Response to Anonymous Referee #2:

The authors compare the impact of different runoff schemes on the hydrological simulations in different basins at a global scale. The paper is well-written and organized overall which is easy to read. The methodology is described in sufficient detail and provides a clear description of the results. I reviewed the paper, and I would highlight the following concerns.

Major comments:

1) Throughout the paper, it emphasizes the improvements in hydrological models, specifically highlighting this necessity. However, as the paper is written, it seems more focused on the evaluation of the different runoff generation schemes within the Noah-MP model. While this analysis is valuable, the paper could benefit from a more thorough exploration of how these findings can be applied to enhance global hydrological modeling, particularly in the context of discharge simulation, which I understand is the central aspect of the paper.

    - ***Thank you for this insightful feedback. We agree that while the paper's focus on evaluating runoff generation schemes within the Noah-MP model is essential, the application of these findings to enhance global hydrological modelling and discharge simulation could be further clarified. Therefore, in response to the shortcoming of the original manuscript, we have added a dedicated section "3.5 Implications for Global Discharge Simulation" (given below) discussing how our findings could contribute to improve global hydrological models, emphasizing implications for discharge simulation and practical applications in water resource management and climate adaptation. We believe this addition strengthens the paper's relevance to global hydrological modelling advancements.***

3.5 Implications for Global Discharge Simulation:

"This study provides a comprehensive analysis of how distinct Noah-MP runoff schemes impact discharge simulation in a global hydrological context, paving the way for enhanced modelling accuracy across different climate zones. By revealing the performance variability of different runoff schemes—such as Schaake, BATS, VIC, and XAJ—across cold, warm temperate, tropical, and arid regions, this research suggests that tailored scheme selection could improve discharge simulations for specific hydrological conditions. For instance, Schaake, BATS, and VIC exhibited reduced biases in warm temperate and tropical regions, while TOPMODEL-based schemes with groundwater performed notably better in arid areas, underscoring the need for strategic scheme selection based on regional climate and hydrological characteristics. This targeted approach to scheme selection can minimize bias and enhance model reliability in both regional and global discharge simulations, improving the accuracy of water resource management.

This study also addresses a crucial challenge in hydrological modelling: the significant biases in high-flow extremes by certain schemes. Given that accurate high-flow discharge predictions are essential for flood forecasting and disaster management, this finding suggests an urgent need for refining high-flow calibration. This enhancement is particularly relevant for global flood risk management, as it enables more reliable flood predictions that are vital for preparing for extreme weather events. By identifying critical parameters and proposing spatially variable adjustments, such as using data from sources like remote sensing products, this study sets a practical foundation for developing global calibration strategies that could

yield more accurate discharge predictions (Beck et al., 2017). These strategies could be applied universally across a range of climates, creating a more adaptable global model without extensive customization.

This research further advances current hydrological modelling by demonstrating the value of multi-model comparisons, which allow for a holistic approach to discharge simulation. Rather than depending on a single runoff scheme and potentially inheriting its limitations (Diks and Vrugt, 2010; Shoaib et al., 2018), a multi-scheme approach enables researchers to capture river discharge dynamics more comprehensively (Georgakakos et al., 2004; Huo et al., 2019). This approach aligns with a broader hydrological perspective that considers the interactions between multiple runoff dynamics, offering a pathway for more nuanced simulations that acknowledge the strengths and limitations of each scheme.

For coupled ocean-atmosphere regional models lacking complete river and discharge representations, integrating findings from this study could significantly improve their hydrological modules, particularly in complex regions like the Mediterranean where the freshwater flux from rivers remarkably affects the salinity near the coast close to river mouths (e.g. Reale et al., 2020). These refinements are expected to enhance the overall representation of the global water cycle within climate models, providing more realistic freshwater flux predictions and supporting more accurate climate projections.

Additionally, this study's analysis of seasonal and regional discharge cycles reveals new insights into the variability of discharge patterns across climates. This detailed understanding could facilitate the development of models better suited to capture seasonal dynamics in tropical and temperate regions, where runoff schemes like Schaake and ERA5-Land-driven simulations performed particularly well. By capturing the discharge seasonality more accurately, our findings have direct applications for both short- and long-term water resource planning (Pires and Martins, 2024), especially in regions facing pronounced seasonal changes in water availability.

