoff was HTESSEL, and the river routing model component was LISFLOOD, run with a 0.1 x 0.1 degree lat-lon resolution.

More details about the product are given in the Documentation section.

DATA DESCRIPTION	
Horizontal coverage	Global except for Antarctica (90N-60S, 180W-180E)
Horizontal resolution	0.1° x 0.1°
Vertical resolution	Surface level for river discharge
Temporal coverage	1979-01-01 to near real time for the most recent version.
Temporal resolution	Daily data
Update frequency	A new river discharge reanalysis will be published with every major update of the GLOFAS system. The latest version will always be the version used in operations. For more information on the model versions, we refer to the documentation.
File format	NetCDF
Data type	GRID
Versions	GloFAS v2.1

MAIN VARIABLES

Name	Units	Description
River discharge	$m^3 s^{-1}$	Volume rate of water flow, including sediments, chemical and biological material, in the river channel averaged over a time step through a cross-section. The value is an average over a 24-hour period.

RELATED VARIABLES

Name	Units	Description
Upstream area	m^2	Static file - upArea.nc, Upstream area for the point in the river network

Record updated 2019-11-05 13:49:03 UTC

Contact

copernicus-support@ecmwf.int

Licence

CEMS-FLOODS datasets licence

Publication date

2019-11-05

References

DOI: 10.24381/cds.a4fdd6b9

Related data

River discharge and related forecasted data by the European Flood Awareness System

River discharge and related historical data from the European Flood Awareness System

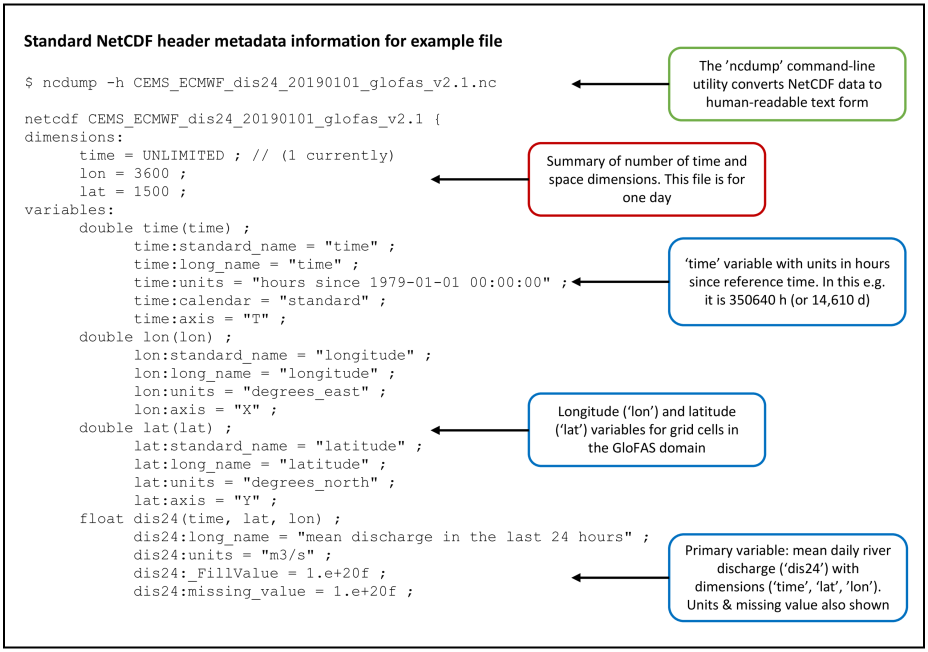
Figure 11~~9~~: The GloFAS-ERA5 river discharge reanalysis landing page on the C3S Climate Data Store (CDS: https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-glofas-historical?tab=overview).

6. Conclusions

This paper outlines the production, description, evaluation, and access to the new GloFAS-ERA5 operational global river discharge reanalysis dataset available from 1979 and updated in near real time. This dataset is central to two key steps within GloFAS, i.) calculation of flood thresholds against which real time ensemble forecasts are compared to determine the probability of a flood signal, and ii.) more consistent hydrometeorological initial conditions for the real time flood and seasonal forecasts. The evaluation against observations showed that the product is skilful in 86 % of catchments according to the modified Kling-Gupta Efficiency Skill Score against a mean flow benchmark. However, skill varies considerably with location with several regions such as central US, Africa, eastern Brazil, and western coast of South America having large systematic positive biases. The results from the evaluation are comparable with other long-term global river discharge products (e.g. Lin et al., 2019). The attribution of such biases in the GloFAS-ERA5 reanalysis is outside the scope of this data paper, but ongoing investigations such as Zsoter et al. (2019) on the biases introduced by the real time land data assimilation within the HTESSEL land surface model will help better understand existing limitations. GloFAS is an operational system which undergoes constant developments with intensive research on future versions of the model. It is foreseen that a new model version will be made operational in 2021~~0~~ based on the full LISFLOOD hydrological model and an improved model calibration (Alfieri, et al. ~~2019~~2020).

