Dear Jim,

Please find below our responses to the three reviewers. We highlight where we have made changes to the resubmitted manuscript considering their comments. As a general point, the number of citations, particularly in the introduction and discussion sections, were too few in the original submission (as highlighted by you when we first submitted our paper). We have therefore increased the breadth of research cited.

Kind regards,
Shaun Harrigan on behalf of all co-authors

Response to RC1

Anonymous Referee #1 (R#1)'s original text in black *with our initial response in* blue*.*

Summary
This paper describes the most recent version of the GloFAS ensemble streamflow forecasting system. While there are no major advanced in methods used to generate forecasts, GloFAS is a system of international significance, and highly relevant to readers of HESS. The manuscript is well structured, admirably clear and succinct, and was a pleasure to read. Figures are well presented, and while references are sparse (especially in the introduction), as this paper is essentially focused on presenting an operational system this is ok. As the authors note, a major development is the availability of GloFAS forecast outputs in near-real time, and this is well-explained and documented.

I therefore believe the study ultimately deserves publication. I nonetheless had two major issues with this paper, listed below. I therefore recommend the paper be revised before it can be published.

We thank the reviewer for their positive words about our manuscript and constructive comments below.

Major comments
1) There appeared to me to be an error in the calculation of CRPSS with respect to (wrt) persistence - see specific comments below. If this is not due to an error, I would like the authors to explain what to me were counterintuitive results.

We provide a detailed explanation of the pattern of CRPSS wrt persistence below at your specific comment and show the results are as expected.

2) The authors earmark the assessment of reliability to future work. I do not think this is good enough, given 1) that reliability is a key attribute - in my view at least as important as skill - of ensemble forecasts and 2) their statement in the introduction that "not also having direct access to the raw data precludes the use in further downstream applications (e.g. impact modelling, multi-model forecast systems, production of value-added products for specific sectors such as river transport and hydropower industries, and advancement in techniques requiring large-scale datasets such as machine learning)." This statement implies that the authors expect the outputs in the ways specified - i.e. as direct inputs to impact assessment models of some kind or other. In my experience such models very often require reliable ensembles wrt to observations (or at least unbiased ensembles) as inputs. As GloFAS does not treat hydrological uncertainty, it is highly likely that ensembles are overconfident, particularly at short lead times (e.g. Bennett et al. 2014). I think this is information that users of these outputs, and therefore readers of this paper, would want to know. I therefore would like to see the authors present an assessment of reliability as well as skill, and the ramifications of this assessment discussed. Given the forecasts are likely to be treated as continuous variables in impact models, I suggest using probability integral transforms (PIT, e.g. Gneiting and Katzfuss 2014) to assess reliability (noting the need to generate 'pseudo'-PIT values in cases where streamflow observations can equal zero). If the

authors prefer, PIT values can then be summarised with either the alpha-index (Renard et al. 2010) or the beta-score (Keller et al. 2011) (whichever is more suitable) for presentation in plots similar to Figure 5 or 6.

We agree that reliability is indeed an important aspect of hydrological forecast quality, but there are many important aspects of forecast quality relevant for GloFAS users (for example, forecast skill for extreme events). The focus of this paper (as outlined in L70-72) is to provide a detailed description of how the GloFAS forecast datasets (both real-time and reforecasts) are generated and present a first global assessment of ensemble forecast skill against two of the most common benchmarks in the hydrological literature; thus defining the new GloFAS "headline skill score" that is added as a new layer on the GloFAS web interface. We do not claim that this first evaluation covers all forecast quality aspects, nor do we believe this specific paper is the right place to add the evaluation of just reliability and not other aspects that might be important for the diverse range of users. By providing the large-sample reforecasts dataset openly, we strongly encourage users of GloFAS foreacsts to conduct their own specific and local evaluation. We see this paper as the first step, and as part of the ongoing GloFAS evolution will expand global-scale evaluation efforts to other forecast quality aspects. Thank you for your suggestion on the method for evaluation of reliability, we will certainly take this into consideration going forward.

Specific comments
L88-97 Please provide the model time step at some point in this paragraph.

The ECMWF ENS is run at a 6-hourly forecast time step and for ingestion into the GloFAS hydrological modelling chain, data from the 00 UTC run is extracted and aggregated to 24-houly time step. This sentence has been added to the end of this paragraph in Sect. 2.1.

L125 "https://www.globalfloods.eu/" the hyperlink associated with this text 1) differs from the text and 2) returns a 404 error.

Thank you for noticing this. The hyperlink should have pointed to the main GloFAS web site: "https://www.globalfloods.eu/" and has been corrected in the resubmitted manuscript.

L250 Figure 5. To me, there's something very counterintuitive (and perhaps erroneous?) about the persistence skill plot. The accuracy of persistence (the benchmark, and the demoninator in eq 1) is often very high at short lead times and then declines with lead time - often rapidly. In my experience, this decline is usually much faster than the decline in the accuracy of forecasts. So I would expect CRPSS wrt to persistence to be very low perhaps even close to 0 - at very short lead times, and then to rise with lead time. But Fig 5 shows the opposite of these trends - i.e. CRPSS wrt persistence starts high and falls with lead time. I can't see how this can occur without a calculation error - though perhaps I've missed something? Even if this is not due to an error, these results at least requires some discussion/explanation. CRPSS calculated wrt to climatology looks sensible to me, which makes the persistence results even more puzzling.

We do not think the results are counterintuitive, but agree it is very useful to have access to the individual components of the skill score equation 1 (i.e. $CRPS_{fc}$ and $CRPS_{bench}$) to better interpret the accuracy of the GloFAS forecasts *relative* to the accuracy of both persistence and climatology benchmark forecasts, as a function of lead time. We therefore show in Fig. A (below) the individual CRPS accuracy components in equation 1 (i.e. CRPS of GloFAS forecasts (black line), persistence benchmark (blue line) and climatology (red line)) as a median across n=5997 river points. This plot helps interpret the global median CRPSS results (solid lines) presented in Figure 5 in the original manuscript. While the CRPSS in Fig. 5 is dimensionless with an optimum value of 1, the CRPS error is measured in units of the variable being evaluated (here m^3/s) and so has an optimum of 0 (i.e. perfect accuracy against the reanalysis).