Furthermore, the findings related to groundwater interactions underscore the importance of accurate groundwater dynamics in discharge simulation, especially in arid regions. The effectiveness of TOPMODEL-based schemes with groundwater dynamics in these areas suggests that future modelling efforts should prioritize improving groundwater parameterizations, particularly where groundwater plays a critical role in maintaining streamflow. This refinement could improve discharge simulations (Decharme and Colin, 2024) in water-scarce areas, supporting more efficient resource allocation and resilience against drought.

Finally, the implications of these findings extend to climate adaptation strategies, where reliable hydrological models are critical for anticipating shifts in water availability under changing climates. By advancing the accuracy of discharge simulations, particularly in high-flow and seasonal scenarios, this research provides a basis for better-informed adaptation planning, enabling decision-makers to prepare for anticipated changes in river flow and water availability. This study not only enhances current global hydrological modelling but also lays a foundation for more resilient water resource management, which is increasingly critical as climate variability challenges water availability worldwide."

2) Given that the results align with expectations across different regions and are not particularly surprising (lines 399 – 406, 461 – 462, and 469 – 470), it raises the question

of what the primary contribution of this study is. If the findings largely confirm well-established patterns, it would be helpful to clarify how this research advances current understanding or introduces novel insights into hydrological modeling. A clearer articulation of the contribution of this study would strengthen its impact and ensure that it is seen not just as a validation of existing knowledge, but as a meaningful step forward in hydrological research.

- ***Thank you for your comment. We agree that the results were theoretically expected, and this study indeed confirms those expectations. However, as per the clarification on how this research advances hydrological modelling as a meaningful step forward, we have added a dedicated section "3.5 Implications for Global Discharge Simulation" to discuss the implications for hydrological simulation. See above.***

3) The paper offers a detailed analysis of the biases in different runoff generation schemes related to discharge, which is valuable. However, it would benefit from a deeper discussion of the underlying physical processes that contribute to these differences. By incorporating a more thorough exploration of the hydrological mechanisms driving these variations, the paper could provide a more comprehensive understanding of the findings and their implications.

- ***Thank you for your insightful comment. In response, we have added a discussion (given below) that explores the underlying hydrological processes contributing to the biases observed in different runoff schemes. This section emphasizes how variations in the partitioning of precipitation into surface and subsurface runoff, as well as soil moisture dynamics, influence the distinct biases across schemes.***

"The differences in biases between the runoff schemes are driven by how each scheme handles critical hydrological processes, particularly the partitioning of precipitation into surface and subsurface runoff, as well as the treatment of soil moisture dynamics. Although the formulas for some runoff schemes appear similar, the variations in specific parameters and their physical representations cause distinct biases to emerge.

For example, in the TOPMODEL-based schemes, while the surface runoff follows the same formula across both experiments, subsurface runoff differs in the way it is computed. In EXP1, subsurface runoff is influenced by the soil hydraulic conductivity of the first unsaturated layer above the water table, while in EXP2, the subsurface runoff is controlled by a fixed base flow coefficient and a fixed runoff decay factor. These differences lead to distinct sensitivities in how each scheme responds to variations in soil properties and terrain. The water table depth also plays a pivotal role in the calculation of subsurface flow in these schemes, introducing differences in regions with shallow or deep groundwater. These variations affect the magnitude and timing of runoff, which ultimately manifests as bias in the discharge simulation.

The surface runoff in the TOPMODEL-based schemes and BATS also shares the same formula; however, the differences lie in how the saturated area fraction (fsat) is calculated. In the TOPMODEL-based schemes, fsat depends on the water table depth and a runoff decay factor, which differs between the two schemes, while in BATS, it is computed as the fourth power of the degree of saturation in the top two meters of soil. This distinction between the two

approaches introduces variability in how surface runoff is generated across regions with differing soil moisture profiles and saturation conditions. The BATS scheme also handles subsurface runoff differently, using a free drainage approach where it is calculated as the product of soil hydraulic conductivity and (1 - fimp,max). This method leads to a distinct response to soil permeability and introduces varying biases depending on the frozen or compacted soil conditions.

For the other free-drainage schemes, including Schaake, VIC, XAJ, and Dynamic VIC, the calculation of subsurface runoff follows a similar approach. However, the key differences between these schemes lie in how surface runoff is generated. In the Schaake scheme, surface runoff is governed by an infiltration-excess mechanism, which depends on the total maximum holdable soil water content and the rate at which the soil can infiltrate water. This mechanism tends to produce lower biases in regions where infiltration-excess processes dominate, such as cold regions (Decharme, 2007).

