We would like to thank Referee Prof. Hubert H.G. Savenije for his interest in this topic and for the valuable comments to improve our manuscript. Based on the comments additional calculations have been performed in the revised manuscript. Our point-by-point response to the comments is given in the following (**Comments in black**, Answers in blue and the corresponding changes in the revised manuscript are marked in orange.):

First of all, I would like to mention that I find this an important paper. In my view, the authors have convincingly shown that their model is a very valuable addition to the set of existing global hydrological models. Its innovation is that it uses the root zone storage capacity (RZSC) determined independently by remote-sensing-based global products for precipitation and evaporation and does not calibrate obtain it by calibration. As far as I know all other global models either calibrate the RZSC or determine it on the basis of incomplete soil maps and inaccurate maps for rooting depth. The authors using climate-derived RZSC has the intuitive advantage that ecosystems apparently adjust their RZSC to climate variability by creating a buffer against dry periods. In hydrological models the RZSC is the key variable determining the partitioning of precipitation into transpiration, recharge and surface runoff, making it the most important hydrological parameter for land-atmosphere interaction and runoff generation. The fact that the authors demonstrated that a remote-sensing-based estimate of the RZSC can be efficiently used in a global hydrological model is nothing less than a breakthrough.

We thank the referee for this comment.

On top of this, the authors demonstrated in their validation that the NDII, a simple remote sensing based proxy for root zone moisture stress, is a powerful tool to validate (and possibly calibrate) global hydrological models. Highly sophisticated satellites claim to monitor soil moisture, with limited success (e.g. SMOS, ERS, and AMSR-E). But NDII, a readily available remote sensing product observing the moisture content of vegetation, apparently can do this better, because it connects to the root zone moisture tension and not the moisture content of the surface. (Sriwongsitanong et al., 2016).

We thank the referee for this comment.

Of course this paper is a modelling paper, and should be treated as such. In that respect I think that the authors should make the code of the model freely available and not merely on request. The model builds on earlier work by Gao et al. (2014a and 2014b), and by Wang-Erlandsson et al. (2014 and 2016), and I think it is fair that the software is freely made available so that other people can advance this approach further. In fact, I think that a more sophisticated evaporation module as in Wang-Erlandsson et al. (2014) could improve the model even further.

Thank you for the suggestion. We will make the code of WAYS model freely available after the manuscript is accepted. Moreover, we completely agree that the evaporation module in the STEAM model (Wang-Erlandsson et al., 2014) could further improve the WAYS model, because the former (Wang-Erlandsson et al., 2014) separates the evaporation fluxes in a more detailed way. We are also very interested in coupling the STEAM model with WAYS in our future work by cooperating with the authors of the STEAM model.

Authors' change in the manuscript.

Page 26, Line 9: (the changes is marked as blue)
The precise simulation of variables in the root zone could benefit the simulation of other elements in the model, thus advancing the model simulation toward an advanced philosophy, i.e., obtaining the right answers for the right reasons rather than simply obtaining the right answers (Kirchner, 2006). In addition, the WAYS model can be further improved by integrating a more sophisticated evaporation module, e.g., the STEAM model developed by Wang-Erlandsson et al. (2014), which separates the evaporation fluxes in a more detailed way. Finally, a runoff generation module recently developed by Gao et al. (2019), HSC-MCT, could provide another possibility to improve the WAYS model, as it offers another venue for determining one of the key parameters in WAYS (β) independently without calibration. This calibration-free module could actually benefit any conceptual hydrological model.

Having said this, the paper requires some (major) revision. I shall highlight the major points.

We thank the referee for the constructive comments. Below, we give a point-to-point reply to the comments posted by the referee.

1. The comparison in Figures 4 and 5 is not entirely fair. The models of the ISIMIP2a data set are not calibrated, whereas WAYS is. This is mentioned in the paper, but the comparison in these figures suggests otherwise. The caption should mention this.

Thank you. Actually, the simulated runoff of the WAYS model is first compared with the reference data ERA-Interim/Land runoff. The performance of the WAYS model in runoff simulation is evaluated mainly based on the comparison between ERA-Interim/Land data and WAYS simulation. Since WAYS uses the same driving data as ISIMIP2a models and the ISIMIP2a simulations are widely studied and discussed in many studies, we believe the additional comparison between WAYS and ISIMIP2a models can provide added-value for examining our model. Therefore, ISIMIP2a simulations are also shown in the results section together with the ERA-Interim/Land data.

We agree with the referee and have revised the captions of Figures 4 and 5 accordingly. We would also like to note that because Referee #2 suggested the use of ERA-Interim/Land data instead of reference data in the captions of Figures 4 and 5, these changes are also shown in the captions. In addition, in short comment #1 (comment 10), the reviewer suggested us to move the Figures 2 and 3 from the main text of the manuscript. Thus, the figures in the revised manuscript are re-sorted.

Authors' change in the manuscript.

Page 14: Figure 2 caption is updated

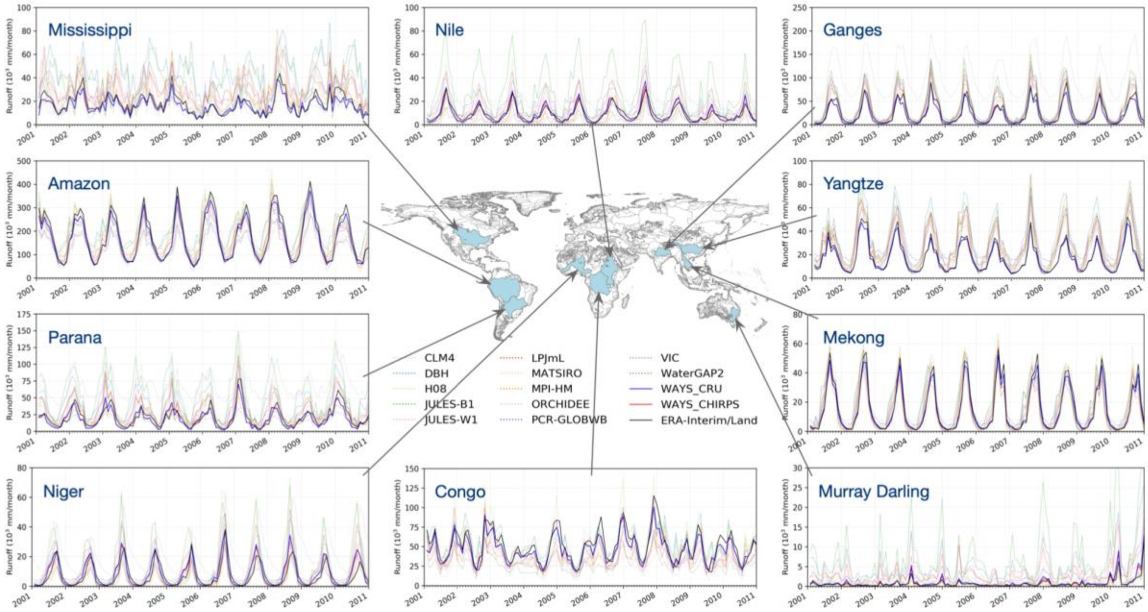

Figure 2. Time series of monthly runoff simulated by WAYS and the ISIMIP2a models, as well as the reference data. The basins highlighted in the world map indicate the selected catchments for model evaluation. The solid lines in blue and red indicate the WAYS simulations with two different RZSC products. The solid line in black indicates the ERA-Interim/Land data, and dashed lines represent the ISIMIP2a model simulations. In some plots, the red line is not visible and is covered by the blue line due to the small differences between the two WAYS runs. WAYS is calibrated using Composite Monthly Runoff data, while the ISIMIP2a models are not calibrated for the simulation.

Page 15: Figure 3 caption is updated

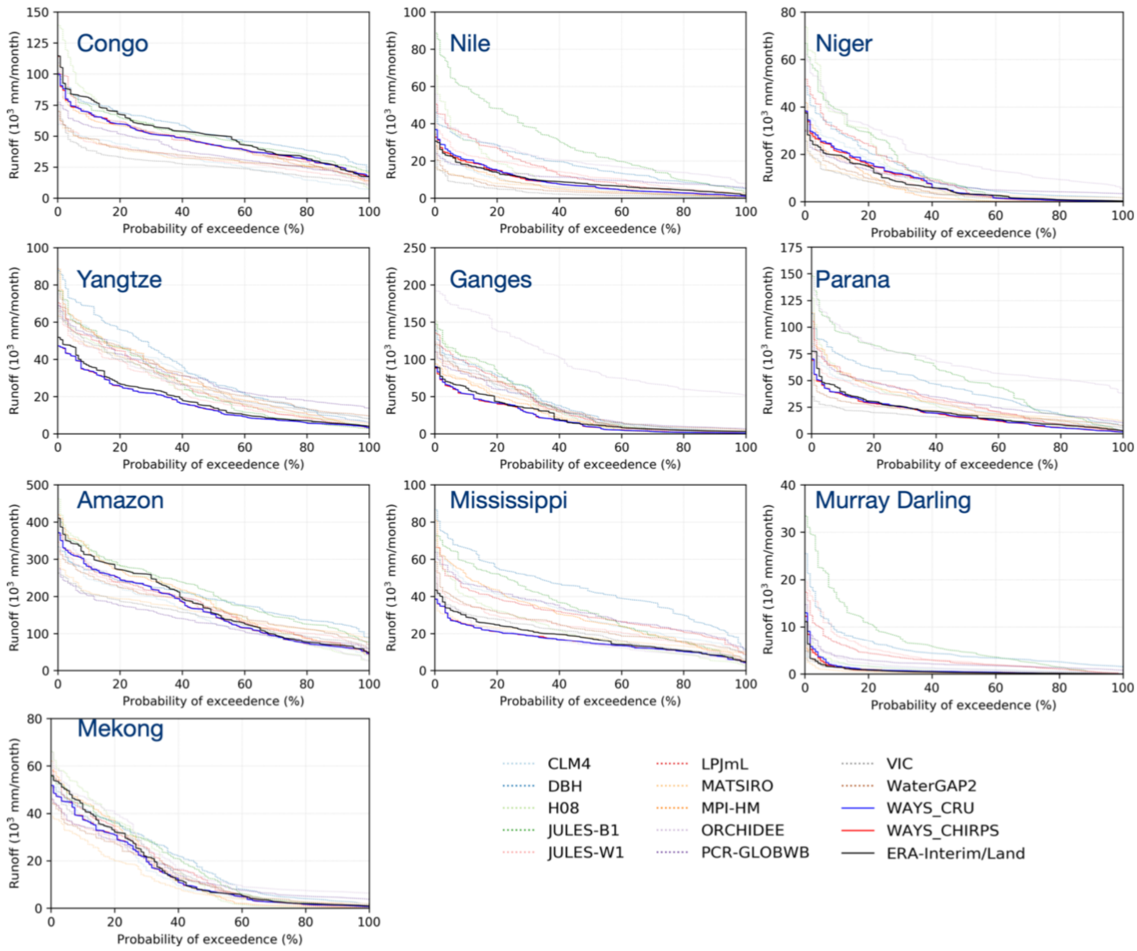

Figure 3. The probability of exceedance for monthly runoff simulated by different models as well as the reference data in ten selected basins. The solid lines in blue and red indicate WAYS simulations with two different RZSC products. The solid line in black indicates the ERA-Interim/Land data, and dashed lines represent the ISIMIP2a model simulations. In some plots, the red line is not visible and is covered by the blue line due to the small differences between the two WAYS runs. WAYS is calibrated using Composite Monthly Runoff data, while the ISIMIP2a models are not calibrated for the simulation.

2. It is important that the authors indicate which parameters are input independently (from what I can see: S_(rz,max), K_s, f_s, R_(s,max), S_(I,max)) and which are calibrated (I guess: Beta, K_ff, . . .). The fact that a number of these have been input as independently obtained parameters is crucial information, but we should also know which have been obtained by calibration. It is well known that there is equifinality between Beta and the RZSC, so this is not trivial. I would also want to see a Table with the calibrated values. There should be an openly shared data set with all parameters used, whether obtained by calibration or independently.

We agree with the referee's comments and have inserted a table to describe the parameters that are used in the WAYS model as well as their ranges. WAYS has 13 parameters in total, seven of which are obtained from the literature and the rest (six parameters) from the calibration (see page 11, table 2 in the revised manuscript). We will share all the model parameters after the manuscript is accepted. Since the calibrated parameters are spatially varied, it is not appropriate to show them in tables. Here we provide the spatial patterns of two key parameters (β, C_e) that are calibrated, as these two parameters mostly affect the partitioning of precipitation (see Figure S21 and Figure S22). The rest of the calibrated parameters are uploaded to the response thread in terms of netCDF files (parameters.cn4) as Supplements.