It is clear from Fig. A and consistent with your comment: the accuracy of persistence (blue line) is highest at short lead times then gets rapidly less accurate as lead time increases. But it is also the case that the accuracy of GloFAS forecasts (black line) are highest at short lead times, and get less accurate as lead time increases. The decline of accuracy of persistence is however faster than the decline of the accuracy of GloFAS forecasts; this is also consistent with your comment. The persistence benchmark is very simple (use the reanalysis river discharge value from day before the forecast for all lead times), whereas the GloFAS forecast includes both information on the initial conditions as well as meteorological forecast information. Therefore, the accuracy of the GloFAS forecasts is (on average) higher than persistence, even for short lead times. In our opinion this is intuitive, and it would be more surprising if the considerably more sophisticated GloFAS forecasts were only as accurate or marginally more accurate than a simple persistence forecast, including at short lead times. Further, the core meteorological variables that drive GloFAS forecasts (e.g. precipitation and temperature) are most accurate at short lead times (Haiden et al., 2019). We also include the CRPS for climatology (red line) in Fig. A for completeness.

To help users better interpret the CRPSS for their stations of interest, we have included CRPSS as well as CRPS plots as a clickable "pop out" window as part of the new GloFAS "forecast skill" layer on the GloFAS Web Map Viewer for the release of version 2.2 on 2 December 2020 (https://confluence.ecmwf.int/display/COPSRV/Latest+operational+release%3A+GloFAS+v2.2).

We have added Figure A as an additional panel - now Figure 5b in the resubmitted manuscript. To reflect the update to the CRPSS/CRPS plots within the "Forecast skill" layer on the GloFAS website, we have updated Sect. 4.2 and Fig. 9 in the resubmission.

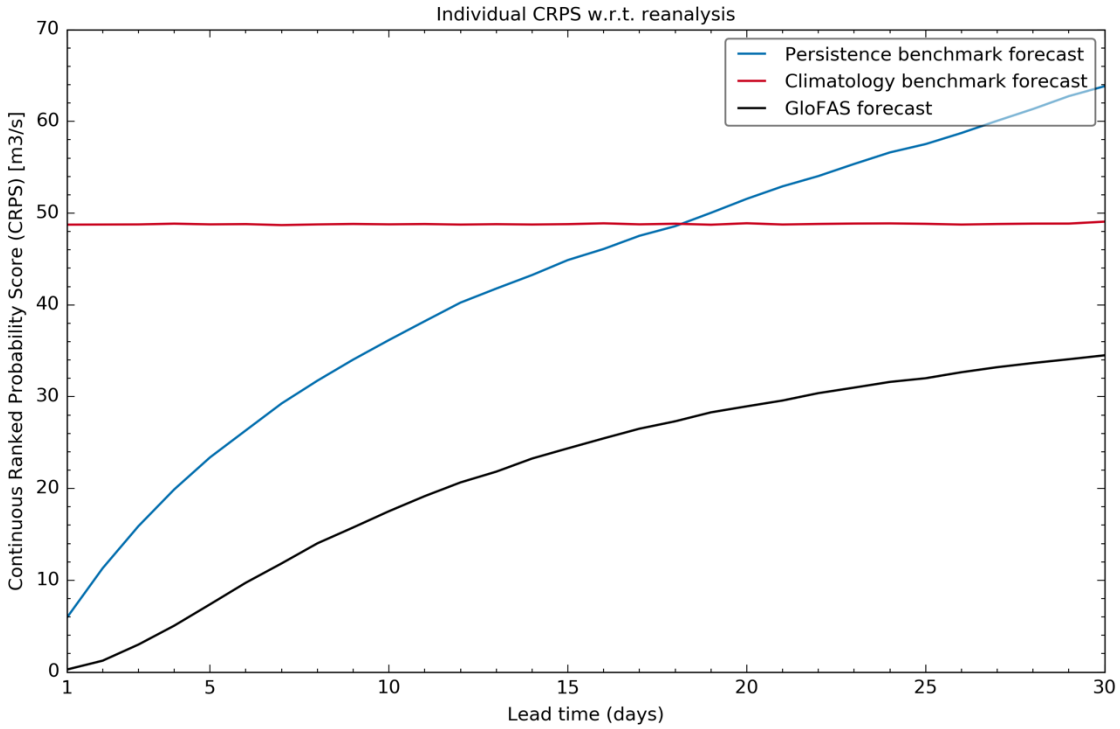


Figure A (new Figure 5b).: Global median Continuous Ranked Probability Score (CRPS) for GloFAS forecasts (black line) and both persistence (blue line) and climatology (red line) benchmark forecasts from 1- to 30-day lead times with respect to GloFAS-ERA5 river discharge reanalysis across 5997 diagnostic river points.

L271 Figure 6 As with Fig 5, I would expect skill wrt to persistence to rise with lead time, not to fall.

As per the response to comment above, the accuracy of both the persistence benchmark forecast and GloFAS forecasts themselves decrease with lead time, but the accuracy of GloFAS forecasts decrease at a slower rate (Figure A above).

L343-345 "Future work should assess other aspects of forecast quality such as reliability (Robertson et al., 2013), value (Cloke et al., 2017) or performance during extreme events (Bischiniotis et al., 2019)." Not suggesting any change here, but the authors may also like to consider calculating the skill/reliability of accumulated volume forecasts (e.g. accumulated 30-day streamflows), as this may well be of interest to reservoir operators and others. The ability to simply sum streamflows of individual ensemble members over various lead times is a major benefit of ensemble streamflow forecasting systems such as this one (as opposed to probabilistic forecasts generated at discrete lead times).

We currently we use weekly river discharge averages within GloFAS-Seasonal operationally and for seasonal forecast evaluation (see Emerton et al., 2018). However, providing forecast products (and forecast evaluation) at a range of different accumulations is something we will take on board and seek feedback from GloFAS users, thank you for your comment.

Typos/grammar/style

L79 "descripted" - 'decribed'?

This should have been "described" and has been updated in the resubmitted manuscript.

L140-141 "see for https://confluence.ecmwf.int/display/COPSRV/01.+GloFAS+operational+system a description" should be "see https://confluence.ecmwf.int/display/COPSRV/01.+GloFAS+operational+system for a description

This has been updated in the resubmitted manuscript.

L152-155 "Twice per week ... as real time (Vitart 2014)." Suggest breaking this long sentence in two at the comma.