The VIC scheme, on the other hand, calculates surface runoff based on the infiltration and maximum infiltration capacity of the soil, which introduces a different partitioning of rainfall into surface and subsurface components. The scheme's reliance on current soil moisture conditions, particularly in the tension water storage in the top layers of the soil, leads to varying biases depending on whether the region is experiencing wet or dry conditions. Similarly, XAJ introduces a unique approach by using a shape parameter to calculate surface runoff, which adjusts runoff generation based on the catchment's topographic and moisture characteristics. This leads to differences in performance depending on the terrain and hydrological profile of the region.

Dynamic VIC incorporates both infiltration-excess and saturation-excess runoff, further complicating the balance between surface and subsurface flow. The detailed soil moisture capacity parameters used in this scheme contribute to its dynamic nature but also make it more sensitive to inaccuracies in modelling infiltration and saturation, leading to large biases in discharge performance. The different ways each scheme handles these physical processes—whether through the treatment of soil moisture, the representation of surface and subsurface interactions, or the response to topographic and climatic variability—accounts for the differences in bias observed across the experiments. Understanding these physical distinctions is essential for improving the accuracy of runoff and discharge simulations, especially in regions with complex hydrological behaviour."

Minor comments:

1) it would be beneficial to replace informal phrases like: "On the flip side" (line 39) with more formal language.

   - ***Thank you for your suggestion. We have revised the expression to a more formal tone as recommended ("On the other hand, …").***

2) Section 2.1.1 would benefit from incorporating a table listing the different experiments, the runoff scheme used and their corresponding equations, making the text easier to read.

- ***Thank you for your suggestion. We have incorporated a table (Table 1 below) in Section 2.1.1 listing the different experiments, the runoff schemes used, and their corresponding equations to enhance readability.***

Table 1: Summary of the experiments (EXPs), runoff schemes, and corresponding equations

EXP	Runoff Scheme	Surface Runoff (R_s) Equation	Subsurface Runoff (R_{sub}) Equation
1	TOPMODEL with groundwater	$R_s = P_e \times \left[\left(1 - f_{imp}(1)\right) \times fsat + f_{imp}(1)\right]$ (5)	$R_{sub} = (1 - f_{imp,max}) \times C_{baseflow} \times e^{-I_{topo}} \times e^{(-F_{decay} \times dwt)}$ (6)
2	TOPMODEL with an equilibrium water table	Equation (5)	Equation (6)
3	Schaake	$R_s = P_e - Q_{infil,max}$ (7) $R_s = P_e \times \left[1 - \frac{w_{soil,tot} \times (1 - e^{-Kdt \times \Delta t})}{P_e \times \Delta t + w_{soil,tot} \times (1 - e^{-Kdt \times \Delta t})}\right]$ (8) The $Q_{infil,max}$ is further corrected for frozen soil as follows: $Q_{infil,max} = min(max(Q_{infil,max} \times f_{imp}; DK); P_e)$ (9)	$R_{sub} = S_{drain} \times DK$ (10)
4	BATS	Equation (5)	$R_{sub} = (1 - f_{imp,max}) \times DK$ (11)
6	Variable Infiltration Capacity (VIC)	If $i + P_e \geq i_{max} : R_s = P_e - W_{max} + W$ (12) If $i + P_e \leq i_{max}$: $R_s = P_e - W_{max} + W + W_{max} \times \left[1 - \frac{i + P_e}{i_{max}}\right]^{(1+b)}$ (13) If $i_{max} = 0 : R_s = P_e$ (14)	Equation (10)
7	Xinanjiang (XAJ)	$R_s = (P_e \times A_{im}) + R \times \left(1 - \left(1 - \frac{S}{S_{max}}\right)^{E_x}\right)$ (15)	Equation (10)
8	Dynamic VIC	$R_s = R_{ie} + R_{se}$ With: $R_{ie} = \begin{cases} if\ \frac{P - R_{se}}{f_m \times \Delta t} \leq 1, \\ P - R_{se} - f_{mm} \times \Delta t \times \left[1 - \left(1 - \frac{P - R_{se}}{f_m \times \Delta t}\right)^{b+1}\right] \\ otherwise, \\ P - R_{se} - f_{mm} \times \Delta t \end{cases}$ (16) $R_{se} = \begin{cases} if\ 0 \leq y < i_m - i_0, \\ y - \frac{i_m}{b+1} \times \left[\left(1 - \frac{i_0}{i_m}\right)^{b+1} - \left(1 - \frac{i_0 + y}{i_m}\right)^{b+1}\right] \\ if\ i_m - i_0 \leq y < P, \\ R_{se}\vert_{y=i_m-i_0} + y - (i_m - i_0) \end{cases}$ (17)	Equation (10)