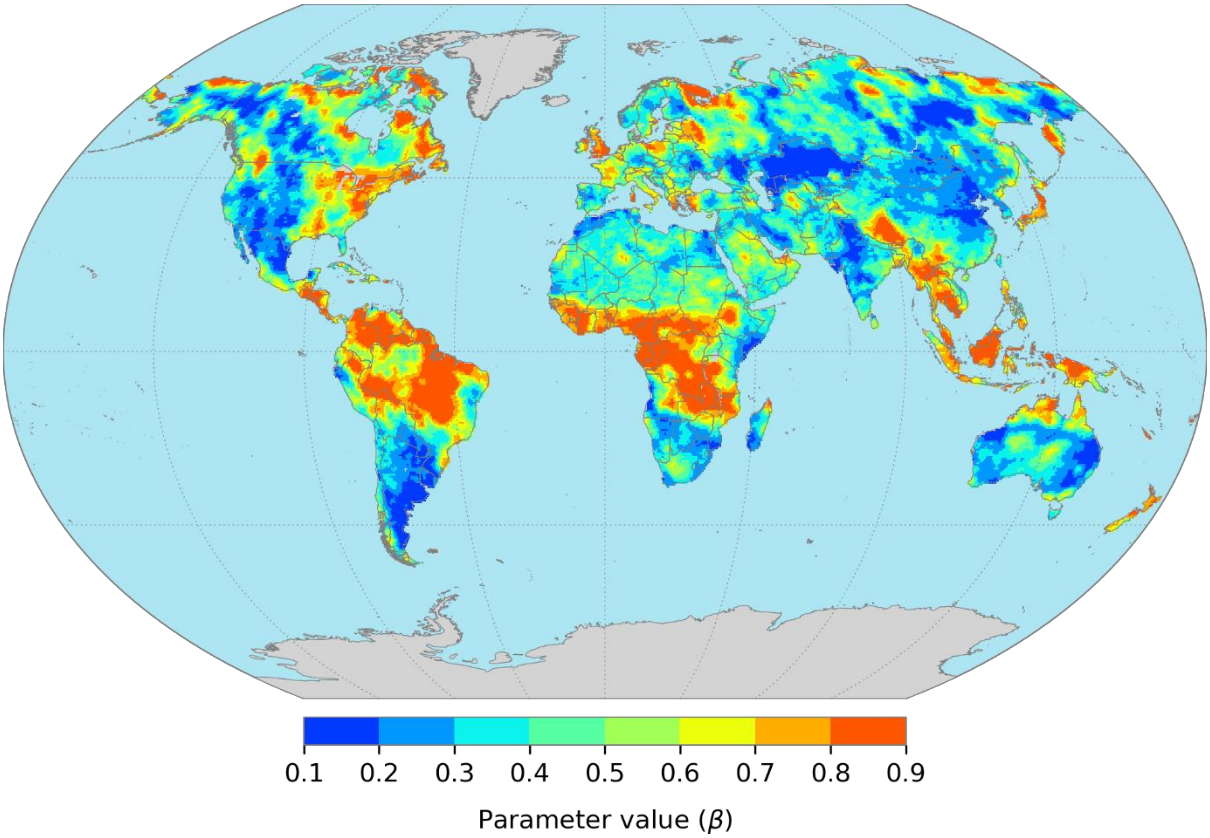

Figure S21. The spatial distribution of the model parameter β

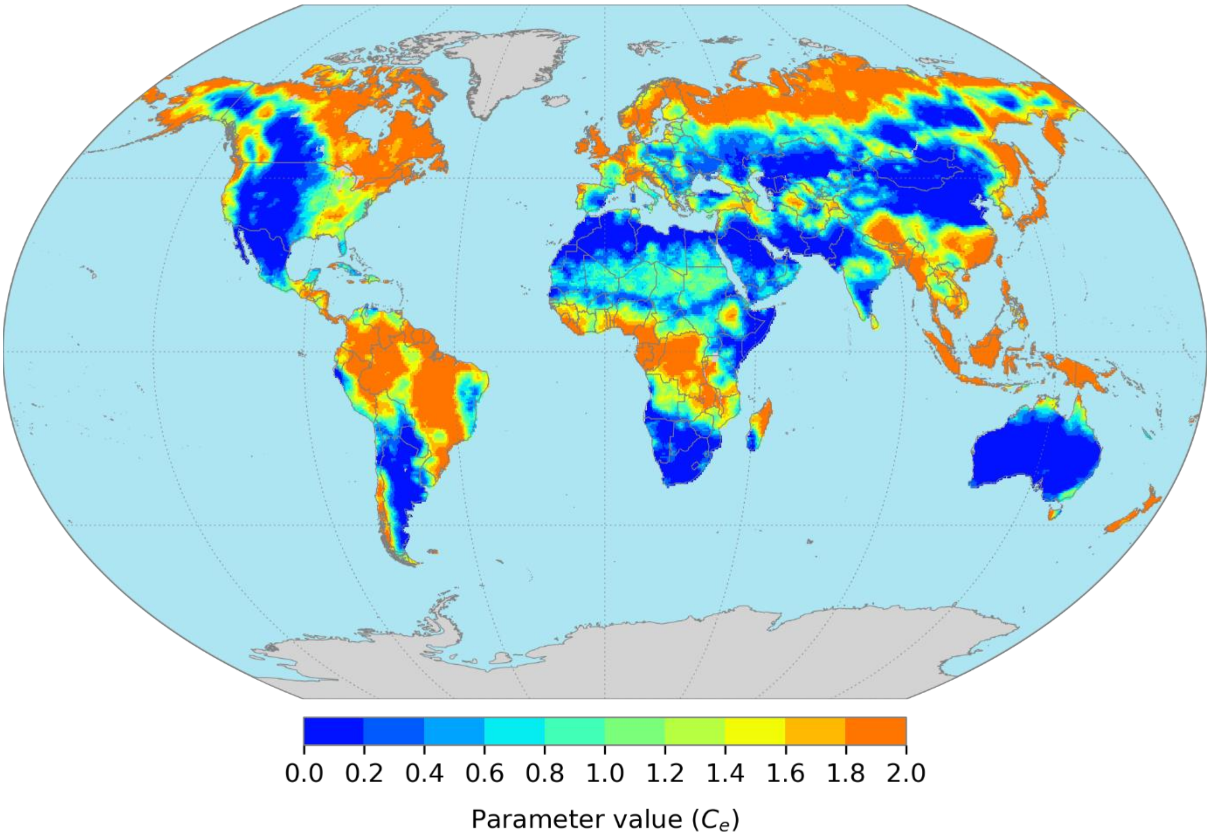

Figure S22. The spatial distribution of the model parameter C_e

Authors' change in the manuscript.

Page 12: A table is added

Table 2. Parameter ranges of the WAYS model

Parameter	Range	Literature	Parameter	Range
$S_{i,max}$	distributed	Wang-Erlandsson et al. (2014)	β	(0, 2)
$S_{rz,max}$	distributed	Wang-Erlandsson et al. (2016)	C_e	(0.1, 0.9)
$R_{s,max}$	7/4.5/2/5 (Sand/Loam/Clay)	Döll and Fiedler (2008)	K_f	(1, 40)
K_s	100	Döll et al. (2003)	K_{ff}	(1, 9)
f_s	distributed	Döll and Fiedler (2008)	S_{ftr}	(10, 200)
F_{DD}	distributed	Müller Schmied et al. (2014)	T_{lag}	(0, 5)
T_t	0	Müller Schmied et al. (2014)		

3. In my view, the Beta parameter is crucial. It affects the partitioning of precipitation into transpiration and runoff. The time scales K_s, K_ff and K_f merely affect hydrograph shape, but not the water balance. In this regard, it is interesting to know that Gao et al. (2019) developed a HAND-based method to determine Beta from independent topographical information. This method assumes that the dominant mechanism is Saturation Excess Overland Flow and therefore is not applicable on hillslopes. So it should be used with good judgement, but it offers another venue of estimating Beta independently without calibration.

We completely agree that parameter β is crucial as it controls the precipitation partitioning, thus mostly affecting the water balance. In addition, parameter C_e plays an important role in water balance control as it affects the evaporation and consequently influences the root zone water storage, which determines the precipitation partitioning. Indeed, the rest of the parameters (e.g., K_s, K_{ff} and K_f) are more important for hydrograph shape adjustment rather than the water balance.

We would like to thank the referee for sharing the recently published paper by Gao et al. (2019). The authors developed a calibration-free module (HSC-MCT) for runoff generation based on the Height Above Nearest Drainage (HAND) data. They found that the runoff coefficient can be ingeniously linked with the HAND-based area fraction, and thus β can be determined accordingly. This finding offers another venue for determining β independently without calibration. The HSC-MCT module can provide added-value for any conceptual hydrological model. We agree that it would be very interesting to integrate HSC-MCT into WAYS and that it can further improve the WAYS model. However, at the current stage, the main purpose of our work is to demonstrate the value of integrating a remote-sensing-based RZSC into a global hydrological model, especially for RZWS simulation. The integration of HSC-MCT could potentially introduce uncertainties into the model as HSC-MCT is currently only applicable to regions dominated by Saturation Excess Overland Flow. Moreover, HSC-MCT is heavily dependent on HAND data, and there are currently no available HAND data at 0.5 degrees. Self-derived HAND data could further introduce uncertainties as HAND is very sensitive to the drainage threshold and the open water elevation (Nobre et al., 2016). A thorough validation of HAND on a global scale is necessary before it can be applied in subsequent analyses. In these regards, we would like to skip the integration of the HSC-MCT module into WAYS at the current stage, but we will examine its inclusion in our future works.

Authors' change in the manuscript.

Page 26, Line 9: (the changes is marked as blue)
The precise simulation of variables in the root zone could benefit the simulation of other elements in the model, thus advancing the model simulation toward an advanced philosophy, i.e., obtaining the right answers for the right reasons rather than simply obtaining the right answers (Kirchner, 2006). In addition, the WAYS model can be further improved by integrating a more sophisticated evaporation module, e.g., the STEAM model developed by Wang-Erlandsson et al. (2014), which separates the evaporation fluxes in a more detailed way. Finally, a runoff generation module recently developed by Gao et al. (2019), HSC-MCT, could provide another possibility to improve the WAYS model, as it offers another venue for determining one of the key parameters in WAYS (β) independently without calibration. This calibration-free module could actually benefit any conceptual hydrological model.

4. I found a mistake in Equation (2). The correct equation should read: P_tf = MAX{0, P_r – (S_imax – S_i)/Delta t }. The Delta t is required to make the equation dimensionally correct and to prevent that if the model is used at another time step, no error is made. The MAX{0,x} operator is essential since P_tf is an overflow. Forgetting the MAX{0,x}

operator can lead to negative P_tf values for small amounts of rainfall. This may trigger relatively small errors, but particularly in wet environments (the Amazon?) this can create errors. I fear that the authors have to rerun the models to correct this mistake.

We thank the referee for pointing out the mistake in Equation (2), which has been corrected, and the codes have been changed accordingly (see Figure 1). As a result, the model has been rerun and the results updated. We would like to state that before rerunning of the model, parameter RZSC ($S_{rz,max}$) was also updated in the model based on the comment of Referee #3 (comment 6). Referee #3 suggested that RZSC should be updated by applying the Gumbel normalization, as Wang-Erlandsson et al., (2016) found that normalizing the RZSC using the Gumbel distribution by land cover type further improves performance. The model results are updated in the revised manuscript. In comparison to the previously simulated results, both simulations of runoff and RZWS are only slightly altered due to the correction of the precipitation throughfall equation as well as the update of the RZSC data. In the Amazon basin, the rank correlation between simulated RZWS and NDII are improved from 0.533 (WAYS_CRU) and 0.506 (WAYS_CHIRPS) to 0.593 (WAYS_CRU) and 0.552 (WAYS_CHIRPS).

WAYS is currently run on a daily scale, and the **Delta t** suggested by the referee is necessary for running the model at other time scales. **Delta t** is required not only for the precipitation throughfall equation but also for all the time scale-related parameters. Therefore, we have updated the table of model equations and stated the following at the end of the table: "Note: all time scale-dependent parameters need to be divided by Δt to make the equation dimensionally correct and suitable for any other time scales".

```
def intercept(pr, si, simax):
    """interception"""
    # ptf: precipitation throughfall
    if simax == 0:
        si = 0
        ptf = pr
    else:
        if pr + si > simax:
            ptf = pr - (simax - si)
            si = simax
        else:
            ptf = 0
            si += pr
    return ptf, si
```

Figure 1. the codes for the precipitation throughfall (P_{tf}) calculation

Authors' change in the manuscript.

Page 8: Table 1 is updated. (the changes are marked as blue)

Table 1. Water balance and constitutive equations used in WAYS

Reservoirs	Water balance equations		Constitutive equations		Reference
Interception reservoir	$\frac{dS_i}{dt} = P_r - E_i - P_{tf}$	(1)	$P_{tf} = max(0, P_r - (S_{i,max} - S_i))$	(2)	-
			$E_i = E_p \left(\frac{S_i}{S_{i,max}}\right)^{2/3}$	(3)	Deardorff (1978)
			$S_{i,max} = m_c L$	(4)	Wang-Erlandsson et al. (2014)
Snow reservoir	$\frac{dS_w}{dt} = \begin{cases} -M & \text{if } T > T_t \\ P_s & \text{if } T \leq T_t \end{cases}$	(5)	$M = \begin{cases} min(S_w, F_{DD}(T - T_t)) & \text{if } T > T_t \\ 0 & \text{if } T \leq T_t \end{cases}$	(6)	Rango and Martinec (1995)
Root zone reservoir	$\frac{dS_{rz}}{dt} = P_e - R - E_a$	(7)	$P_e = P_{tf} + M$	(8)	-
			$\frac{R}{P_e} = 1 - \left(1 - \frac{S_{rz}}{(1+\beta)S_{rz,max}}\right)^{\beta}$	(9)	Sriwongsitanon et al. (2016)
			$E_a = (E_0 - E_i) \cdot min\left(1, \frac{S_{rz}}{C_e S_{rz,max}(1+\beta)}\right)$	(10)	Sriwongsitanon et al. (2016)
Slow response reservoir	$\frac{dS_s}{dt} = R_s - Q_s$	(11)	$R_s = min(f_s R, R_{s,max})$	(12)	Döll and Fiedler (2008)
			$Q_s = S_s / K_s$	(13)	Döll et al. (2003)
Fast response reservoir	$\frac{dS_f}{dt} = R_f - Q_{ff} - Q_f$	(14)	$R_f = R - R_s$	(15)	-
			$Q_{ff} = max(0, S_f - S_{ftr}) / K_{ff}$	(16)	-
			$Q_f = S_f / K_f$	(17)	-

Note: all the time scale-dependent parameters need to be divided by Δt to make the equations dimensionally correct and suitable for any other time scales.

- in the reference column indicates that the formula is taken from the FLEX model.

Page 14: Figure 2 is updated

To avoid repetition, please to see the changes in response to comment 1

Page 15: Figure 3 is updated

To avoid repetition, please to see the changes in response to comment 1

Page 17: Figure 4 is updated

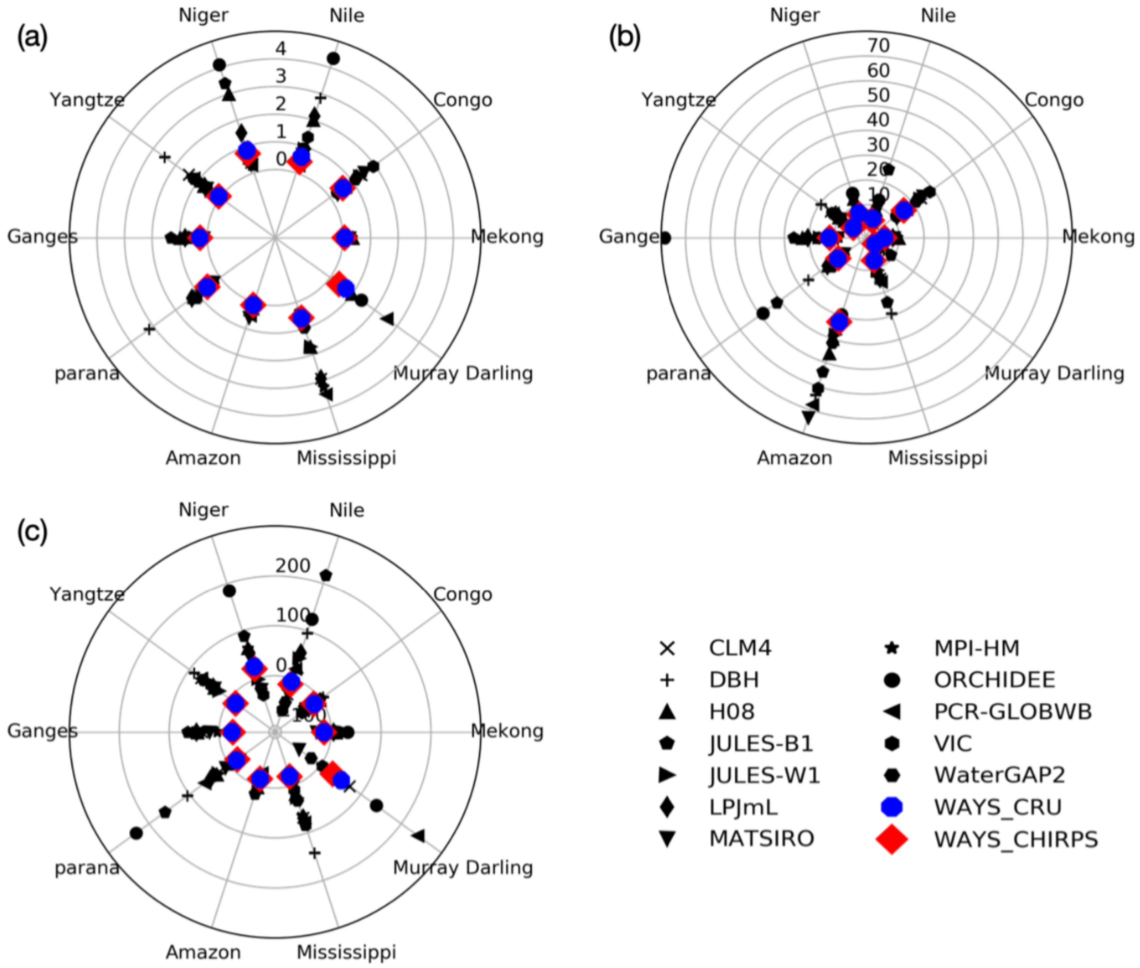

Figure 4. The catchment clockwise pole plot according to different metrics, (a) 1-NSE, (b) RMSE, and (c) PBIAS. Colored markers indicate the score for the WAYS model with two different simulations, and black markers represent the score for ISIMIP2a models. For all the metrics, the value of 0 is the benchmark.