We have broken this long sentence into two in the resubmission:

"A reforecast task is run twice per week (on Mondays and Thursdays) in parallel to the real-time forecast, using ERA5 atmospheric reanalysis (Hersbach et al., 2020) for initial conditions of past dates. A reforecast of the corresponding date for the previous 20 years is produced with a reduced number of 11 ensemble members but using the same model version as real-time (Vitart, 2014)."

Thank you again for your insight and we appreciate your time to review our manuscript,

Kind regards,
Shaun Harrigan on behalf of all co-authors

Response to RC2

Berit Arheimer (R#2)'s original text in black *with our initial response in* blue*.*

This paper shows recent progress in global river forecasts from the Glofas modelling system. Such data is indeed very useful and appreciated by many users at the global scale, especially by low- and middle-income countries who might not have access to their own river-forecast system. Accordingly, it is very important to evaluate such systems scientifically before launching them operationally.

The paper gives a very good overview of a river-discharge forecast system, which is indeed valuable for the scientific community to learn more about, as such systems are dedicated to national/international institutes with advanced IT infrastructure and operational production.

We thank Berit for her positive words about our manuscript and constructive feedback and suggestions that have helped refine our paper.

My main concern with this paper is that I miss a scientific question and the story of what kind of new scientific knowledge we have learnt from using the forecasting system and evaluation method described.

The Glofas model and forecasting system has been described before in the scientific literature and the focus of this paper seem to be that the results are now part of the climate service C3S, but this is hardly a scientific finding. New datasets should rather be published in ESSD, in which Glofas results have already been published. Likewise, the methods used for forecast evaluation are standard and has been published before. For publications in HESS I expect a more scientific analysis of the results and conclusions about new knowledge from the identified scientific achievements with impact on our understanding of Hydrology or Earth Systems. Right now, I have difficulties to find a clear take-home message in the current version of this paper. It is very descriptive and less analytic.

We take on board your point that the take-home messages in the current version could be clearer and will ensure they are sharper in the resubmitted manuscript. The original pre-operational GloFAS (version 1) was indeed described by Alfieri et al. (2013), however we disagree with your point that the scientific details of the fully operational GloFAS (version 2) have already been published in the hydrological scientific literature. Our manuscript is the first time the fully operational real-time forecast configuration has been published. Uniquely, this is the first time the large-sample and long-term reforecast strategy we use for generating and evaluating the forecast skill of GloFAS has ever been published, and we think this provides an important advancement in the area of global hydrological forecasting as well as users of GloFAS forecasts. We do not claim the evaluation method is new, but what is novel is the scale of the evaluation (both in space and across the long forecast range) and how the data and results are delivered to the hydrological community. Additionally, to our knowledge (apologies if incorrect), no other global operational hydrological forecasting system currently provides such a long-term and large-sample set of reforecasts, delivered in a free and open way, with summary evaluation results available on the user interface – we think this is a significant advancement towards transparency and as such, this procedure will be implemented with each new major release of GloFAS; we very much encourage other systems to follow in this direction. Once large sets of ensemble reforecasts are available from multiple forecast systems, even more interesting scientific questions around predictability can be uncovered, and we look forward to future collaborations with your group and WWH in this regard!

Our paper is not simply a data paper so we disagree ESSD is the most appropriate outlet. We want to communicate with the wider hydrological science community our scientific description of the GloFAS configuration, our method for evaluating the skill of GloFAS, and the findings of when and where in the world GloFAS ensemble forecasts are skilful against the two primary benchmark forecasts used in hydrological forecasting. HESS in particular has become a key journal for publishing papers in the area of hydrological forecasting and therefore we hope the editor agrees is a good home.

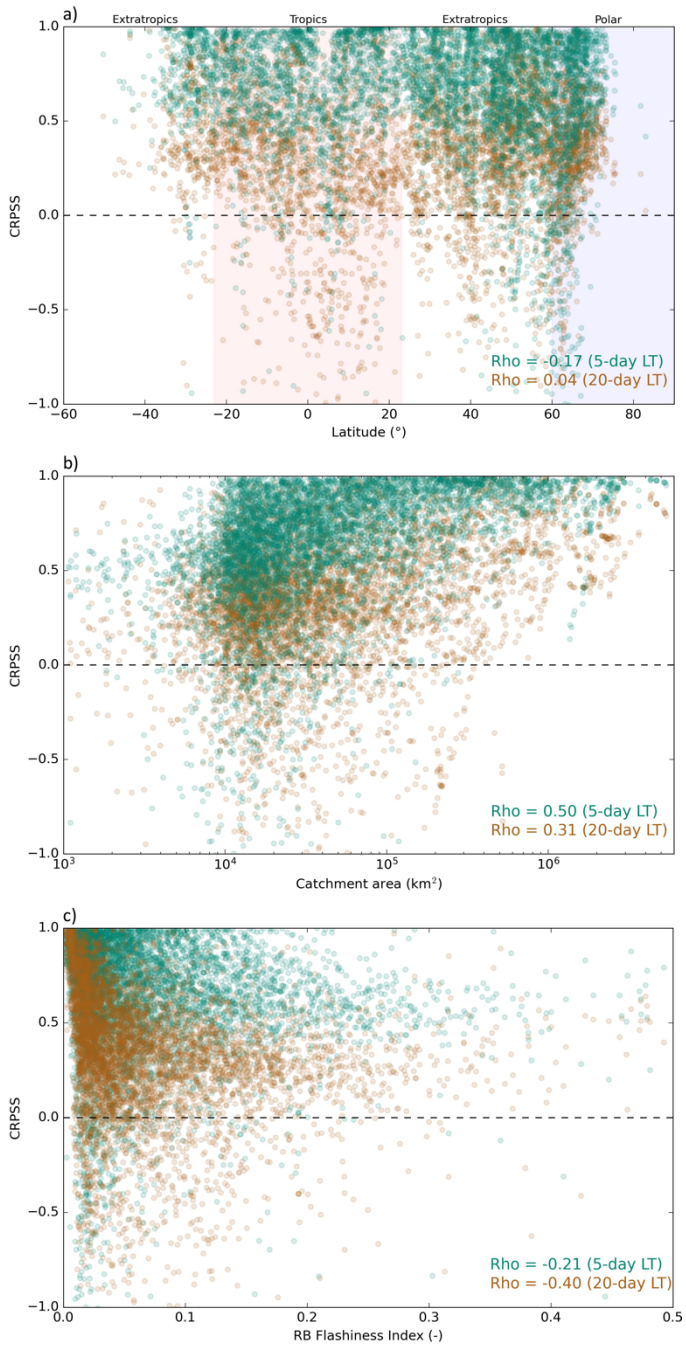
I therefore suggest to find a scientific angle from current discussions in the research community and tell the story of the results from that perspective.