$f_{imp}(i)$: the ith soil layer impermeable fraction; $Q_{infil,max}$: the maximum soil infiltration rate; $w_{soil,tot}$: the sum of the maximum holdable soil water content in the unit of depth; Kdt: a coefficient for computing maximum soil infiltration rate; P: the amount of precipitation over a time step Δt; f_{mm}: the average potential infiltration rate over the 1-As area estimated based on the Philip infiltration scheme (Liang and Xie, 2003); f_m: the maximum potential infiltration rate; y: vertical depth; i_0: the point soil

moisture capacity corresponding to the initial soil moisture; i_m: the maximum point soil moisture capacity; $C_{baseflow}$: a baseflow coefficient; I_{topo}: the gridcell mean topographic index.

3) In section 2.3, model evaluation, some paragraphs describe the actual models/data used (lines 243-248, and 272-276), I would suggest reorganizing these paragraphs in the corresponding sections.

   - ***Thank you for your suggestion. We have reorganized the paragraphs as recommended: lines 243-248 have been moved to Section 2.1.2 (Input Data), and lines 272-276, which are associated with Table S1, have been moved to the supplement as Text S1.***

4) The text describing Figure 2 sometimes uses the "mm/year" units and sometimes %, I would suggest using the same units that appear in the figure (%) and indicate in brackets (mm/year), since using different units makes the text confusing.

   - ***We have revised the text describing Figure 2 to consistently use "%" as in the figure, and included "(mm/year)" in brackets for clarity.***

5) Figure 3 could be improved to show only the basins mentioned in the text, this would make it easier to follow the findings described in the text directly in the figure. The rest of the basins could be included as a complementary figure.

   - ***Thank you for your feedback. We have revised Figure 3 to include only the basins mentioned in the text for better clarity (figure below), while moving the original figure to the supplement as Figure S1.***