Page 18: Figure 5 is updated

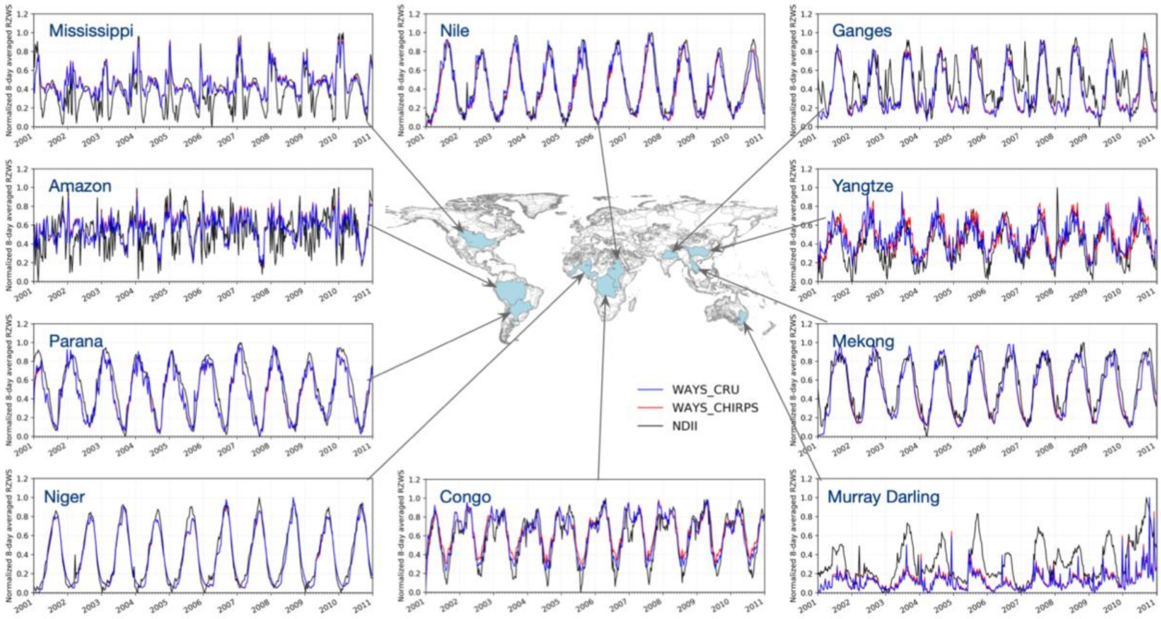

Figure 5. Time series of 8-day normalized RZWS simulated by the WAYS model and NDII value.

Page 19: Table 3 is updated

Table 3. The rank correlation of NDII and WAYS-simulated RZWS in ten selected basins

Selected River Basins	Models	
	WAYS_CRU	WAYS_CHIRPS
Congo	0.872	0.871
Nile	0.951	0.967
Niger	0.975	0.975
Yangtze	0.713	0.764
Ganges	0.803	0.817
Parana	0.931	0.934
Amazon	0.593	0.552
Mississippi	0.689	0.677
Murray Darling	0.614	0.636
Mekong	0.936	0.938

5. In the validation against NDII, one should realise that some ecosystems (particularly Australian) tap into groundwater, so that in those ecosystems the NDII may not be the correct proxy for moisture stress in the root zone during dry periods. This may be another reason why the Murray Darling performs less well in the comparison with NDII.

Thanks for the comment. We agree with the referee and have mention this in the manuscript.

Authors' change in the manuscript.

Page 20, Line 8: (the changes is marked as blue)

In contrast, WAYS shows a trend of underestimation in the Murray Darling. A possible reason could be that deep rooted plants are widespread across the Murray Darling basin and can tap into groundwater (Runyan and D'Odorico, 2010; Lamontagne et al., 2014); thus, the NDII may not be the correct proxy for moisture stress in this region. A vast amount of groundwater drawing from the saturated zone to the root zone could explain such underestimation of RZWS (Leblanc et al., 2011). Other reasons behind these findings could be the underestimated RZSC in this region as well as the intensive human activities, including dam construction, a water diversion system and river management, which will impact both the RZSC estimation and RZWS simulation (Reid et al., 2002; Kingsford, 2000).

6. This brings me to another point, that the FLEX model used apparently does not include capillary rise. In wetlands, this is a dominant mechanism, and also some dryland vegetation is known to tap water from deeper layers. A landscape-based model as developed by Gao et al. (2014a) could cater for this and could also distinguish between an independently derived Beta function for the wetland-terrace-plateau continuum and a calibrated Beta for hillslopes

Thank you for the comment. We agree that the capillary rise is important in regions in which surface water and groundwater exchanges are intense, e.g., in wetlands and regions with deep root plants. The upward capillary fluxes can impact the root zone water storage and thus the water budget between the surface and the lower atmosphere (Vergnes et al., 2014). In fact, WAYS does include the capillary module from Gao et al. (2014a), a key publication of the FLEX model. At the current stage, it is, however, disabled due to the lack of global information on the groundwater table. Of course, this will affect the simulated results in this work, e.g., the evaporation and RZWS. However, we disabled the capillary module based on our analysis.

We set up two experimental runs for the WAYS model, for which one run with the capillary module was active and the other with the capillary module inactive. For both runs, the RZSC data ($S_{R,CRU-SM}$) that are derived based on CRU, SSEBop and MOD16 are used. The model is calibrated before running for each simulation run, and the parameter range of C_{Rmax} is set to (0.01, 2), where C_{Rmax} is the key parameter for the capillary module that controls the maximum capillary rise. The simulation period is set to 1989-2005 for both runs, as we compared the simulated evaporation with the LandFluxEVAL data set, which is only available in this period. The LandFluxEVAL data are a merged benchmark synthesis product of evaporation on the global scale and comprise a combination of land-surface model simulations, remote sensing products, reanalysis data and ground observation data (Mueller et al., 2013). The LandFluxEVAL data are used in many studies as refence data for evaporation evaluations (Lorenz et al., 2014; Martens et al., 2017; Wartenburger et al., 2018). The results show that the simulated evaporation is significantly overestimated for the run in which the capillary module is switched on. The global averaged annual evaporation is estimated as 513 mm/year by WAYS with the capillary module switched off, while the global averaged annual evaporation is simulated as 697 mm/year by switching on the capillary module. In the LandFluxEVAL data, the global averaged annual evaporation is 491 mm/year. The significant overestimation of evaporation by WAYS with capillary module switched on.

This is mainly because there is no observed groundwater table information to constrain the capillary rise amount. Therefore, we decided to disable the capillary module in the current version of WAYS; it can be active once the global groundwater table information is available. To clarify this information in the manuscript, we have revised the text accordingly by stating our analysis-based decision regarding capillary module deactivation as well as discussing the impacts of ignoring the capillary rise. The revisions can be found in "Authors' change in the manuscript" below.

Regarding the issue of "using an independently derived Beta function for the wetland-terrace-plateau continuum and a calibrated Beta for hillslopes in the model.", we agree with the referee that this would be an interesting experiment and the derivation of parameter β from HSC-MCT without calibration can benefit any conceptual hydrological models. However, the HSC-MCT module is heavily dependent on the HAND data, and a verified global data set on HAND is not currently available. The landscape classification for wetland, terrace, plateau and hillslopes is also based on the HAND data. Indeed, HAND can be simply derived from DEM data. However, HAND data that are not well verified could potentially introduce large uncertainties because HAND is very sensitive to the drainage threshold and the open water elevation (Nobre et al., 2016).

Given that the manuscript is already quite extensive, including these results would not necessarily contribute to improving the manuscript clarity. In addition, it is not the main objective of the paper to focus on deriving the beta function independently from the HAND data. Therefore, we prefer not to include these results in the paper.

Authors' change in the manuscript.

Page 25, Line 4: The following paragraph is inserted in the discussion part
Moreover, the current study does not consider the groundwater access and irrigation mainly due to the lack of global information. The groundwater table information is crucial for capillary rise simulation (Vergnes et al., 2014). Capillary rise simulation without proper water table information could significantly overestimate the evaporation. Thus, the capillary rise flux is ignored in this study. A similar strategy has also been applied by other works due to the absence of the information on the global water table (Döll et al., 2003; De Graaf et al., 2015; Hanasaki et al., 2018). Observations of irrigation on the global scale are also not available (Leng et al., 2015). Although there are simulated irrigation data available on the global scale, the inherent uncertainties could be propagated in our model simulation. Therefore, irrigation is also not considered at this time. However, this neglect could potentially introduce biases into the model simulation in irrigated areas and deep rooted plant-distributed regions, as both irrigation and capillary rise are an additional supply of soil water recharge. The biases may cause an underestimation of evaporation, especially in the dry summertime (Vergnes et al., 2014). This underestimation could consequently affect the simulation of RZWS and runoff because of the interlinkage of these three elements (Rockström et al., 1999). It is found that ignoring the capillary rise could reduce soil water content in the root zone (RZWS), while the runoff will also be reduced (Vergnes et al., 2014). However, these shortcomings can be simply overcome once the global data are available.

7. I don't understand the last sentence in the abstract. Indeed CHIRPS-CSM is limited to lower latitudes, but CRU-SM covers the entire globe. I think the sentence "Therefore, the performance etc." can be deleted.

Thanks for the comment. We have deleted this sentence in the manuscript.

Authors' change in the manuscript.

Page 1, Line 14:

The following sentence is deleted in page 1, line 12.
~~"Therefore, the performance of the model in such regions is not justified."~~

8. There are many typos. I think the paper requires copyediting, which probably Copernicus can take care of.

Thank you for the comment. The revised manuscript has now been edited by a professional academic language and manuscript service company.

So in summary, I think this is an important paper, but additional work needs to be done before the paper can be published.

The references used in this comment also occur in the discussion paper, except the following:
Gao, H., Birkel, C., Hrachowitz, M., Tetzlaff, D., Soulsby, C., and Savenije, H. H. G., 2019. A simple topography-driven and calibration-free runoff generation module, Hydrol. Earth Syst. Sci., 23, 787-809, https://doi.org/10.5194/hess-23-787-2019.

We would like to express our sincere thanks again to Referee Prof. Hubert H.G. Savenije for his time reviewing our manuscript and for the valuable comments to improve our manuscript.

Reference:
Nobre, A. D., Cuartas, L. A., Momo, M. R., Severo, D. L., Pinheiro, A. and Nobre, C. A.: HAND contour: A new proxy predictor of inundation extent, Hydrol. Process., 30(2), 320–333, doi:10.1002/hyp.10581, 2016.

We would like to thank Referee #2 for his/her interest in this topic and for the valuable comments to improve our manuscript. Based on the comments some calculations have been performed. Our point-by-point response to the comments is given in the following (**Comments in black**, Answers in blue and the content related to the changes in the revised manuscript are marked in orange.):

A correct representation of root zone water storage is important for a robust hydrological modeling. However, in reality, obtaining reliable soil water information is difficult. In many previous studies, the root zone water storage has been quantified as the soil moisture in a certain depth rather than the water stored in the entire rooting system. This leads to an under- or over- estimation of root zone water storage depending on individual site conditions, including the types of vegetation covers on the land surface. The aim of the paper by Mao and Liu is to develop a hydrological model, WAYS, that is capable for simulating root zone water storage on a global scale, without constraining the quantification to a certain depth. Overall, I think the development of such a model is valuable to the hydrological community and can largely advance the eco-hydrological studies which tackle the interactions between the hydrological cycle and vegetation dynamics on the land surface. I personally also think with the further development and improvement, WAYS has the potential to be applied in the investigation of land-vegetation-climate-water integrations which is very important for the global change impact assessments. Below I give some comments on the paper and hope the authors can address them in the revision.

We would like to thank the referee for this comment. Based on the referee's comments, our point-to-point reply to the comments is given in the following.

General comments

1. The model structure of WAYS is the core of this paper (Figure 1). Its scientific clarity is essential for others to understand the processes and also is important for possible future wider applications of the model beyond the authors' group. In the current version, the variables in the flow chat depicted in the small window and the ones in the schematic are not all matched. E.g., in the small window, Si, Pe, Rr, Sf, and Ss are used, but they are not indicated in the schematic. Even if their meanings are clear (some are not clear to me), the authors still need to denote them properly in the schematic. In addition, given the central role of Figure 1 in the entire paper, I suggest the authors to add some text elaborating the flow of the figure. This is different from the following sections describing individual processes in the model.

Thank you for the comment. We have updated the figure accordingly. S_f and S_s are the two conceptual reservoirs in the model representing the fast and slow response in hydrological cycling. They are slightly different from the other three conceptual reservoirs, S_i, S_{rz} and S_w, which represent the actual water storages (Gao et al., 2014). Therefore, we have marked these response reservoirs with a dashed line in the schematic. Moreover, some of the fluxes are intermediate variables, e.g., R_f is the generated preferential runoff in the root zone layer before the split of runoff into surface runoff and subsurface runoff. The effective precipitation P_e is the sum of snowmelt and precipitation throughfall. These fluxes are shown in the flowchart but cannot be properly visualized in the schematic drawing. We have explained this mis-match issue in the text in the revised manuscript.

In addition, we have added a few sentences to further elaborate the flow of the figure in the revised manuscript. The changes can be found in the following section "Authors' change in the manuscript."

Authors' change in the manuscript.

Page 4: Figure 1 is updated

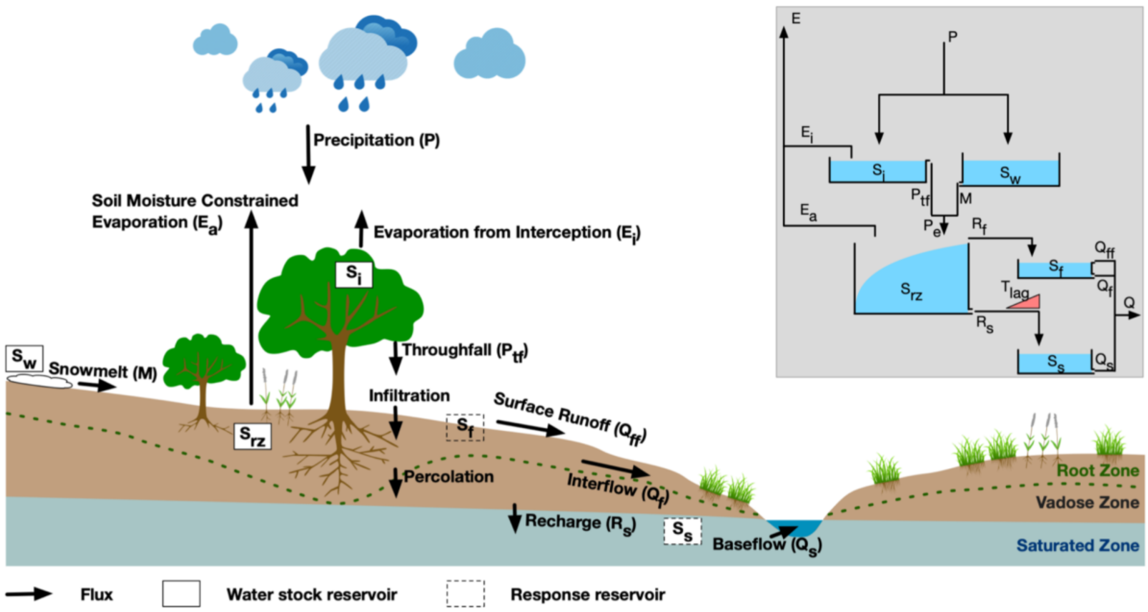

Figure 1. Model structure of WAYS

Page 3, Line 25: The following text is inserted.