Interesting scientific questions could for instance be:

- On the method side: How should we evaluate forecasts – _what metrics are there, how do they compare and what does different metrics contribute in understanding/reliability for the user community and research community, respectively?
- Could the metrics presented (and argued for?) in this paper be compared with other metrics, to show their excellence and benefits to users/scientists? (is there a take-home message or guide-lines to the scientific community from using a specific metric/evaluation method compared to another?) What are the options?
- On the understanding of hydrology: what are the attributes for catchments/regions with high or low skills in forecasting? i.e. which processes do we need to learn more about to improve the quality of river-discharge forecasts?
- How does different global river-discharge forecast systems compare to each other? Can we learn from different model setups and elaborations on procedures, process descriptions or geophysical representation?

Thank you for this valuable list of avenues for further research. Most of these would be very interesting standalone studies in their own right. We agree with your bullet point 3 that the results of forecast skill could be expanded in the revised manuscript to provide more insight into the regions/catchments with with high or low skill.

To address this we have added a new Figure 8 (below) to the revised manuscript. The new figure shows GloFAS forecast skill (CRPSS) by latitude (a), catchment area (b) and the Richards-Baker Flashiness Index (c). Results have been worked into the existing results text in Sect. 4.2.2 and a new section 4.2.3 titled 'GloFAS skill by catchment area and hydrological flashiness' has been added. These new results together with a more broad discussion of the literature have led us to focus future research and development of GloFAS in three main areas to improve the quality of river discharge forecasts: i.) the need for higher spatial and temporal resolution hydrological modelling, ii.) the need to improve precipitation forecasts within the ECMWF global weather model, especially for convective events in the tropics and how that might improve hydrological forecasting, and iii.) further investigation into the representation of snow processes and their impact on forecast skill.



New Figure 8: GloFAS 2.1/2.2 Continuous Ranked Probability Skill Score (CRPSS) for 5-day (green dots; against persistence benchmark) and 20-day (brown dots; against climatology benchmark) lead times at 5997 diagnostic river points by degree latitude of the river point (a), catchment area (b), and RB Flashiness index (c). Spearman Rank correlation coefficients (Rho) for each combination given in text in the bottom right.

Please, find some detailed comments on current manuscript below. Apologies for mentioning my own work, but I am very eager to start comparing model results at the global scale soon. 😊

Yes indeed, we are already collaborating on a comparison between GloFAS and World-Wide HYPE in terms of hydrological simulation performance, but the work is not yet completed. We also agree that the prospect of being able to compare multiple operational global forecasting systems (and not only GloFAS and WWH, but others as well) in terms of ensemble forecast skill would provide extremely valuable information to the scientific and forecast user community and are too are very eager to participate further.

Introduction

Line 31: Reference Blöschl, et al. 2019 does not evaluate risks or hazards.

This sentence has been modified to "Hydrological extremes, such as floods and droughts, have severe negative socio-economic impacts and climate change is expected to alter their timing and magnitude (Blöschl et al., 2017, 2019; Ward et al., 2020)"

Line 37: also note the global and continental scale forecasting based on sharing the world-wide HYPE model:

> *Arheimer, B., Pimentel, R., Isberg, K., Crochemore, L., Andersson, J. C. M., Hasan, A., and Pineda, L., 2020. Global catchment modelling using World-Wide HYPE (WWH), open data and stepwise parameter estimation, Hydrol. Earth Syst. Sci. 24, 535–559, https://doi.org/10.5194/hess-24- 535-2020*

Thank you for the suggested paper. We have added it to this section in the resubmitted manuscript.

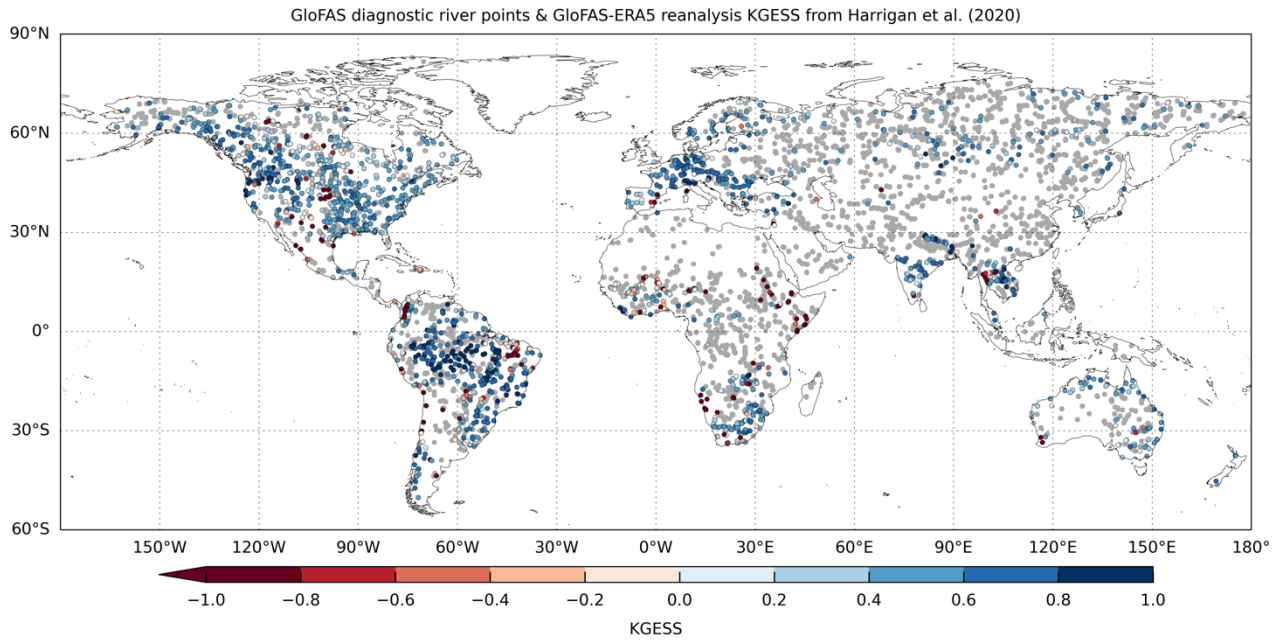
Line 60-70: In fact, global river forecasts and reforecasts are also available at https://hypeweb.smhi.se/ where the user can subscribe to seasonal forecasts with monthly data. In addition, 1-10 days forecasts with thresholds based on return periods of high flows can be ordered at https://hypeweb.smhi.se/water-services/data-delivery-services/

Thank you for this information. GloFAS has been providing an on-demand tailored user data service free of charge since it went pre-operational in 2011, but the present manuscript outlines a step-change in the service of large scale GloFAS data. What would be fantastic for the community is to be able to access sets of reforecasts generated from many hydrological forecast centres in a standardised format and central data service portal. This has been common practice in the weather and climate fields for years and has really facilitated advancement in forecasting science.