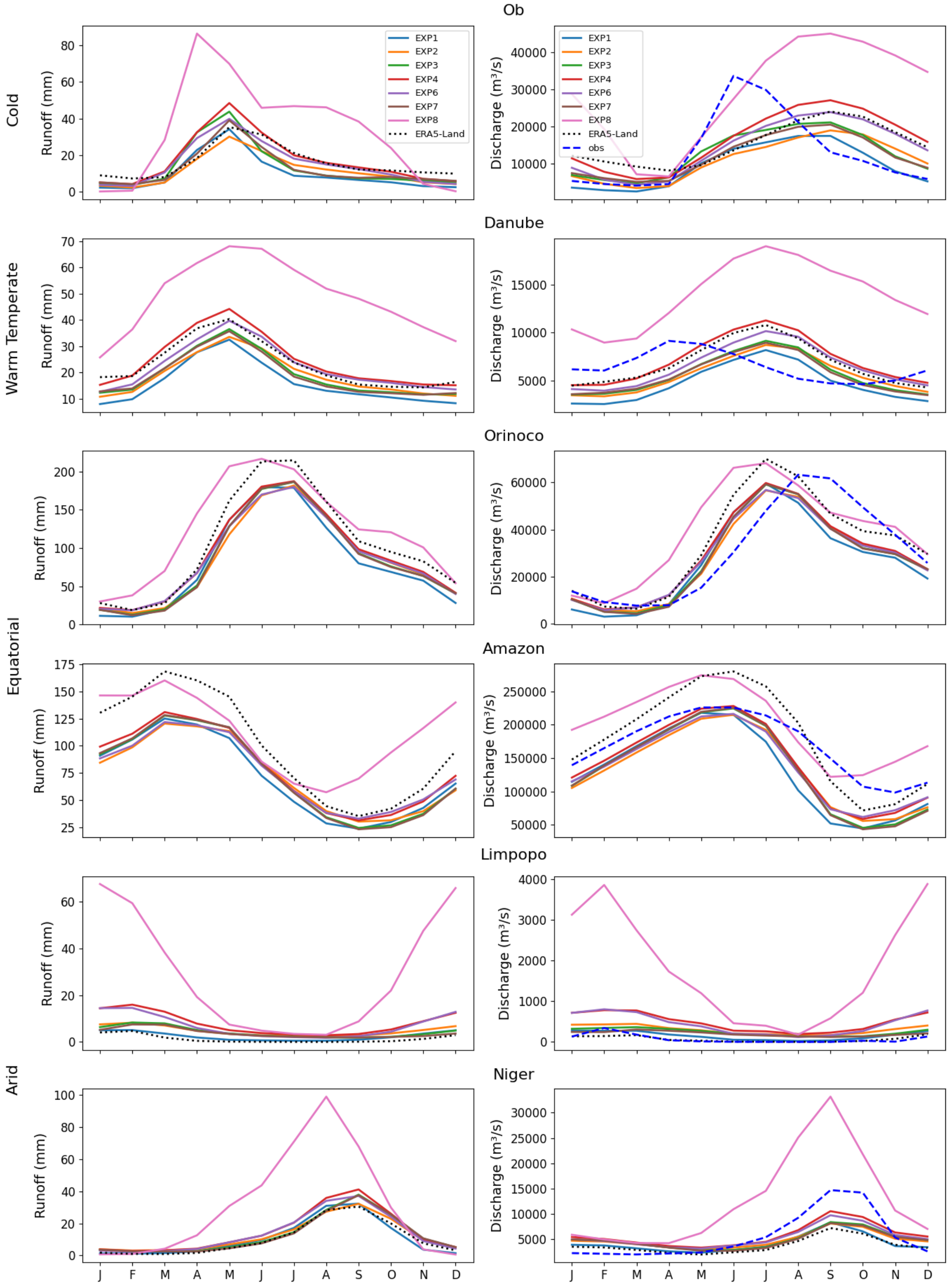

Figure 3: Mean seasonal cycle of runoff (mm) and river discharge (m3/s) simulated by the different Noah-MP runoff schemes and CaMa-Flood, for 6 selected river basins representing four climate regions (cold, warm temperate, equatorial and arid). Discharge data includes simulated and observed values (obs) for the period 1985–2023. Observation years contributing to the monthly mean vary depending on their availability, with a minimum of 5 years per catchment.

6) Lines 357 – 362, While the central idea is clear, the text is somewhat difficult to follow due to its current structure and phrasing. I recommend restructuring this paragraph to improve coherence and enhance the link with the next paragraph.

- ***Thank you for your helpful feedback. We have restructured the paragraph in lines 357-362 to improve coherence and enhance the link with the following paragraph, as follows:***
  "Across many basins, the seasonal cycles of runoff and discharge generally agree. However, a noticeable lag often exists between the peak runoff and peak discharge, especially in large river basins like the Amazon. This lag, which can extend up to three months (Liang et al., 2020; Sorribas et al., 2020), is due to the natural routing process within the river network. This process involves the time it takes for water to travel through the system and the storage effects within river channels, depending on basin characteristics such as size, shape, drainage density, river length, and slope. In some cases, this lag could also reflect limitations in the CaMa-Flood routing model, particularly for large-scale river basins where routing dynamics are complex. A detailed sensitivity analysis of the routing parameterisation (such as river velocity, roughness coefficients, or floodplain dynamics) could offer valuable insights into how model-specific limitations impact the timing of peak discharge. This could be an important direction for future research, with the potential to enhance model performance in accurately simulating discharge timing."

7) Line 405: David et al., 2019. That reference was previously cited in the text and should be properly referred to again in this section. Instead of using a link, it would be more appropriate to use the established citation format.

- ***We have revised this line to properly reference David et al. (2019) using the established citation format.***

8) I suggest reordering Section 3.4 to enhance clarity. Starting with the description of the global performance metrics (and not at the end as it is presented now) and then moving to the findings in detail for each of the regions (cold, warm, etc.), would improve section structure.

- ***Thank you for your suggestion. We have reordered Section 3.4 to start with the description of the global performance metrics, followed by detailed findings for each region.***

9) The authors highlight that further improvements are necessary, such as refinement across diverse climatic regions, and calibration at finer resolutions (lines 336-338, 490 – 494). However, they could provide suggestions or hypotheses for improving global hydrological models and discuss potential refinements in more detail.