In Figure 1, the flowchart represents the conceptualized hydrological cycle in the model, and the schematic drawing shows the corresponding water fluxes and stocks in the real world. Since some of the fluxes are intermediate variables, they are shown in the flowchart but not visualized in the schematic drawing. For instance, Rf is the generated preferential runoff in the root zone layer before the split of the runoff into surface runoff and subsurface runoff. The effective precipitation Pe is the sum of snowmelt and precipitation throughfall. The conceptualized hydrological cycle of the model can be briefly described as follows. The precipitation that can drop as rainfall or snowfall depends on the temperature. The snowfall will be stored in the snow reservoir, and the rainfall will be intercepted by the canopy before it reaches the surface. After the interception, the rainfall penetrates the canopy and reaches the surface as precipitation throughfall. The effective precipitation that consists of the throughfall and the snowmelt will partially infiltrate into the soil, and the rest runs away as runoff. The runoff is then split into surface runoff and subsurface runoff depending on the texture. A part of the infiltration will be stored in the soil for plants, and the rest will percolate into the deep soil and reach the groundwater table as groundwater recharge.

2. Table 1 gives all the equations concerning the water balance in WAYS. This is very useful for examining the processes and evaluating the robustness of the model. As all the equations are from the relevant literature (the authors give the references in the text), it would be good to provide the major references in the last column of Table 1.

Thank you for the comment. We have updated the Table 1 accordingly. The updated table can be found in the following section "Authors' change in the manuscript."

Authors' change in the manuscript.

Page 8: Table 1 is updated. (the changes are marked as blue)

Table 1. Water balance and constitutive equations used in WAYS

Reservoirs	Water balance equations		Constitutive equations		Reference
Interception reservoir	$\frac{dS_i}{dt} = P_r - E_i - P_{tf}$	(1)	$P_{tf} = max(0, P_r - (S_{i,max} - S_i))$	(2)	-
			$E_i = E_p\left(\frac{S_i}{S_{i,max}}\right)^{2/3}$	(3)	Deardorff (1978)
			$S_{i,max} = m_c L$	(4)	Wang-Erlandsson et al. (2014)
Snow reservoir	$\frac{dS_w}{dt} = \begin{cases} -M & \text{if } T > T_t \\ P_s & \text{if } T \le T_t \end{cases}$	(5)	$M = \begin{cases} min(S_w, F_{DD}(T - T_t)) & \text{if } T > T_t \\ 0 & \text{if } T \le T_t \end{cases}$	(6)	Rango and Martinec (1995)
Root zone reservoir	$\frac{dS_{rz}}{dt} = P_e - R - E_a$	(7)	$P_e = P_{tf} + M$	(8)	-
			$\frac{R}{P_e} = 1 - \left(1 - \frac{S_{rz}}{(1+\beta)S_{rz,max}}\right)^{\beta}$	(9)	Sriwongsitanon et al. (2016)
			$E_a = (E_0 - E_i) \cdot min\left(1, \frac{S_{rz}}{C_e S_{rz,max}(1+\beta)}\right)$	(10)	Sriwongsitanon et al. (2016)
Slow response reservoir	$\frac{dS_s}{dt} = R_s - Q_s$	(11)	$R_s = min(f_s R, R_{s,max})$	(12)	Döll and Fiedler (2008)
			$Q_s = S_s / K_s$	(13)	Döll et al. (2003)
Fast response reservoir	$\frac{dS_f}{dt} = R_f - Q_{ff} - Q_f$	(14)	$R_f = R - R_s$	(15)	-
			$Q_{ff} = max(0, S_f - S_{ftr})/K_{ff}$	(16)	-
			$Q_f = S_f / K_f$	(17)	-

Note: all the time scale-dependent parameters need to be divided by Δt to make the equations dimensionally correct and suitable for any other time scales.
- in the reference column indicates that the formula is taken from the FLEX model.

3. Are there any other values used for Rx,max rather than 7, 4.5 and 2.5 for sandy soil, loamy soil and clayey soil? May be worth a checking for uncertainties stemmed from the use of Rx,max values for the mentioned soils.

Thank you. Since the groundwater recharge module in WAYS is based on the work of Döll and Fiedler (2008), the values are directly taken from that publication. These values are also used for other global groundwater recharge simulation-related works, e.g., Müller Schmied et al. (2014). However, these are indeed empirical parameter values. We agree with the referee that the uncertainty/sensitivity analysis is necessary for $R_{s,max}$. We have performed the uncertainty/sensitivity analysis, and the results are shown in Supplementary Information (SI).

The following part is put in the SI.

Since the groundwater recharge module in WAYS is based on the work of Döll and Fiedler (2008), the values are taken directly from it. These values are also used for other global groundwater recharge simulation-related works, e.g., Müller Schmied et al. (2014). However, as these are indeed empirical parameter values, uncertainty/sensitivity analysis is necessary for $R_{s,max}$. Three pixels from different soil types are selected for the $R_{s,max}$-induced uncertainty investigation. Figure S1 shows the grouped soil texture classes for this study based on the FAO Harmonized World Soil Database and the selected pixels for the uncertainty analysis. Pixel 1, pixel 2 and pixel 3 represent the soil type of clay, loam and sand, respectively.

$R_{s,max}$ (mm/day) directly influences the matrix flow (contributes 100% to groundwater recharge with a certain time lag) based on equation 12 in Table 1 in the manuscript, as it controls the maximum groundwater recharge for different soil types. Consequently, it will also impact the preferential flow, as the runoff is partially split into matrix flow and the rest to the preferential flow. Therefore, parameter $R_{s,max}$ will have light effects on the runoff generation but could have considerable impacts on the matrix flow and preferential flow. Thus, the sensitivity of the simulated preferential flow and matrix flow to the maximum groundwater recharge $R_{s,max}$ is investigated, and the results are shown in Figure S2 (pixel with clayey soil), Figure S3 (pixel with loamy soil) and Figure S4 (pixel with sandy soil). The sensitivities of WAYS to $R_{s,max}$ are checked by perturbing the parameter. We set the simulation with soil texture-specified $R_{s,max}$ as the control run, and perturbed $R_{s,max}$ by -80%, -50%, -20%, 20%, 50% and 80% for the sensitivity test. Figure S2 (bottom plot) shows the impacts of the values of $R_{s,max}$ on the simulated daily matrix flow with the soil type of clay. With the increase in $R_{s,max}$, the simulated daily matrix flow has a higher peak, while the opposite is observed with the decrease in $R_{s,max}$. It changes the scale of the simulated matrix flow but not its shape at the daily scale. Moreover, due to the change in daily simulation, the monthly simulation of the matrix and preferential flow are affected accordingly, as seen in Figure S2 (top and middle plots). The results show that parameter $R_{s,max}$ has opposite impacts on preferential flow and matrix flow, which is logical because both are part of the runoff. A similar phenomenon is found in daily simulated time series. Thus, for pixel 2 and pixel 3, only monthly simulated matrix and preferential flow are shown to visualize the uncertainties stemming from $R_{s,max}$ for loamy and sandy soil. The simulated matrix flow time series with a decreased value of $R_{s,max}$ shows are found to have larger uncertainties than time series with an increased value of $R_{s,max}$, because the maximum value of matrix flow is not only determined by $R_{s,max}$ but also the groundwater recharge factor f_s.

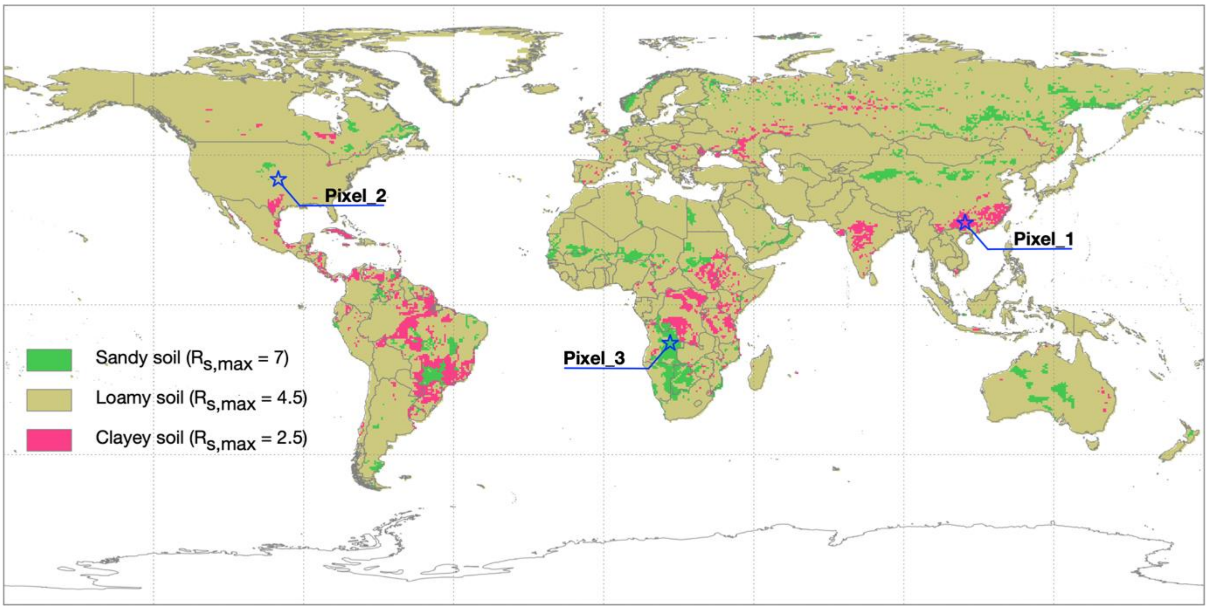

Figure S1. Grouped soil texture classes for the study based on the FAO Harmonized World Soil Database.

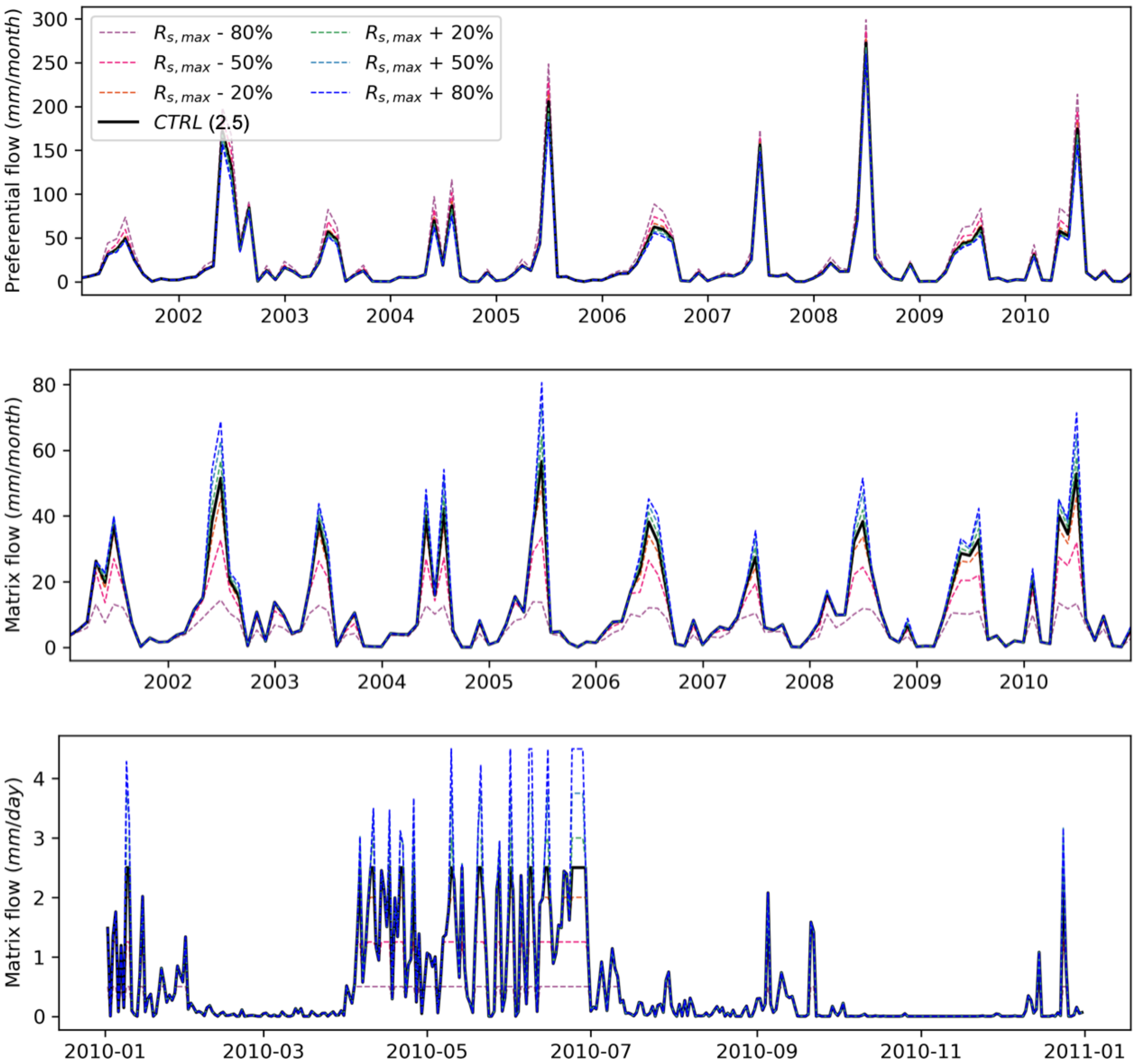

Figure S2. Sensitivity of the simulated preferential flow and matrix flow to the maximum groundwater recharge $R_{s,max}$ for the pixel with clayey soil.

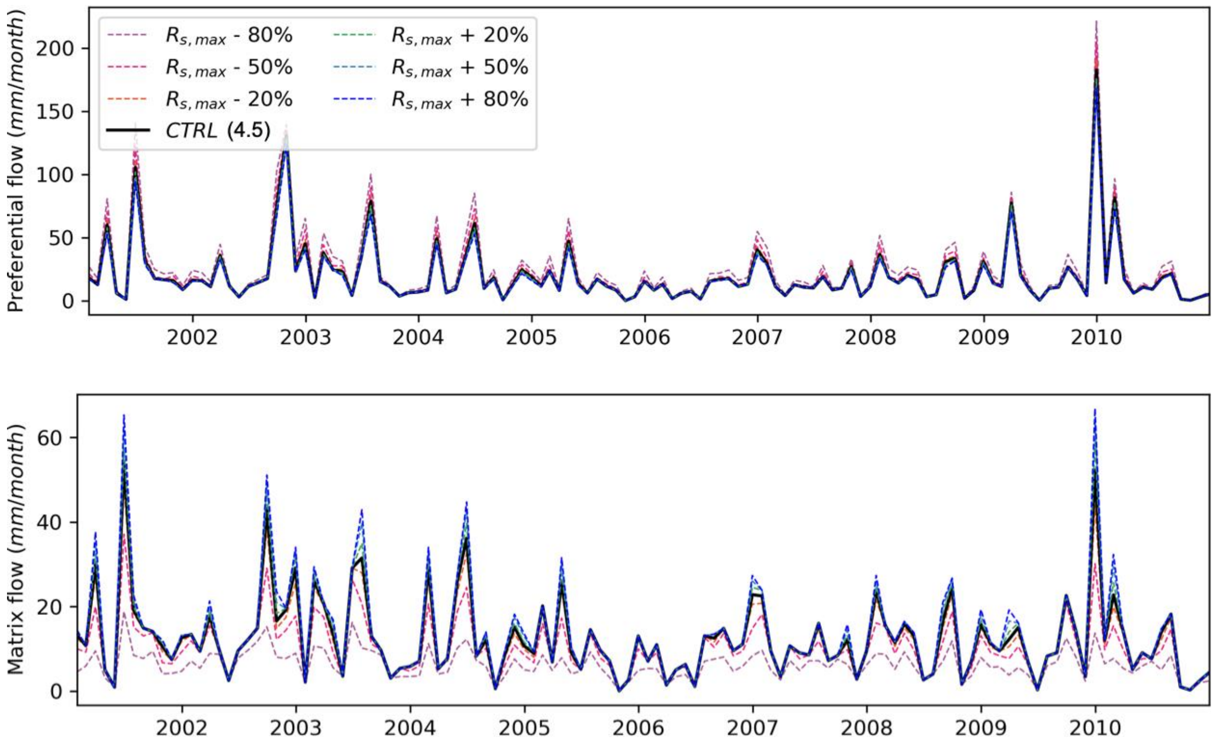

Figure S3. Sensitivity of the simulated preferential flow and matrix flow to the maximum groundwater recharge $R_{s,max}$ for the pixel with loamy soil.