Section 2. even though Glofas has been evaluated against observed river flow in previous publications, it would be helpful to include such information about model performance vs absolute values also. For instance, Fig 4 could also include colors of KGE performance (modelled values vs observed values) in the circles showing location of gauges. This would make this figure much more informative and help the reader a lot to judge model performance. Please, check the color coding in Arheimer et al., so the overall pattern of model performance could be compared. Please, also mention median KGE at global scale (no you only say that it was skillful, which is very vague).

Given the full evaluation of the hydrological model performance of GloFAS is published in another paper (Harrigan et al., 2020) we only summarised the results briefly here and pointed the reader to the original paper where the detailed statistics (such as median KGE at the global scale, which is 0.31) and indeed all raw statistics for each of the 1801 stations were provided within the Supplementary Information of Harrigan et al. (2020) to allow for comparison.

However, we agree that having the hydrological model performance results summarised in Figure 4 would help the reader would be help for the reader in the present manuscript. We believe it is most helpful to do so using the modified KGE as a skill score (KGESS) against a mean flow benchmark, following Knoben et al. (2019) as done in Harrigan et al. (2020), and have updated Figure 4 in the resubmitted manuscript (also shown below).



Updated Figure 4. GloFAS diagnostic river points (n=5997) are highlighted by grey dots. Coloured dots show hydrological performance of GloFAS-ERA5 river discharge reanalysis against a subset of GloFAS diagnostic river points with observations (n=1801) from Harrigan et al. (2020) using the modified Kling–Gupta efficiency skill score (KGESS). Optimum value of KGESS is 1. Blue (red) dots show catchments with positive (negative) hydrological skill.

Section 3: please start with some sentences summarizing the evaluation concept – _e.g. that you use scores with met. model vs observed met. model (_“a perfect weather model”) and correlation with observations. It would also be interesting for many users to actually see some scores to absolute values as well – or at least to discuss the difficulties here.

We mention explicitly that the forecast skill using the CRPSS (i.e. Sect. 3.3) is “verified against GloFAS-ERA5 river discharge reanalysis used as proxy observations [or ‘perfect model’] (following Alfieri et al., 2014)” in L254-235. We have made it clear that both the benchmark forecasts and the verifying observations are based on the river discharge reanalysis rather than in situ station observations. This approach is common practice in forecast evaluation (e.g. as in Pechlivanidis et al. (2020) mentioned below), but for the benefit of a broader audience we have added the justification of this approach at the end of Sect. 3.3 in the resubmitted manuscript as follows:

“Calculating forecast skill against proxy observations such as reanalysis is common in hydrological forecasting as it has the advantage of providing a spatiotemporally complete picture of forecast skill, currently not possible based on availability of the current global in situ observed river network (Lavers et al., 2019). It also allows the forecast predictability range to be isolated in the absence of systematic hydrological model errors. There is a disadvantage of forecast evaluation against proxy observations for catchments that represent hydrological dynamics poorly. While Harrigan et al. (2020a) demonstrate the performance of GloFAS-ERA5 reanalysis is largely hydrologically skilful, readers should be aware that there are areas where performance is poor and that there are large parts of the world where the performance is unknown due to the lack of in situ observations to evaluate against (Figure 4).”

Section 4: the Glofas results could be compared with results from another model, using the same metrics across Europe, presented by:

Pechlivanidis, I. G., Crochemore, L., Rosberg, J., & Bosshard, T. (2020). What are the key drivers controlling the quality of seasonal streamflow forecasts? Water Resources Research, 56, e2019WR026987. https://doi.org/10.1029/2019WR026987

One of the key benefits of providing the GloFAS data openly and free of charge on the Copernicus Climate Data Store (CDS) is that it now facilitates further scientific evaluation and inter-comparisons of similar forecasting systems offering their data in the same way. We however think a more appropriate comparison of GloFAS forecasts with Pechlivanidis et al. (2020) is to undertake it with the GloFAS-Seasonal system (Emerton et a., 2018), which is forced by the SEAS5 climate output. All GloFAS-Seasonal data including a comprehensive set of reforecasts are now available through the CDS: https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-glofas-seasonal-reforecast?tab=overview; for a higher resolution hydrological seasonal forecasting system at European scale, the EFAS-Seasonal complete dataset is also available from the CDS (https://cds.climate.copernicus.eu/cdsapp#!/dataset/efas-seasonal-reforecast?tab=overview).

To further explore and evaluate the added value of the Glofas system, it could also be compared to warning issued by National forecast services for specific regions or countries, or to soft information from new items reporting floods, to check if the alerts actually captured something real.

Evaluation of flood events against a wider set of observations is a very good idea and something that will be expanded in future assessments, but is outside the scope of this first evaluation to determine overall ensemble forecast skill against the two key scientific benchmark forecasts: persistence and climatology.

Line 265: Attribution is also discussed in the above-mentioned paper. It is another interesting scientific analysis, which deserves much more attention – _also in this global study of model performance. Such an analysis would make this paper much more scientifically interesting.

This point is related to the one you bring up in the above bullet list of interesting further scientific questions. We agree and have now expanded section 4.2 and include new Figure 8 (see response above) in the resubmitted version.

I am looking forward to read a new more elaborated version of this paper, with a scientific discussion linked to the methodological description.

We appreciate your time to review our manuscript and thank you again for your constructive feedback and many ideas for further research and collaborations!