- ***Thank you for the suggestion. We agree with the need for detailed refinement strategies and have provided examples (see below) on potential refinements to improve global hydrological models, including calibration and region-specific adjustments.***

"An area for improvement would involve calibrating these parameters, particularly at finer resolutions, to more precisely simulate runoff behaviour across diverse regions. For example, fsatmax is often set as a global mean, but recent studies, such as (Zhang et al., 2022), illustrate that using spatially variable values informed by remote sensing data (e.g., GIEMS-2) could yield more accurate regional simulations. Similarly, the fixed soil depth used in each scheme could be improved through further spatially variable parametrization within Noah-MP, which may help modulate runoff according to regional soil profiles and enhance the model's representation of subsurface flow dynamics. By exploring such refinements, future applications of these models could achieve better performance, especially when simulating high-flow events critical for flood risk assessments and water resource management."

10) While the conclusions offer valuable insights into the regional outcomes, as they are written, it seems that they do not adequately reflect the global perspective outlined in the paper: "Our study transcends the boundaries of individual schemes and specific regions, highlighting the need for a holistic assessment…". It would be beneficial to rephrase the conclusions to present a more unified global argument, aligning with the objective of the research

- ***Thank you for this observation. We have revised the conclusions to present a more unified global perspective:***

4 Conclusions

"This study evaluated the performance of seven different Noah-MP runoff schemes in discharge simulations, as simulated using the CaMa-Flood River routing model. Using ERA5-Land runoff data as a benchmark for runoff evaluation and streamflow observations for discharge evaluation across various climatic regions, key findings from the analysis reveal significant differences in how each scheme handles runoff dynamics. These findings have important implications for global hydrological modelling and water resource management.

The progression from TOPMODEL-based schemes through Schaake, BATS and other saturation-excess schemes showed a trend of decreasing bias magnitudes and improved performance in simulating global runoff dynamics. TOPMODEL with groundwater and TOPMODEL with an equilibrium water table significantly underestimated runoff in many regions, particularly in the Northern Hemisphere, while runoff schemes like Schaake, BATS, VIC, and XAJ demonstrated progressively better performance with relatively lower biases. Dynamic VIC consistently overestimated runoff across nearly all regions.

Seasonal cycle analysis using CaMa-Flood driven by different Noah-MP runoff schemes highlighted considerable regional and seasonal variability in discharge patterns. ERA5-Land runoff-driven discharge and several Noah-MP experiments successfully replicated the general patterns of mean seasonal discharge cycles across diverse river basins. However, Dynamic VIC showed a significant positive bias, indicating a tendency to overestimate discharge globally, due to the strong runoff overestimation.

Globally, our findings reveal that EXP4 offers the best performance in discharge simulation, achieving the highest KGE, strong temporal correlation, and balanced error metrics. This indicates its robust applicability for capturing the daily discharge dynamics on a global scale.

ERA5-Land and other models such as Schaake and VIC also demonstrate solid performance, particularly in regions with distinct hydrological characteristics.

Regionally, ERA5-Land and Schaake scheme consistently exhibited strong performance across different climate regions, closely aligning with observed data and demonstrating low error metrics. In contrast, TOPMODEL and Dynamic VIC showed higher error metrics, with more significant biases for Dynamic VIC, indicating the need for further refinement, although TOPMODEL with groundwater stands out as the most effective in arid regions.

The Noah-MP model demonstrated robust versatility, performing effectively regardless of land cover type, soil type, basin size, or topography. This suggests that the model can provide reliable simulations across diverse environmental conditions without extensive customisation.

While the experiments generally captured the overall patterns of river discharge, significant biases remained, particularly in high-flow extremes. This underscores the need for ongoing calibration of tuneable variables and parameters, especially at finer resolutions, to enhance the accuracy and reliability of hydrological simulations.

In conclusion, this study transcends the limitations of individual schemes and specific regions, providing a holistic assessment of runoff dynamics on a global scale. The analysis underscores the significant impact that the selection of a particular runoff scheme can have on discharge patterns and bias, emphasizing the necessity for careful scheme selection based on specific hydrological contexts. Enhanced calibration and refinement efforts are essential for achieving more accurate hydrological predictions, which are vital for effective water resources management and climate adaptation strategies across diverse global environments."

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