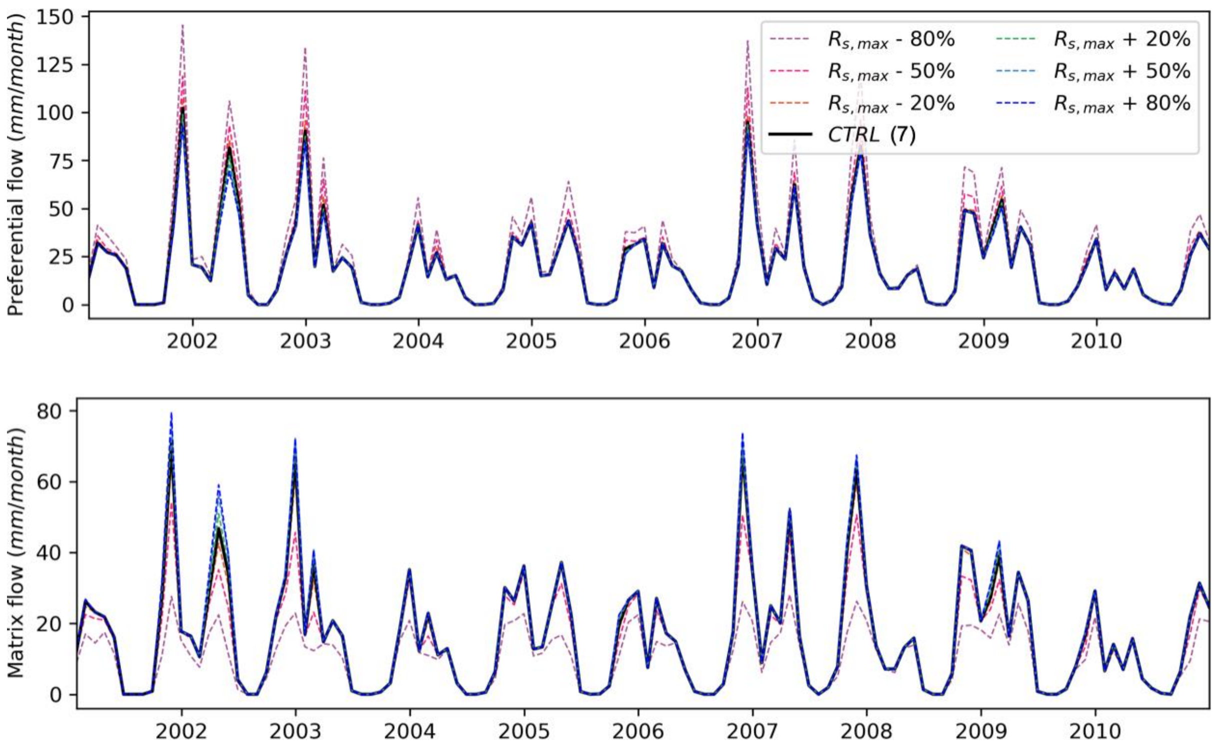

Figure S4. Sensitivity of the simulated preferential flow and matrix flow to the maximum groundwater recharge $R_{s,max}$ for the pixel with sandy soil.

4. In the captions of Figures 4 and 5, the ERA-Interim/Land represents the reference data. I think it is better to directly use ERA-Interim/Land here, because in the Figures, the ERA is used and no reference data is indicated. Also in Figure 4, WAYS-CHIRPS is not visible. Need to give a note for it, e.g., covered by . . .. The scale for Y axis for Murray Darling should be enlarged to show the simulated runoff more clearly.

Thank you for the comment. Figure 4 and Figure 5 are updated accordingly. The scale for the Y axis for Murray Darling is slightly enlarged because the uncertainty range from the other model is quite large. A big enlargement will erase the simulations from ISIMIP2a models. We would also like to note that because Referee #1 suggested us to mention the non-calibration issue of ISIMIP2a model simulations in the captions of Figures 4 and 5, these changes are also shown in the captions. In addition, in short comment #1 (comment 10), the reviewer suggested us to move the Figures 2 and 3 from the main text of the manuscript. Thus, the figures in the revised manuscript are re-sorted.

Authors' change in the manuscript.

Page 14: Figure 2 caption is updated

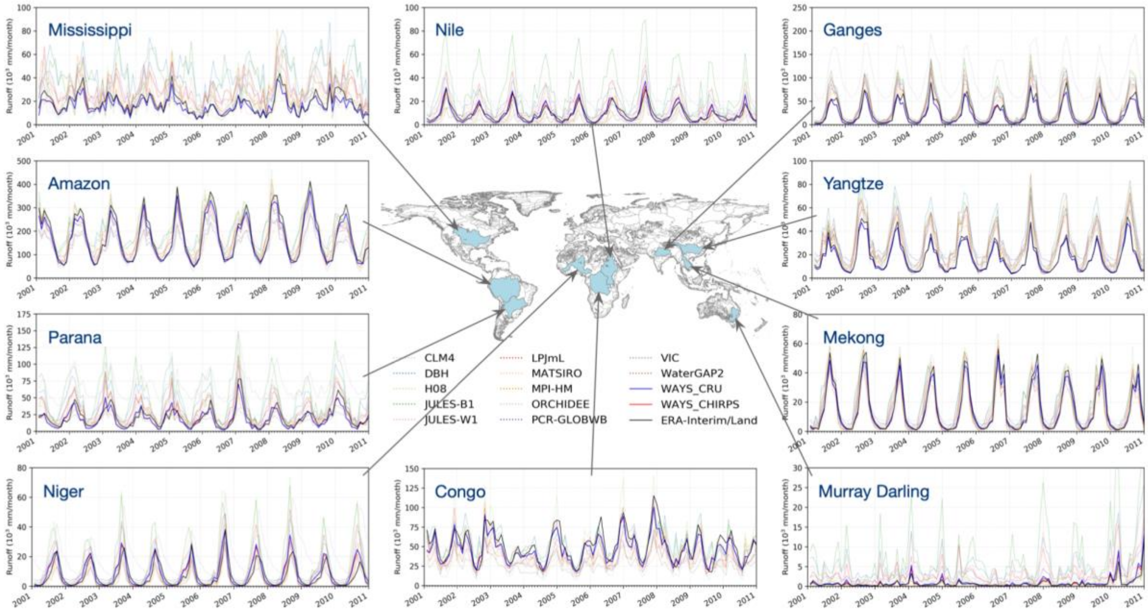

Figure 2. Time series of monthly runoff simulated by WAYS and the ISIMIP2a models, as well as the reference data. The basins highlighted in the world map indicate the selected catchments for model evaluation. The solid lines in blue and red indicate the WAYS simulations with two different RZSC products. The solid line in black indicates the ERA-Interim/Land data, and dashed lines represent the ISIMIP2a model simulations. In some plots, the red line is not visible and is covered by the blue line due to the small differences between the two WAYS runs. WAYS is calibrated using Composite Monthly Runoff data, while the ISIMIP2a models are not calibrated for the simulation.

Page 15: Figure 3 caption is updated

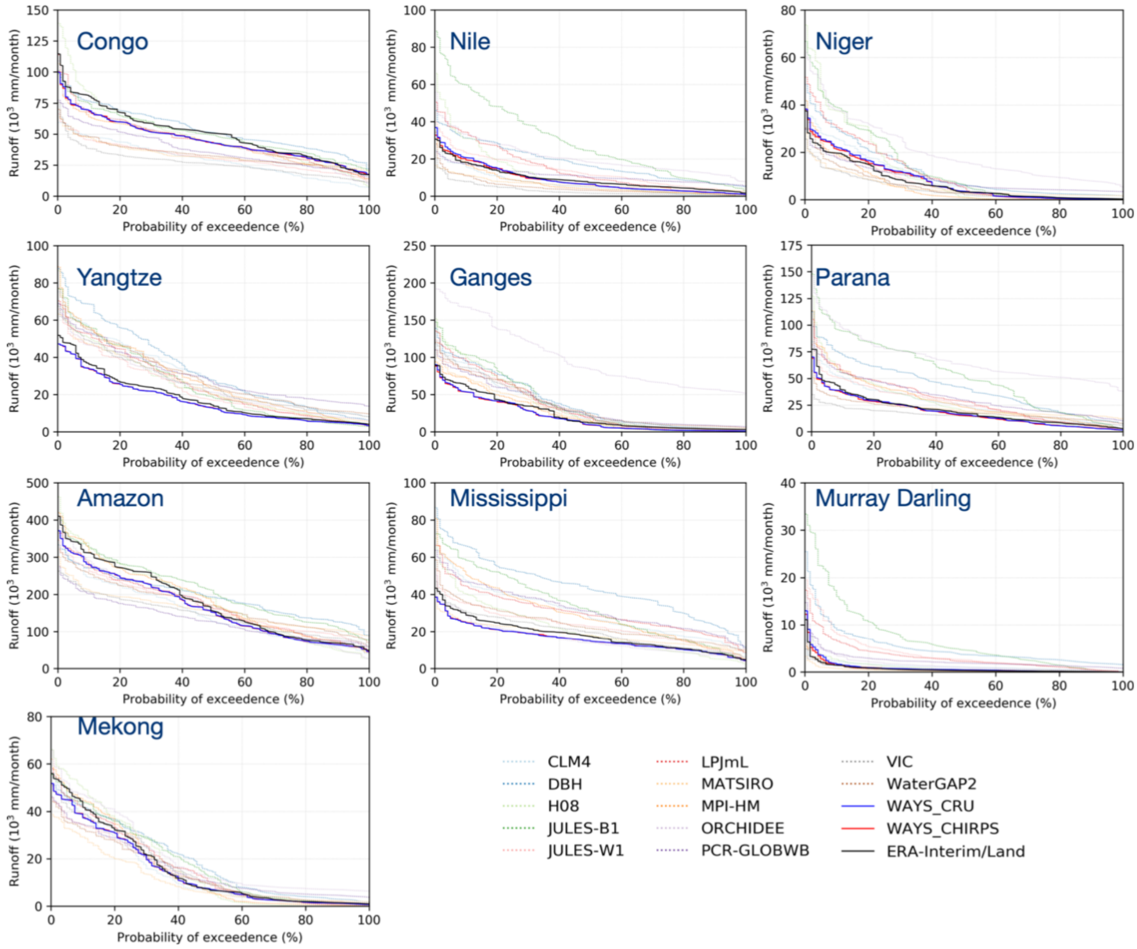

Figure 3. The probability of exceedance for monthly runoff simulated by different models as well as the reference data in ten selected basins. The solid lines in blue and red indicate WAYS simulations with two different RZSC products. The solid line in black indicates the ERA-Interim/Land data, and dashed lines represent the ISIMIP2a model simulations. In some plots, the red line is not visible and is covered by the blue line due to the small differences between the two WAYS runs. WAYS is calibrated using Composite Monthly Runoff data, while the ISIMIP2a models are not calibrated for the simulation.

5. The authors demonstrated the good performance of WAYS compared to ISIMIP2a models. However, no direct reasons are given to explain the better performances. I assume that the authors want to say that this is because of the better representation of the root zoon water storage in WAYS. The authors should make this point clear. It justifies the effort for developing WAYS in this paper. Also, it seems to me not very convincing to state that the better performance is really from the better representation of the root zoon water storage. Could some other processes in the WAYS model be also influential for the better performance compared with the results from the models in ISIMIP2a?

Thank you for the comment. In fact, the simulated runoff from WAYS is first compared with the reference data ERA-Interim/Land runoff. The performance of WAYS in runoff simulation is evaluated mainly based on the comparison between ERA-Interim/Land data and WAYS simulation.

Since WAYS uses the same driving data as the ISIMIP2a models and the ISIMIP2a simulations are widely studied and discussed in many studies, we believe the additional comparison between WAYS and ISIMIP2a models can provide added-value for examining our model. Therefore, ISIMIP2a simulations are also shown in the results together with the ERA-Interim/Land data. It is also important to state that the ISIMIP2a models are not calibrated for global simulation, which could explain the better performance of WAYS than the ISIMIP2a models.

However, it is not easy to justify the impacts of better representation of root zone water storage without the comparative experiment. In this regard, we have performed an experimental test to investigate whether the better performance is truly due to the better representation of the root zone water storage. Since this part could support the conclusion of this paper regarding the importance of correct representation of RZSC in models, we would like to include this it in the main text of the manuscript by including some figures in the Supplementary Information (SI). Please refer to the changes in the revised manuscript.

Authors' change in the manuscript.

Page 21, Line 26: (the following paragraphs are added)
RZSC is a key parameter of the WAYS model. Therefore, it is important to investigate how RZSC could affect the model simulation. In addition to the model simulated with satellite data-derived RZSC products ($S_{R,CHIRPS-CSM}$ and $S_{R,CRU-SM}$), we have additionally conducted WAYS simulations with RZSC derived from uncertain root depth and soil data. The uncertain RZSC ($S_{R,LOOKUP-TABLE}$) is derived based on literature values of root depth and soil texture data (Müller Schmied et al., 2014; Wang-Erlandsson et al., 2016). Due to the global coverage of the RZSC data ($S_{R,CRU-SM}$), only the simulation with $S_{R,CRU-SM}$ is used for comparison. The spatial distribution of the uncertain RZSC is shown in Figure S17, and the differences between $S_{R,CRU-SM}$ and $S_{R,LOOKUP-TABLE}$ are shown in Figure S18. It can be seen that there are large differences between the two RZSC products. The simulation with uncertain RZSC $S_{R,LOOKUP-TABLE}$ shows overestimation globally except for some regions around low-middle latitudes. The latitudinal averaged RZSC further confirms the overestimation of $S_{R,LOOKUP-TABLE}$ at middle-high latitudes (Figure S19).

The large differences between these two RZSC data sets also introduce differences in simulated hydrological elements. Figure S20 shows the impacts of RZSC on the model simulation, including runoff, evaporation and RZWS. A blue color (decrease of RMSE and increase of the ranked correlation) indicates an improvement of the simulated results by replacing the uncertain RZSC ($S_{R,LOOKUP-TABLE}$) with satellite data-derived RZSC ($S_{R,CRU-SM}$), while a red color implies the opposite. For comparison, reference data are used for different variables. For runoff, evaporation and RZWS, the reference data are ERA-Interim/Land (2001-2010, monthly), LandFluxEVAL (1989-2005, monthly) and NDII (2001-2010, 8-days), respectively. Generally, the model simulations are improved by using the RZSC $S_{R,CRU-SM}$. This result emphasizes the importance of an appropriate representation of RZSC in WAYS. A decline of the model performance is also found in some
regions at high latitudes and low latitudes. This result can be partially explained by the inherent uncertainty in the $S_{R,CRU-SM}$ data, as they are derived from other data sets. The RZSC derivation method itself as well as the input data can also introduce biases (Wang-Erlandsson et al., 2016).