Kind regards,
Shaun Harrigan on behalf of all co-authors

Response to RC3

Anonymous Referee #3 (R#3)'s original text in black *with our initial response in* blue*.*

This paper described the development, application and user service upgrade of GLOFAS to include reforecasts and reforecast-based skill calculations. It probably contains more engineering-related detail than is typical in a HESS paper, but it does advance the science as well in providing a working example of the applied science concept that reforecasts can help to usefully complement the information available from forecasts alone – thus I think it is appropriate for HESS. It would be nice to see a bit more framing on where a forecast effort

such as GLOFAS fits in overall field of hydrologic forecasting, but the authors may deem that after some years of running GLOFAS, it is now a widely understood / accepted approach, and that the overall GLOFAS rationale is adequately addressed in prior papers. I don't actually think it is as well understood outside of Europe, where EFAS served as an introduction to this type of service. Partly for that reason, I'd suggest that the authors do more to highlight some expected limitations of GLOFAS relative to a local/regional forecast (suggestions below), particularly given the use of perfect model benchmarks. On the plus side, the paper could strengthen the context framing by noting that it represents one of the first large operational scale effort at reforecasting in hydrology, in contrast to the introduction of reforecasting more broadly for weather and climate over 10 years ago. Overall, however, I find the paper to be a high-quality, very readable effort, presenting a range of accessible and useful information, hence I recommend publication with relatively minor clarifications and adjustments listed below.

We thank the reviewer for their positive words about our manuscript and constructive comments.

We agree very much with you on the need to frame the justification/reason for a system such as GloFAS in the context of local systems and within the overall field of hydrological forecasting - thanks for the suggestion! GloFAS aims to provide complementary information in addition to, rather to instead of, locally calibrated catchment forecast systems. In the first instance a global system is useful for providing a hydrological forecast in regions where there is currently no operational local system, or when a local system covers only part of a larger, often transboundary basin. Further, there are users that require a global overview of potential upcoming extreme events, such as international disaster and humanitarian agencies.

We have expanded the introduction section to include the following:

"GloFAS is not designed to be a replacement for local operational hydrological forecasting systems; in many parts of the world however a local or national system for operational forecasts of river discharge does not yet exist so it might be the only information available. GloFAS covers all river basins out to medium- and extended-range lead times (30-days ahead) and updated daily, with GloFAS-Seasonal (Emerton et al., 2018) updated monthly out to a 16-week lead time. Therefore, it has been used to complement local forecast systems by allowing forecasters to gain information on surrounding and upstream basins, monitoring for potential flood signals where advanced warning is needed."

Specific comments:
53: 'originally designed for large/transboundary river basins' – this is surprising because those would almost all be regulated and impaired, yet glofas does not represent such effects. could this statement be sharpened? if glofas can't be expected to forecast mainstem flows in such basins accurately, what was glofas designed to do more specifically? eg forecast runoff anomalies in such basins? or smaller tributaries across large basin domains? or natural flow changes and risks?

As mentioned in L114-115, 667 of the largest reservoirs are represented in GloFAS. Nevertheless, the reservoir scheme is of course a simplification of reality and the actual real-time release schedules of individual reservoirs is sensitive information and typically not publicly available. However, to help guide forecasters, the locations of the reservoirs explicitly modelled in GloFAS together with the ratio of reservoir volume to mean annual discharge for all downstream river cells are provided to users as supporting map layers within the GloFAS Web Map Viewer (https://www.globalfloods.eu/). While GloFAS generates raw river discharge magnitudes, the nature of a global-scale system means it must rely openly available datasets and is run typically at coarser resolution than locally calibrated models, thus provides varying degrees of accuracy with significant biases, as documented in Harrigan et al. (2020). Nevertheless, GloFAS forecasts are compared relative to thresholds derived from the same model, and therefore can provide awareness of anomalously high river discharge. For example, if 80 % of forecasted ensemble members exceeded the 1 in 20-year modelled threshold then this would signify an extreme forecast 'signal' irrespective to any systematic biases in the hydrological model.

58: there are more service-related gaps, I think. at the end of this paragraph could another sentence be added to suggest that 'Other concerns include : : :' where I could imagine that the lack of information about where glofas reflects upstream management effects might be another one. ideally a user could mask out reaches where it's thought that what is shown cannot represent the reality of the river flow, perhaps because it is 50% determined by a reservoir release or major diversion.

We agree that improving the representation of human controls on the hydrology is a key gap in global hydrological modelling and forecasting. We will highlight this more strongly in the revised manuscript and think it would best fit in "Sect. 4.4 Future directions". As per the response to your above comment, there is already layer called "Reservoir impact" within the GloFAS Web Map Viewer (Fig. B). We think this information is critical for forecast users as this layer informs the degree of control by reservoir operations on a hydrological forecast for a particular location, and therefore on the possible resulting increased uncertainty in the published forecasts.

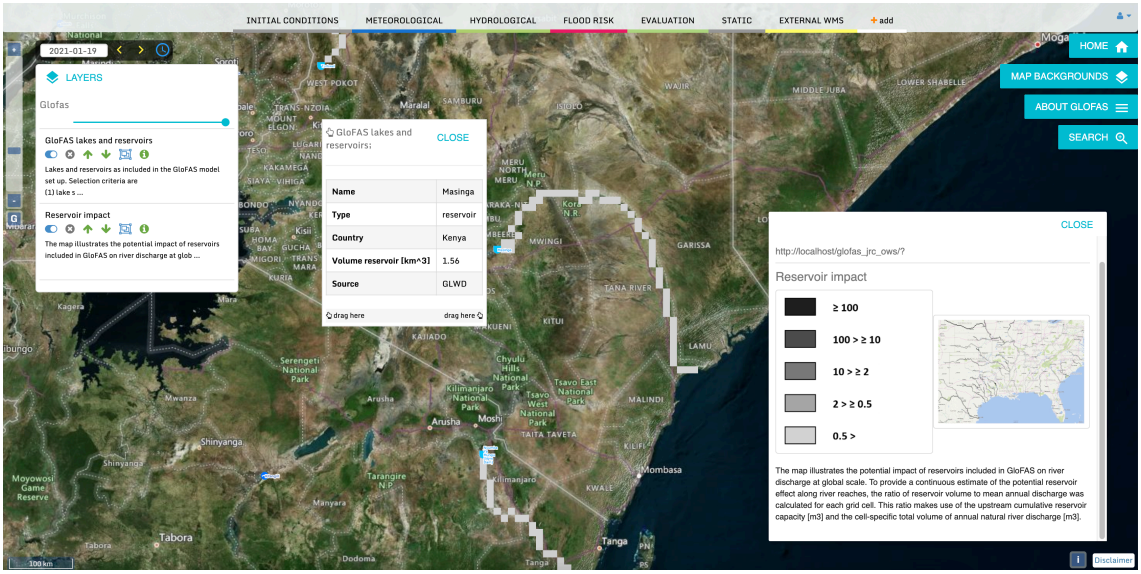


Fig. B.: Screenshot of the GloFAS Web Map Viewer (https://www.globalfloods.eu/) centered over Kenya with the "GloFAS Lakes and reservoirs" and "Reservoir Impact" layers activated, showing the example of the overall potential impact the Masinga reservoir has on the annual natural river discharge or the Tana River.