The long-term and operational nature of the GloFAS-ERA5 reanalysis dataset opens avenues for further applications. Forecast evaluation activities within GloFAS now include skill assessment over longer time periods and has allowed a new operational forecast verification suite to be developed whereby the performance of the forecasts can be tracked in near real time for every river in the world. Other applications are envisaged for monitoring the global status of flood and drought conditions, identification hydroclimatic variability and change, and as raw input to post-processing and machine learning methods that can add further value.

Appendix A



Standard NetCDF header metadata information for example file

```
$ ncdump -h CEMS_ECMWF_dis24_20190101_glofas_v2.1.nc

netcdf CEMS_ECMWF_dis24_20190101_glofas_v2.1 {
dimensions:
      time = UNLIMITED ; // (1 currently)
      lon = 3600 ;
      lat = 1500 ;
variables:
      double time(time) ;
            time:standard_name = "time" ;
            time:long_name = "time" ;
            time:units = "hours since 1979-01-01 00:00:00" ;
            time:calendar = "standard" ;
            time:axis = "T" ;
      double lon(lon) ;
            lon:standard_name = "longitude" ;
            lon:long_name = "longitude" ;
            lon:units = "degrees_east" ;
            lon:axis = "X" ;
      double lat(lat) ;
            lat:standard_name = "latitude" ;
            lat:long_name = "latitude" ;
            lat:units = "degrees_north" ;
            lat:axis = "Y" ;
      float dis24(time, lat, lon) ;
            dis24:long_name = "mean discharge in the last 24 hours" ;
            dis24:units = "m3/s" ;
            dis24:_FillValue = 1.e+20f ;
            dis24:missing_value = 1.e+20f ;
```

The ’ncdump’ command-line utility converts NetCDF data to human-readable text form

Summary of number of time and space dimensions. This file is for one day

‘time’ variable with units in hours since reference time. In this e.g. it is 350640 h (or 14,610 d)

Longitude (‘lon’) and latitude (‘lat’) variables for grid cells in the GloFAS domain

Primary variable: mean daily river discharge (‘dis24’) with dimensions (‘time’, ‘lat’, ’lon’). Units & missing value also shown

Appendix B

```
# Example CDS Python API request script

# Code snippets can be found by clicking ‘Show API request’ at
# bottom of GloFAS-ERA5 reanalysis download form:
# https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-glofas-historical?tab=form

# Instructions on how to download CDS API can be found here:
# https://cds.climate.copernicus.eu/api-how-to


import cdsapi


c = cdsapi.Client()


# Example download consolidated data (GloFAS)for 31 December 2018 (note: date stamp
# represents end of 24 h averaging period)

c.retrieve(
    'cems-glofas-historical',
    {
        'variable':'River discharge',
        'dataset':'Consolidated reanalysis',
        'version':'2.1',
        'year':'2019',
        'month':'01',
        'day':'01',
        'format':'tgz'
    },
    'download.tar.gz')


# Example download near real time intermediate data (GloFAST)for 12 November 2019 (note:
# date stamp represent end of 24 h averaging period)

c.retrieve(
    'cems-glofas-historical',
    {
        'variable':'River discharge',
        'dataset':'Intermediate dataset',
        'version':'2.1',
        'year':'2019',
        'month':'11',
        'day':'13',
        'format':'tgz'
    },
    'download.tar.gz')
```

Author contributions. SH drafted the manuscript and performed the evaluation. EZ wrote the suite to produce the dataset. CB adapted the suite to produce the dataset operationally. FW and CB were responsible for ingestion of the dataset into the Climate Data Store. LA, CP, PS, HC, and FP helped frame the paper. All co-authors contributed to the editing of the manuscript and to the discussion and interpretation of results.

Acknowledgements. We thank colleagues from the Copernicus Climate Change Service (C3S) for helping with ingesting the dataset into the Climate Data Store (CDS), and Cinzia Mazzetti (ECMWF) and Domenico Nappo (JRC) for helpful discussions during the revision regarding LISFLOOD. This work was funded by European Commission Copernicus Emergency Management Service (CEMS) Framework Contract No. 198702 awarded to ECMWF. The providers of observed river discharge observations are greatly acknowledged, both GloFAS partners and the Global Runoff Data Centre (GRDC), 56068 Koblenz, Germany.

Competing interests. The authors declare that they have no conflict of interest.

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