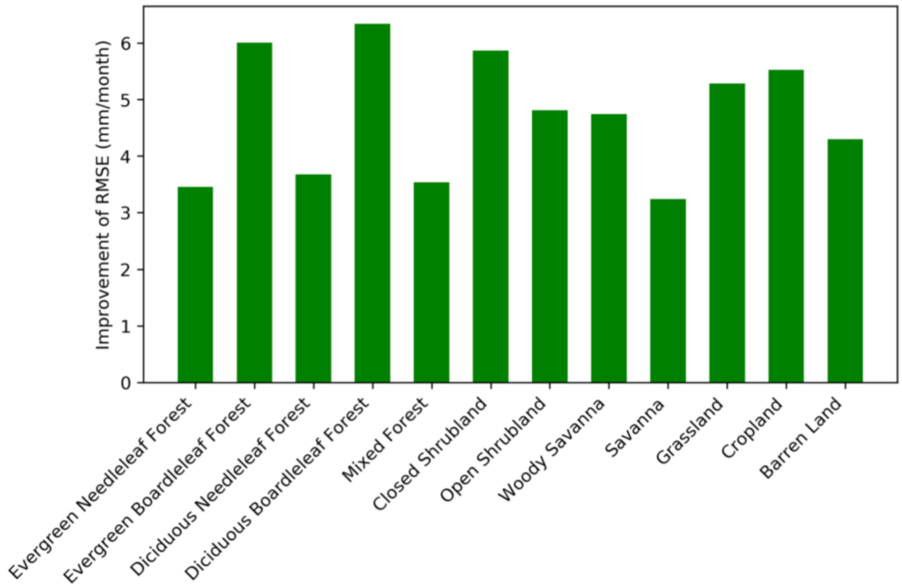

Figure 7. The improvement of RMSE in evaporation simulations for different land covers by using the satellite data-derived RZSC ($S_{R,CRU-SM}$) instead of the uncertain RZSC ($S_{R,LOOKUP-TABLE}$).

Figure 7 shows the RMSE improvements of simulated monthly evaporation for different land covers obtained by implementing the satellite data-derived RZSC ($S_{R,CRU-SM}$) instead of the uncertain RZSC ($S_{R,LOOKUP-TABLE}$). The analysis reveals that the satellite data-derived RZSC ($S_{R,CRU-SM}$) has great potential to improve the evaporation simulation for all kinds of land covers. The largest improvements are found in broadleaf forests. The improvements in the needleleaf forest, mixed forest and savanna are relatively low. The findings also resonate with another work that used a simple terrestrial evaporation to atmosphere model (STEAM) for evaporation simulation (Wang-Erlandsson et al., 2016).

The following figures can be found in the SI of this paper.

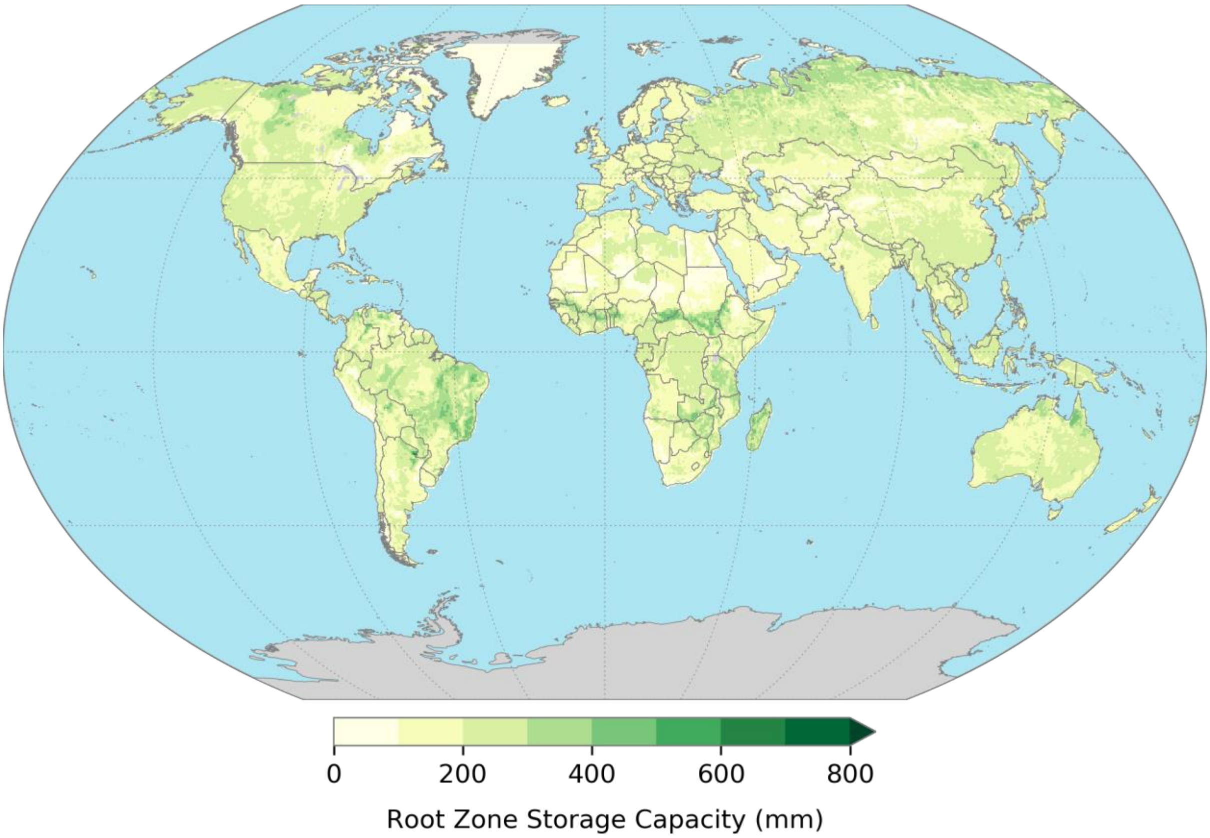

Figure S5. Spatial distribution of uncertain RZSC (SR,LOOKUP-TABLE).

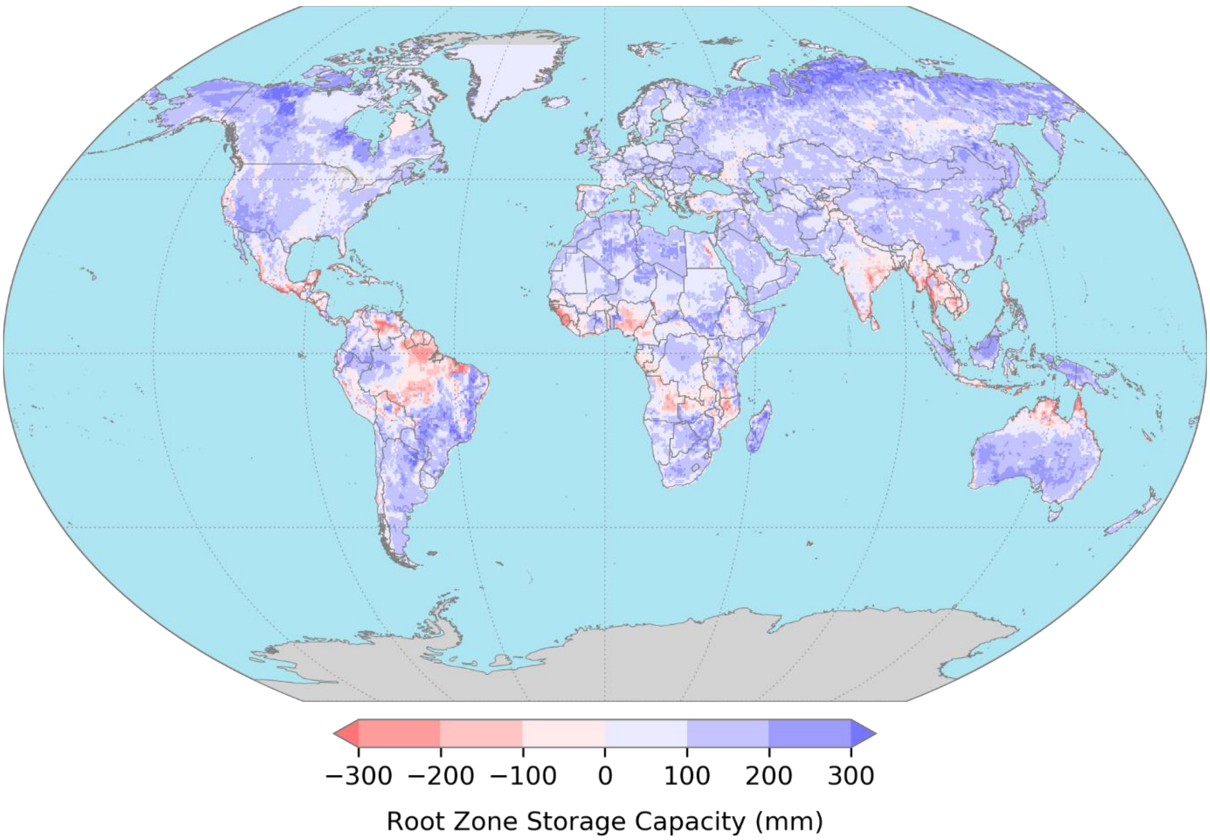

Figure S6. The difference between $S_{R,CRU\text{-}SM}$ and $S_{R,LOOKUP\text{-}TABLE}$ ($S_{R,LOOKUP\text{-}TABLE}$ - $S_{R,CRU\text{-}SM}$).

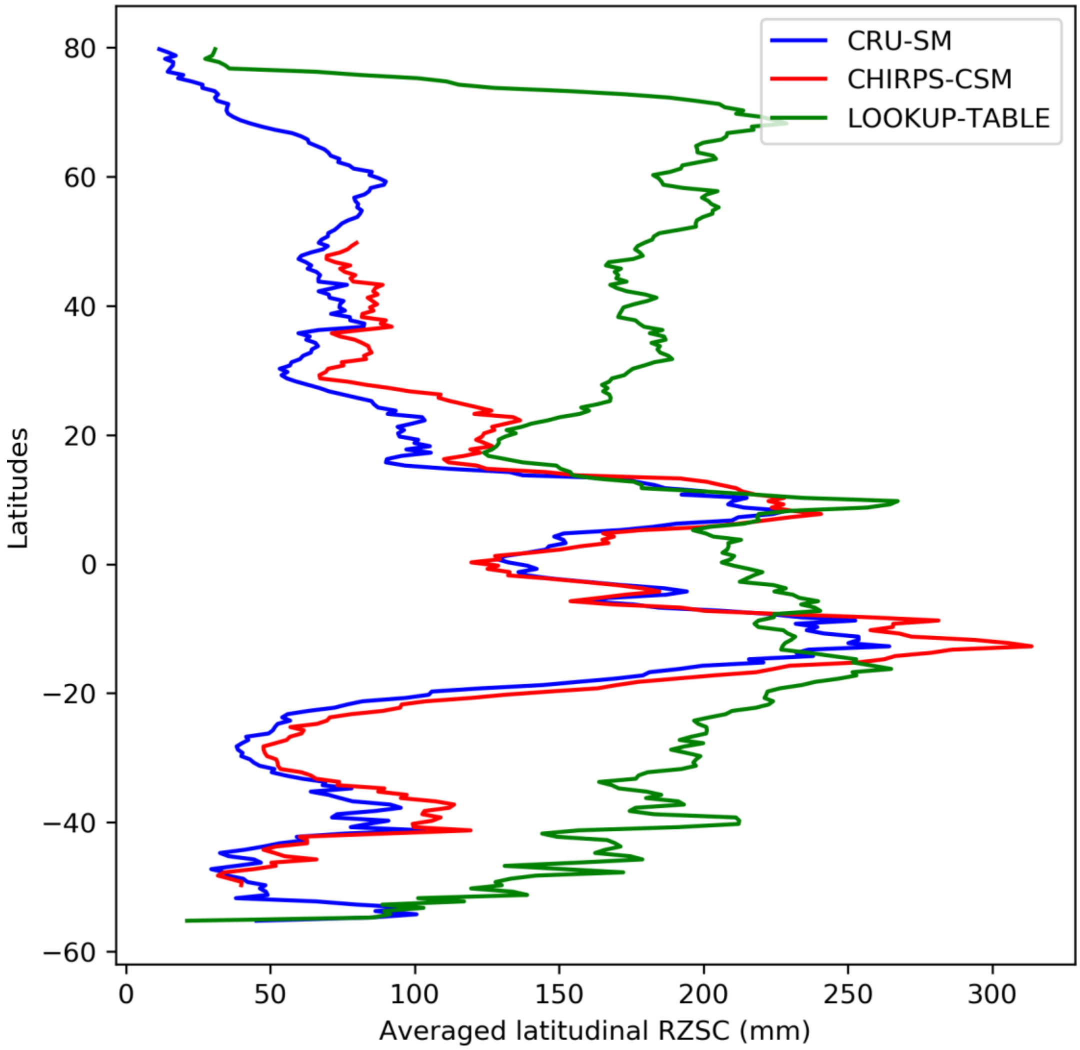

Figure S7. Latitudinal averaged RZSC of different products.

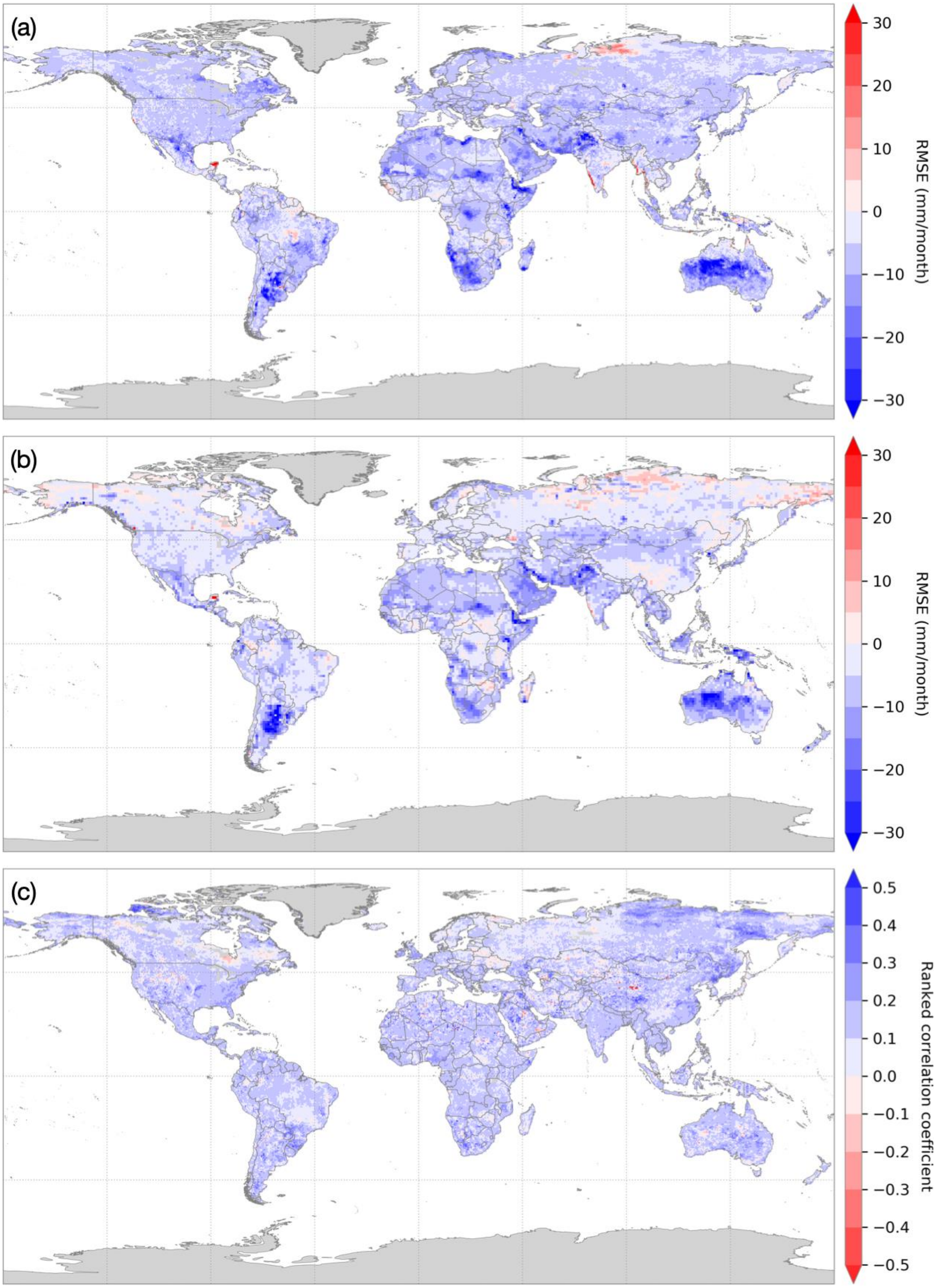

Figure S8. The impacts of RZSC on the model simulation. Blue color indicates the improvement of the simulated results by replacing the uncertain RZSC ($S_{R,LOOKUP-TABLE}$) with satellite data-derived RZSC ($S_{R,CRU-SM}$), while red color implies the opposite. (a) The result for runoff and the reference data for comparison is ERA-Interim/Land data (2001-2010, monthly), (b) the result for evaporation and the reference data for comparison is

LandFluxEVAL data (1989-2005, monthly), and (c) the result for RZWS and the reference data is NDII data (2001-2010, 8 days).