Fig1: The label 'hydrological model' is interesting because most of the hydrological components of LISFLOOD are not used – really it is the empirical groundwater attenuation and the channel routing of runoff. A more descriptive label for this component might be 'Catchment and channel routing' (whether GW or channel it's all a kind of routing, conceptually). Not a big issue but it may be confusing given that a lot of hydrology (runoff generation, snow accum/melt, et) is done by the LSM. btw, LISFLOOD could conceivably also offer a hillslope routing function (gamma or UH distribution).

Thank you for this useful suggestion, this has been changed to 'Catchment and channel routing' in the resubmitted manuscript.

114: Would be helpful to add a sentence to clarify how these reservoirs are represented and their realism – eg level-pool scheme, fixed rule curve

We added the following sentence to the resubmitted manuscript: "Reservoir outflow is calculated with a set of four rules depending on the current reservoir filling level (see Burek et al., 2013)".

174: Perhaps add a sentence or two here or in the later discussion if the reanalysis latency impacts the skill of real-time forecasts (2-5 days is a lot of lag for a flood forecast!) or means that the skill of the hindcasts may be systematically higher than that of the real-time forecasts, since presumably the reanalysis initialization in the past doesn't have latency issues.

It is practically impossible to create identical forecast initialisation for reforecasts versus real-time forecast systems due to the constraint on availability of operational data streams – there will always be some lag. However, we do not simply leave this lag empty in GloFAS. We fill it up with the best estimate we have of real time conditions. In the case of the GloFAS 'fill up' (as shown in Figure 2 in the manuscript), the period from the last available GloFAS-ERA5 until real-time is based on the short-range (i.e. 1-day) ECMWF-ENS forecast control member and is only needed for the real-time forecast and not the reforecast.

178: Can you say what determines 'skillful'? eg 5% kge above benchmark in the SS?

Hydrological skill in Harrigan et al. (2020) is determined using the modified Kling-Gupta Efficiency Skill Score (KGESS) against a mean flow benchmark, with KGESS > 0 defined as skilful.

199, 235: Perhaps add a sentence explaining what fraction of these sites are impaired/ unimpaired and what 'synthetic' means in the context of an observation (eg labeled in the table). In general, it should be quite clear in the paper when you are verifying against the real versus perfect model world. The initial description of verification against in situ gage stations may slightly obscure the later default to benchmarking against the reanalysis discharge. Could a sentence be added at 235 to state what is gained/lost in the interpretation of skill through comparing to the perfect model benchmark?

In the Supplementary table, the label 'synthetic' under the 'Provider' column refers to a GloFAS diagnostic river point where no in situ observed time-series river discharge is available at this station location. These tables have now been updated to provide further metadata and are now publicly available as part of the "Documentation" together with the reforecast download on the CDS: https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-glofas-reforecast?tab=doc as well as added as Supplementary Table 1 in the resubmission.

Your comment regarding what is gained/lost calculating skill from the perfect model benchmark is similar to R#2. This approach is common practice in forecast evaluation, but for the benefit of a broader audience we have outlined the justification of this approach in Sect. 3 in the resubmitted manuscript (see response above to R#2), also mentioned below in response to your final comment.

239: again could you quantify in a sentence what you consider 'skillful'. without going fully statistical (ie significance level of a skill scores X% above 0), what is the rule of thumb used by the authors to consider a forecast 'skillful'?

As defined in L230-231, a CRPSS > 0 shows forecasts are more skilful than the benchmark.

Fig 5: It's curious that the persistence-benchmarked forecast SS is so high at timestep 1. If anything I would expect it to start slightly lower than its peak SS because as you move from longer leads to approach T0 the persistence forecast, in theory at least, approaches zero error, and the persistence and actual forecasts approach each other.

There must be something in practice here that means this is not the case, ie persistence has an offset at T0 that is not present in the actual forecast. Especially in medium to large rivers, much of the time by day 1 the flow from T0 has not changed much. Is it correct that the actual forecast is 95% better than persistence even at day1? Can/should this behavior be explained in the paper?

Your comments regarding interpretation of the forecast skill relative to the benchmark forecast is similar to that made by R#1. We found it useful to look at the CRPS values of individual components of the CRPSS skill score in Equation 1 to interpret the pattern as a function of lead time (Fig. A). While the CRPSS in Fig. 5 is dimensionless with an optimum value of 1, the CRPS error is measured in units of the variable being evaluated (here m^3/s) and so has an optimum of 0 (i.e. perfect accuracy against the reanalysis). It is the case that the persistence benchmark forecast is most accurate at a 1-day lead time and gets increasingly less accurate with longer lead times. But it is also the case that the GloFAS forecast is most accurate at a 1-day lead time with accuracy decaying with increasing lead time, but at a slower rate than the persistence benchmark, hence the CRPSS score comparing both CRPS.

To help users better interpret the CRPSS for their stations of interest, we have included CRPSS as well as CRPS plots as a clickable "pop out" window as part of the new GloFAS "forecast skill" layer on the GloFAS Web Map Viewer for the release of version 2.2 on 2 December 2020 (https://confluence.ecmwf.int/display/COPSRV/Latest+operational+release%3A+GloFAS+v2.2).

We have added Figure A as an additional panel - now Figure 5b in the resubmitted manuscript. To reflect the update to the CRPSS/CRPS plots within the "Forecast skill" layer on the GloFAS website, we have updated Sect. 4.2 and Fig. 9 in the resubmission.

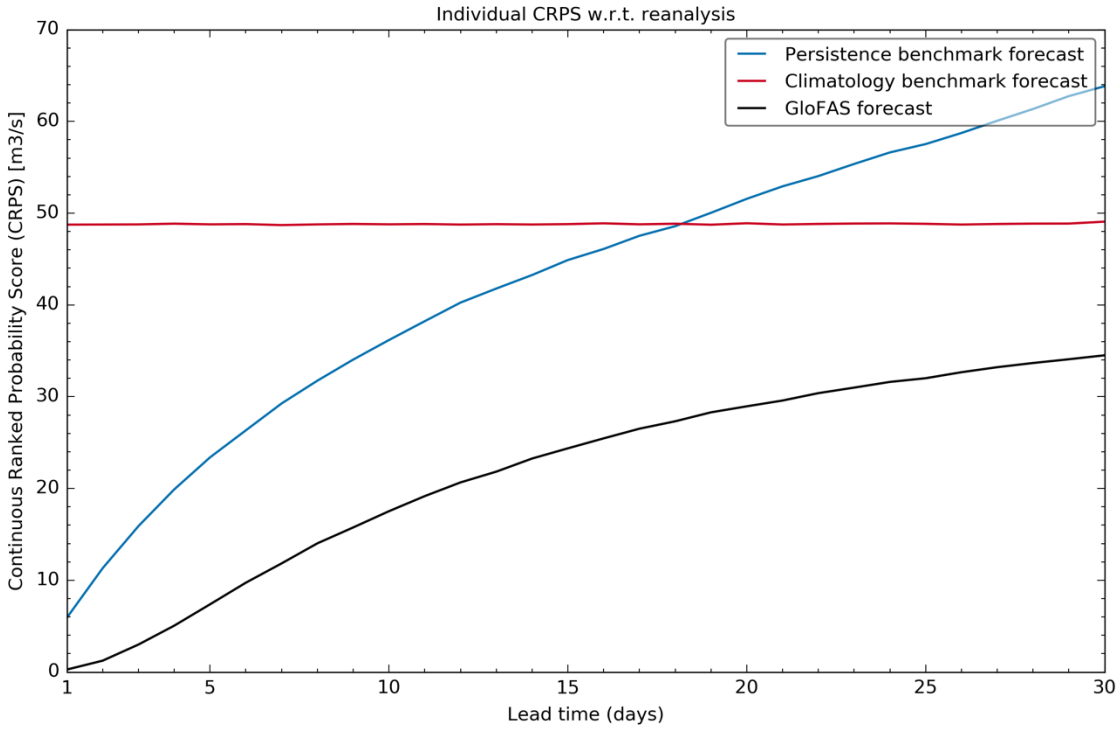


Figure A (New Figure 5b).: Global median Continuous Ranked Probability Score (CRPS) for GloFAS forecasts (black line) and both persistence (blue line) and climatology (red line) benchmark forecasts from 1- to 30-day lead times with respect to GloFAS-ERA5 river discharge reanalysis across 5997 diagnostic river points.

343: I don't quite agree, as I think of bias & mean error-based scores reflecting only accuracy. The use of an integrated score such as crps means the results are sensitive not just to accuracy but to forecast spread (hence reliability). Perhaps rephrase here?

What we tried to say was that we focused on the overall correspondence between forecasts and the verifying reanalyses, and that there are many other aspects of forecast quality such as reliability (and spread) etc. that

could be unpacked in future evaluation work. This could be confused with the technical definition of the CRPS and so has been rephased to "The evaluation carried out here looks at the overall quality of forecasts".

354: It would be helpful to add a discussion returning to some of the major caveats on the applicability of the analysis. I strongly support the overall message of the paper and commend the effort for having generated reanalyses and used them to demonstrate the kind of information one can derive from them, but I also recognize that in many areas the skill / usability estimates are compromised by use of perfect model benchmarks, and the lack of representation of real-world impairments in GLOFAS. Could the authors walk us through some of the possible limitations, eg in a paragraph, discuss a few cases that users may face in interpreting this kind of skill or using the reforecasts? eg, in the best case, through the model may have some biases it generally represents catchment variability such that the perfect model skill analysis is more or less directly transferrable to real world conditions. A use could infer usability qualitatively or even apply quantitative post processing methods for their own site observations to adjust the skill scores accordingly. In a medium case, the model is badly biased (say magnitudes by 50-100% and seasonal timing off by 30 days), but still represents observed variability in high/low flow conditions – what more would be required of a user then? And in the worst case, say on highly regulated rivers, perhaps glofas cannot be used except in the most extreme situations, eg when there is so much or so little water that management effects are secondary. Would this suggest any other future directions, eg providing guidance or tools on such user-based post-processing and analysis?

Reviewer 2 had a similar comment on highlighting the justification and caveats of using proxy observations in the evaluation. We have added the justification of this approach at the end of Sect. 3.3 in the resubmitted manuscript as follows:

"Calculating forecast skill against proxy observations such as reanalysis is common in hydrological forecasting as it has the advantage of providing a spatiotemporally complete picture of forecast skill, currently not possible based on availability of the current global in situ observed river network (Lavers et al., 2019). It also allows the forecast predictability range to be isolated in the absence of systematic hydrological model errors. There is a disadvantage of forecast evaluation against proxy observations for catchments that represent hydrological dynamics poorly. While Harrigan et al. (2020a) demonstrate the performance of GloFAS-ERA5 reanalysis is largely hydrologically skilful, readers should be aware that there are areas where performance is poor and that there are large parts of the world where the performance is unknown due to the lack of in situ observations to evaluate against (Figure 4)."

As GloFAS does not apply any post-processing, there is indeed a lot of room for users to increase the forecast quality if they carry out a further post-processing step at their end – this is a very good point and highly encouraged, we have therefore added the following to Sect. 4.4:

"GloFAS forecasts and reforecasts have not been post-processed, therefore there is room for users to increase further forecast quality by applying post-processing with their local observations data to correct forecast bias or timing errors, for example."

Your last point is probably one of the biggest challenges in large-scale hydrological forecasting. While we can provide information on whether GloFAS is on average skilful or not for a particular location, this becomes more challenging in areas with very little information on river management and/or a lack of situ observations. However, when faced with an emergency situation due to very extreme hydrometeorological conditions, for example tropical cyclone Idai that devastated Mozambique in March 2019, operational experience has shown that despite the uncertainty associated with GloFAS forecasts, useful information on the future evolution of flood risk can be made, when balanced with many additional sources of information (Emerton et al., 2020).

Thank you again for your insight and we appreciate your time to review our manuscript,

Kind regards,
Shaun Harrigan on behalf of all co-authors

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