6. In Figure 4, the authors stated that in the Murray Darling basin, WAYS performed very well in comparison to the ERA data for runoff. In Figure 7, the difference between simulated root zone water storage and the NDII values is quite large. The similar situation is also seen in Mississippi, Amazon and Yangtze. The correlation values provided in Table 2 are rather low for these river basins. The authors stated that this could be caused by either the uncertainty of WAYS or the problem of using NDII as a proxy of root zone water storage in the specific river basin. In general, I think this is reasonable. However, I still feel that some specific reasons should be highlighted with convincing evidence, instead of just saying this is either due to the problem of WAYS or the use of NDII. Besides, in the discussion, it would be good if the authors can give some suggestions on validation of root zone water storage simulations when the validity of using NDII for validation is not so suitable as shown in the above mentioned river basins.

Thank you for the comment. Indeed, the runoff simulation in the Murray Darling basin is much better than RZWS. Since the model is calibrated to the runoff, the performance of the runoff generation could potentially surpass the other variables, e.g., RZWS and evaporation. However, we also agree with the referee that the large difference between NDII and simulated RZWS in some basins could imply other potential issues that may affect the simulation in addition to the model structure itself. We have further strengthened this part of the manuscript, and the corresponding changes can be found in the revised version (see "Authors' change in the manuscript.")

Moreover, we have also discussed the validation issue regarding the possible inappropriate representation of NDII in some basins.

Authors' change in the manuscript.

Page 20, Line 8: (the changes is marked as blue)
In contrast, WAYS shows a trend of underestimation in the Murray Darling. A possible reason could be that deep rooted plants are widespread across the Murray Darling basin and can tap into groundwater (Runyan and D'Odorico, 2010; Lamontagne et al., 2014); thus, the NDII may not be the correct proxy for moisture stress in this region. A vast amount of groundwater drawing from the saturated zone to the root zone could explain such underestimation of RZWS (Leblanc et al., 2011). Other reasons behind these findings could be the underestimated RZSC in this region as well as the intensive human activities, including dam construction, a water diversion system and river management, which will impact both the RZSC estimation and RZWS simulation (Reid et al., 2002; Kingsford, 2000).

Page 19, Line 20: (the changes is marked as blue)
In the Mississippi,
WAYS shows a good performance in large-value simulations, while it struggles to simulate low values, with considerable overestimation of them. Therefore, the rank correlation is also relatively low in this catchment, with values of approximately 0.67. The Mississippi river

basin is the northernmost catchment of our selected basins. The NDII here shows a totally different pattern compared to the others, while the WAYS-simulated RZWS can barely show a clear seasonal variation. There could be multiple reasons for this overestimation: our model has a relatively simple snowmelt module (degree-day method), which could consequently introduce biases into the simulation, especially in relatively cold regions. Additionally, the relatively uncertain forcing data could contribute to the mismatches between NDII and RZWS, as the largest uncertainties in precipitation occur mainly at the higher latitudes (Vinukollu et al., 2011). Some studies also reported that precipitation-induced spurious seasonal and interannual variations also exist in the soil moisture in this basin (Yang et al., 2015).

Page 24, Line 22: (the changes is marked as blue)

However, we have to highlight that the model shows lower performance in some regions, e.g., the Amazon, in the RZWS simulation, where the reference data NDII may have shortcomings in reflecting RZWS. In these regions where NDII might not be a correct proxy for RZWS, an additional data set could be helpful for evaluation, e.g., the solar-induced fluorescence (SIF), which reflects photosynthesis and thus has a close relationship to the available water in the root zone. A combination of vegetation index data, such as EVI and NDVI, could also be alternatives, as they represent different characteristics of plants. However, further investigations need to be performed before this combination can be applied.

7. Page 21, last paragraph. It is stated that 'this added value feature could benefit for many applications related to the root zone processes.' The authors should specify some of the potential benefits here.

Thank you. We have specified the potential benefits of the developed model accordingly. The updates can be found in the revised manuscript.

Authors' change in the manuscript.

Page 28, Line 32: (the changes is marked as blue)

This added-value feature could benefit for many applications related to the root zone processes. For instance, the correct representation of RZWS could help the researchers in the investigation of land-vegetation-climate-water integrations, where RZWS plays a key role. The capacity of RZWS simulation could also bring benefit to the field of agriculture, as RZWS represents the plant available water that closely linked with the crop yields.

8. The aim of the paper is to develop WAYS which is capable of simulating root zone water storage. In the model evaluation section, much text is about the validation of runoff. The elaboration of the importance to correctly represent root zone water storage and the good performance of WAYS in realizing this goal is relatively brief. It would be good if the authors can strengthen this part of the text to highlight the accomplishment of the paper.

Thank you. We agree with the referee that the elaboration of the importance of correct representation of root zone water storage is relatively brief. Therefore, we have performed additional work on the model evaluation to strength this portion of the manuscript. We provide a detailed reply regarding this issue in the previous comment section (comment 5). To avoid repetition, we would like to refer to the response to comment 5. The corresponding revision in the manuscript can also be found there.

9. I like the philosophy stated in the end of the paper, 'get the right answers for the right reasons rather than simply to get the right answers'. In this paper, I feel that the right results are clearly shown. But the right reasons, to me, are relatively weak. The good performance in runoff and root zone water storage simulations could be good results, but reasons for the good results needs to be more clearly and explicitly explained and supported by evidence.

Thank you for the comment. We agree with the referee that in the current version of the paper, the model evaluation part is relatively weak. Hence, we have performed an additional evaluation to demonstrate the importance of proper representation of the RZSC in hydrological models. We provide a detailed reply regarding this issue in the previous section (comment 5). To avoid repetition, we would like to refer to the response to comment 5. A comparative experiment is established to observe the impacts of RZSC. The results reveal that correct representation of the RZSC could significantly improve the model simulation, including runoff, evaporation and RZWS. This finding also confirms one of the objectives of our paper regarding the advanced hydrological philosophy to "get the right answers for the right reasons rather than simply to get the right answers".

Specific comments

10. The window in Figure 1 should be enlarged, as it is important to show components and their connections clearly. Anyway, there is space in Figure to accommodate the enlargement.

Thank you for the comment. It is addressed together with the general comment 1 by enlarging the flowchart in Figure 1.

11. The manuscript contains many typos and grammatical mistakes. A professional editing of the manuscript is necessary, particularly because I think the paper has the potential to be an important paper in the field and could receive a high citation in the coming years.

Thank you for the comment. The revised manuscript has now been edited by a professional academic language and manuscript service company.

All the references are included in the manuscript.

We would like to thank Referee #3 for his interest in this topic and for the valuable comments to improve our manuscript. Based on the comments additional calculations have been performed. Our point-by-point response to the comments is given in the following (**Comments in black**, Answers in blue and the content related to the changes in the revised manuscript are marked in orange.):

General comments

#1 The manuscript presents an interesting extension of the FLEX model with enhanced capability for root zone storage simulation at the global scale. Root zone storage capacity is an Achilles heel in global hydrological modelling that is crucial for determining water stress, but most often dependent on highly uncertain soil and rooting depth data. Thus, the authors are addressing an important issue of high relevance for the hydrological modelling community. However, among other improvement possibilities, I think that the analyses need to be more systematic and rigorous, and the manuscript need to better communicate the motivations underlying the developers' choices. I think the manuscript merits to be published after a major revision. My main concerns are the following:

We would like to thank the referee for assessing the quality of the paper and for providing very constructive and valuable comments. Indeed, the root zone storage capacity (RZSC) is a persistent weakness in global hydrological modeling, while it is crucial for water fluxes partitioning. This is the primary motivation of our work to integrate an advanced RZSC dataset into a hydrological model and to test the capacity of the model for root zone water storage (RZWS) simulation. Based on the referee's comments, we have performed additional computation and analyses to make the results more systematic and rigorous. A point-to-point reply to each specific comment is provided below.

#2 The manuscript could benefit from clearer descriptions of rationale and motivations for the model development, the analyses performed and other choices made. For example, why was runoff selected for evaluation against ERA-Interim/Land and the non-calibrated ISIMIP simulations? Why not use gauged data for a selection of basins and the ERA-Interim/Land and ISIMIP for global gridded comparisons? Were other variables and potentially better datasets considered and rejected for which reasons? How come capillary rise is disregarded on the basis of "lack of information at the global scale" is there are other models that take it into account? Why was Penman-Monteith FAO 56 PM method used (P6L25)? What were the considerations? Etc. Reviewers and readers will always have different views on preferred evaluation datasets and equations, but a clear description of the underlying rationale and motivation could help bridging differences in perspective if choices can be well-justified.

Thank you for the comments. The corresponding responses are provided below. Since there are a numerous questions in this comment, we have repeated the specific comment before the detailed response.

#2-1 For example, why was runoff selected for evaluation against ERA-Interim/Land and the non-calibrated ISIMIP simulations?

The gridded data set ERA-Interim/Land is selected for model evaluation mainly because the current version of the WAYS model does not include a runoff routing module on the global scale. Therefore, the results are not comparable to the observed gauged data. The ERA-Interim/Land data set is a global land surface reanalysis data. It is well assessed and has been used as reference data for many studies (Alfieri et al., 2013; Orth and Seneviratne, 2015; Reichle et al., 2017). Thus, the evaluation of WAYS against ERA-Interim/Land is well-justified.

Since WAYS uses the same driving data as the ISIMIP2a models and the ISIMIP2a simulations are widely discussed in many studies, we believe that the additional comparison between WAYS and the ISIMIP2a models can provide added-value for evaluating our model. Therefore, the ISIMIP2a simulations are also shown in the results section together with the ERA-Interim/Land data. We did mention the purpose of inclusion of the ISIMIP2a simulations in the results (page 13, line 15: "Since WAYS uses the same driving data as the ISIMIP2a models and the ISIMIP2a simulations have been widely discussed in many studies (Schewe et al., 2014; Müller Schmied et al., 2016; Gernaat et al., 2017; Zaherpour et al., 2018), we also perform a comparison between WAYS and the ISIMIP2a models to further evaluate our model."). However, we did not mention this in the validation strategy section in the manuscript. We have now further clarified this issue in the revised manuscript (please see "Authors' change in the manuscript.").

Indeed, the ISIMIP2a models are not calibrated. We have mentioned this issue in the manuscript (page 13, line 30: This result occurs partly because some of the ISIMIP2a models are not calibrated at all (Zaherpour et al., 2018), whereas WAYS is calibrated to a Composite Monthly Runoff data set that assimilates the monitored river discharge (Fekete et al., 2011).). We have now revised the captions of related figures (Figures 2 and 3 in the revised manuscript) to note this issue.

Authors' change in the manuscript.

Page 11, Line 5: (the changes is marked as blue)
In this study, the ERA-Interim/Land runoff data are used for validation of the runoff simulation, and the Normalized Difference Infrared Index (NDII) is used for the validation of the WAYS model for root zone water storage simulation. Considering the time period of coverage of both data sets (ERA-Interim/Land: 1979-2010, NDII: 2000-present) and the study period (1971-2010) of this work, the period 2001-2010 is selected as the validation period. For runoff evaluation, ISIMIP2a simulations are also included, as they use the same climate forcing as our study in the same period. The purpose of inclusion of the ISIMIP2a simulations for comparison can be found in the model evaluation section (see Section 4).

Page 11, Line 9: (the changes is marked as blue)
ERA-Interim/Land is a global land surface reanalysis data set produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Balsamo et al., 2015). The gridded data set ERA-Interim/Land is selected for model evaluation mainly because the current version of the WAYS model does not include a runoff routing model on the global scale. Therefore, the results are not comparable with observed gauge data. Since the ERA-

Interim/Land data set is well assessed with a quality check through comparison with ground-based and remote sensing observations, it has been used as reference data for many studies (Xia et al., 2014; Dorigo et al., 2017).

Page 13, Line 15: (the changes is marked as blue)
"Since the ISIMIP2a simulations are widely discussed in many studies (Schewe et al., 2014; Müller Schmied et al., 2016; Gernaat et al., 2017; Zaherpour et al., 2018), the comparison between WAYS and the ISIMIP2a models can provide added-value for evaluation in addition to examine only with the reference data." is changed to "Since WAYS uses the same driving data as the ISIMIP2a models and the ISIMIP2a simulations have been widely discussed in many studies (Schewe et al., 2014; Müller Schmied et al., 2016; Gernaat et al., 2017; Zaherpour et al., 2018), we also perform a comparison between WAYS and the ISIMIP2a models to further evaluate our model."

#2-2 Why not use gauged data for a selection of basins and the ERA-Interim/Land and ISIMIP for global gridded comparisons?

The simulated results are not compared to the gauged data because the current version of WAYS does not include a runoff routing module on the global scale. Therefore, the results are not comparable to the observed gauged data.

The evaluation of runoff is performed on the basin scale rather because it is difficult to show the global gridded comparisons for the time series simulated runoff. Thus, ten major basins are selected for the validation based on the coverage of the two RZSC datasets ($S_{R,CRU-SM}$ and $S_{R,CHIRPS-CSM}$). However, we agree with the reviewer that a comparison with gauged data is important. Thus, additional calculations have been performed. In the revised manuscript, we have evaluated our results with observed discharges from the Global Runoff Data Centre (GRDC). Since WAYS does not have a native runoff routing module at the moment, a third-part runoff routing tool CaMa-flood is applied to route the WAYS simulated runoff (Yamazaki et al., 2011). Given that the manuscript is already quite extensive, the discharge comparison is not a direct evaluation to WAYS but an evaluation of both WAYS and CaMa-Flood. We have included this information in Supplementary Information (SI).

Authors' change in the manuscript.

Page 18, Line 4: (the following paragraph is inserted in the end of runoff evaluation section)
The performance of WAYS is further evaluated against the gauge observations. Since WAYS does not have a native runoff routing module at the moment, a third-part runoff routing tool, CaMa-flood, is applied to route the WAYS simulated runoff (Yamazaki et al., 2011). The evaluation results can be found in the Supplementary Information (SI).

The following part is put in the SI.
To further evaluate the model performance, we have evaluated our results with observed discharges from the Global Runoff Data Centre (GRDC). The CaMa-flood model is the only available open-source global runoff routing model (http://hydro.iis.u-

tokyo.ac.jp/~yamadai/cama-flood/) that is capable of simulating backwater effects, which is important for plain regions, making it a popular choice for many studies (Hirabayashi et al., 2013; Mateo et al., 2014; Pappenberger et al., 2012).

The GRDC stations along a river were selected with interstation areas larger than 7000 km^2 to omit catchments with hydrological processes that are not properly represented by global hydrological models operating at a 0.5° resolution (Hunger and Döll, 2008). In total, 154 stations are selected for major river basins worldwide. For discharge simulation, the CaMa-flood is run at a 0.5° resolution to maintain consistency with the WAYS simulated runoff. The WAYS_CRU simulation is used for routing due to global coverage of the data. The discharge is simulated for the 1971-2010 period.

For the evaluation, the simulated discharge is compared with the GRDC data at each selected station depending on the data availability. Since the observations provided by GRDC are on a monthly time scale, the simulated data are also aggregated to the monthly scale for the comparison. The correlation coefficient and Nash-Sutcliffe efficiency coefficient are calculated, while the correlation coefficient between the simulated discharges and GRDC station records are visualized in Figure S1.

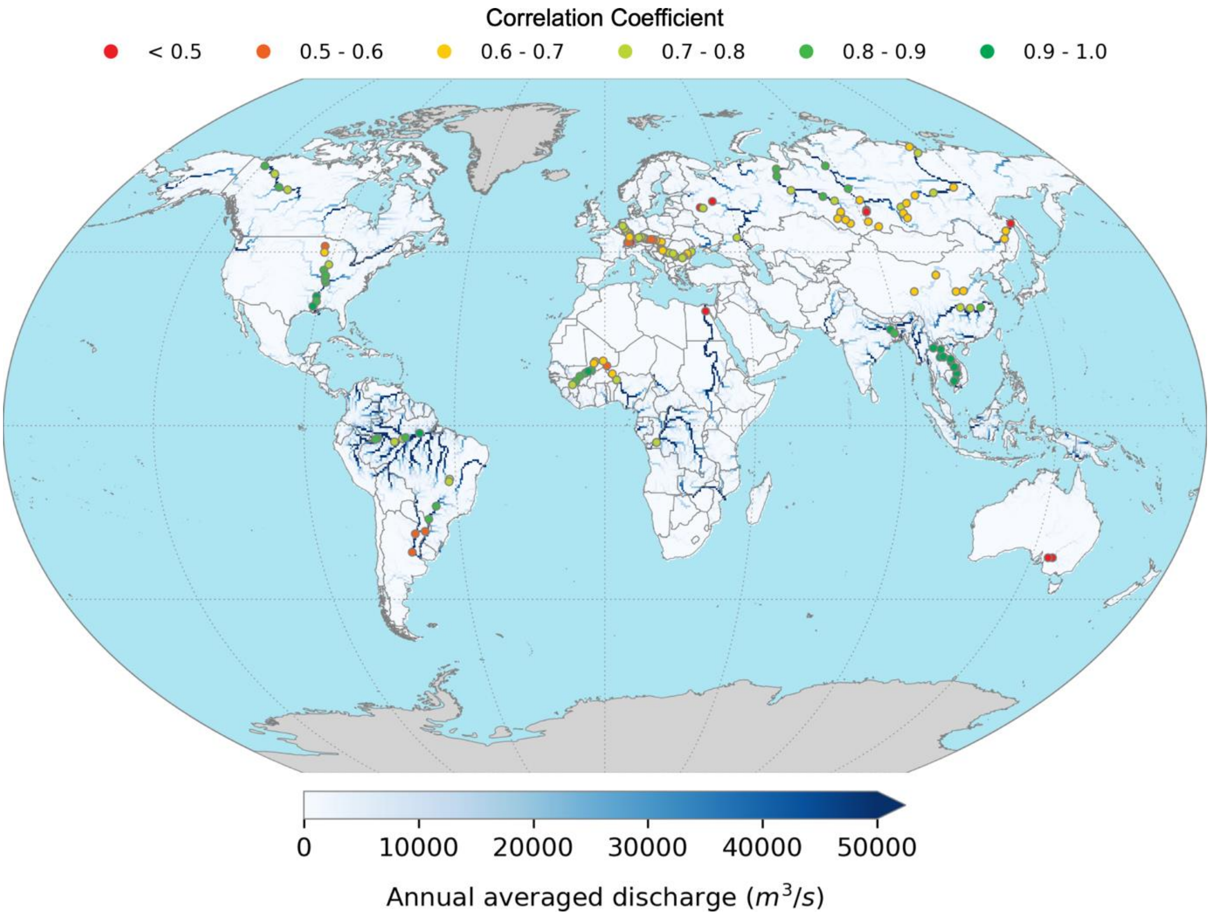

Figure S1. The evaluation of simulated discharge by comparison with the GRDC observations. The discharge is simulated by the CaMa-flood model, and the WAYS simulated runoff based on the RZSC data ($S_{R,CRU-SM}$) is used as the input data for routing. The background of the figure is the annual averaged discharge for the 1971-2010 period. The point indicates the correlation coefficient between simulated discharge and GRDC observations. The location of the points *implies the location of the GRDC station. Different colors at the points represent the magnitudes of the correlation coefficient.*

The simulation shows a generally good correlation with the GRDC observations, while poor performance in the discharge simulation is also found in a few stations. The errors between the simulated discharge and observations could be caused by both the WAYS model for runoff simulation as well as the CaMa-Flood model for runoff routing, as the CaMa-Flood model itself also shows different performances in basins across the world (Yamazaki et al., 2011). The relatively low performance of WAYS is found in middle-high latitudes compared with low-middle latitude regions. This result could be explained by the relatively simple snow-melt module in the WAYS model, which thus could consequently produce low-quality runoff for river routing in cold regions. In Australia, only two GRDC stations in the Murray Darling basin are selected for the evaluation, and the correlation coefficient between simulated discharge and GRDC station is less than 0.5, indicating the large difference between them.

Figure S2 shows the histogram of the data points within different intervals of the correlation coefficient. Only in 7.2% of the stations are the correlations between simulation and observation less than 0.5. For more than half the stations, the correlations are higher than 0.7. The results show a generally good correspondence between the simulated and observed discharge. The generally good performance in the discharge simulation confirms the strong capacity of WAYS for runoff generation.

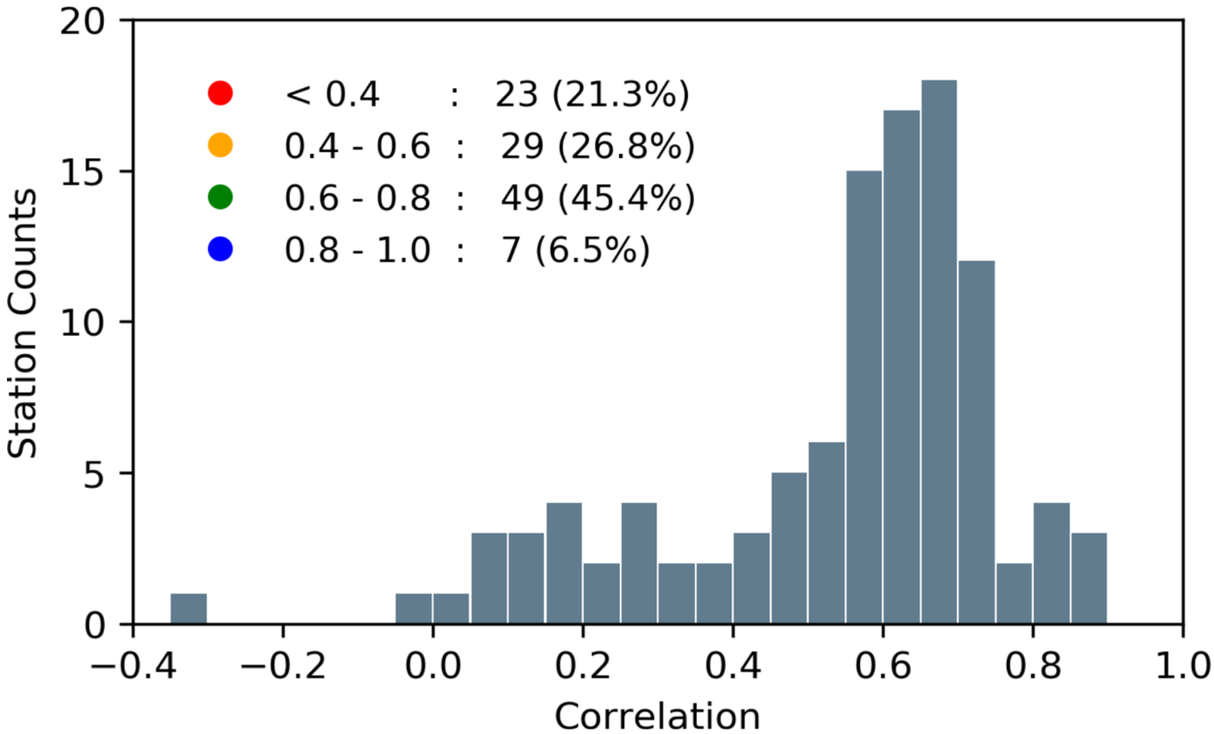

Figure S2. Histogram showing the percentage of data points within different intervals of the correlation coefficient.

#2-3 Were other variables and potentially better datasets considered and rejected for which reasons?

In addition to ERA-Interim/Land, other reanalysis runoff data are available, such as ERA-Interim, GLDAS, and NECP, among others. However, they show low robustness based on the available research results. For instance, GLDAS v1.0-CLM is found to overestimate runoff globally, and GLDAS v1.0-Noah generated more surface runoff over northern middle-high latitudes (Lv et al., 2018). GLDAS v2.0-Noah showed a significant underestimation trend in exorheic basins (Wang et al., 2016). The snowmelt-runoff peak magnitude simulated by GLDAS v2.1-Noah was found to be excessively high in June and July (Lv et al., 2018). NECP runoff is found to be too high during the winter and too low during the summer in the Mississippi River Basin (Roads and Betts, 2000). ERA-Interim is found to be less close to the observed stream flows compared with ERA-Interim/Land (Balsamo et al., 2015).

The ERA-Interim/Land is well assessed with quality checks by comparison with ground-based observations (GRDC observation) and is widely used as benchmark data (Alfieri et al. 2013; Balsamo et al. 2015; Orth and Seneviratne 2015; Reichle et al. 2017; Wang-Erlandsson et al. 2014). Therefore, it is selected as the reference data for this study for runoff comparison.

Authors' change in the manuscript.

Page 11, Line 20: (the following paragraph is inserted in the end of section "3.3.1 ERA-Interim/Land Runoff Data")
It should be noted that there are other reanalysis runoff data available, such as ERA-Interim, GLDAS and NECP. However, they show low robustness based on the available research results. For instance, GLDAS v1.0-CLM was found to overestimate runoff globally, and GLDAS v1.0-Noah generated more surface runoff over the northern middle-high latitudes (Lv et al., 2018). GLDAS v2.0-Noah showed a significant underestimation trend in exorheic basins (Wang et al., 2016). The snowmelt-runoff peak magnitude simulated by GLDAS v2.1-Noah was found to be excessively high in June and July (Lv et al., 2018). NECP runoff was found to be too high during the winter and too low during the summer in the Mississippi River Basin (Roads and Betts, 2000). ERA-Interim was found to be less close to the observed stream flows compared with ERA-Interim/Land data (Balsamo et al., 2015).

#2-4 How come capillary rise is disregarded on the basis of "lack of information at the global scale" is there are other models that take it into account?

WAYS contains the capillary module, which is adopted from the FLEX model. At the current stage, it is, however, disabled due to the lack of global information on the groundwater table, which could affect the simulated results in this work, e.g., evaporation and RZWS. We decided to disable the capillary module based on our experimental analysis.

We set up two experimental runs for WAYS to check the impact of the capillary module in the current version by switching it on/off. Since there is no observed groundwater table information to constrain the capillary rise amount, switching on the capillary module significantly overestimates the evaporation globally. The global averaged annual evaporation reaches 697 mm/year. Switching off the capillary module reduces the evaporation to 513 mm/year. A merged benchmark synthesis product of evaporation, i.e., LandFluxEVAL data, shows only 491 mm/year, which is much closer to the value without the capillary module. Thus, the capillary module is temporary disabled in WAYS until the global information on groundwater table is available. We have mentioned this issue in the revised manuscript. A response to the similar comment can be found in "the response letter to Referee #1" (Comment 6).

In fact, many models ignore the capillary at the global scale due to the absence of groundwater table information (Döll et al., 2003; De Graaf et al., 2015; Hanasaki et al., 2018). Consideration of the capillary in hydrological simulation is more popular in regional studies, mainly due to the local groundwater data availability (Gao et al., 2014; Vergnes et al., 2014).

Authors' change in the manuscript.

Page 25, Line 4: The following paragraph is inserted in the discussion part
Moreover, the current study does not consider the groundwater access and irrigation mainly due to the lack of global information. The groundwater table information is crucial for capillary rise simulation (Vergnes et al., 2014). Capillary rise simulation without proper water table information could significantly overestimate the evaporation. Thus, the capillary rise flux is ignored in this study. A similar strategy has also been applied by other works due to the absence of the information on the global water table (Döll et al., 2003; De Graaf et al., 2015; Hanasaki et al., 2018). Observations of irrigation on the global scale are also not available (Leng et al., 2015). Although there are simulated irrigation data available on the global scale, the inherent uncertainties could be propagated in our model simulation. Therefore, irrigation is also not considered at this time. However, this neglect could potentially introduce biases into the model simulation in irrigated areas and deep rooted plant-distributed regions, as both irrigation and capillary rise are an additional supply of soil water recharge. The biases may cause an underestimation of evaporation, especially in the dry summertime (Vergnes et al., 2014). This underestimation could consequently affect the simulation of RZWS and runoff because of the interlinkage of these three elements (Rockström et al., 1999). It is found that ignoring the capillary rise could reduce soil water content in the root zone (RZWS), while the runoff will also be reduced (Vergnes et al., 2014). However, these shortcomings can be simply overcome once the global data are available.

#2-5 Why was Penman-Monteith FAO 56 PM method used (P6L25)? What were the considerations?

Indeed, many methods are available to estimate potential evapotranspiration (PET) from standard meteorological observations. The Penman-Monteith FAO 56 PM method is recommended by FAO and other studies based on their thorough analysis in PET method intercomparisons (Allen et al., 1998; Lu et al., 2005; Vörösmarty et al., 1998). The Penman-Monteith FAO 56 PM method is based on fundamental physical principles and is found to be the most reliable method for potential evapotranspiration estimation where sufficient meteorological data exist (Chen et al., 2005; Kingston et al., 2009).

We would like to mention that FLEX uses the Hamon method for PET estimation. However, the Hamon method is found to have less robustness in different climatic conditions as well as drawbacks in terms of the daily variability of PET simulation (Bai et al., 2016; Droogers and Allen, 2002). Therefore, we have used the Penman-Monteith FAO 56 PM method in our study.

Authors' change in the manuscript.

Page 7, Line 4: (the changes is marked as blue)
Potential evapotranspiration is derived by the Hamon equation (Hamon, 1961) in the FLEX model, and it is now replaced by the using the Penman-Monteith FAO 56 PM method (Allen et al., 1998) for the following reason. The Hamon method is found to have less robustness in different climatic conditions as well as drawbacks in the daily variability of the PET simulation due mainly to the relatively simple equation in the Hamon method, as it only employs the average air temperature as an input (Bai et al., 2016; Droogers and Allen, 2002). In contrast, the Penman-Monteith FAO 56 PM method is based on fundamental physical principles and is found to be the most reliable method for potential evapotranspiration estimation when sufficient meteorological data exist (Chen et al., 2005; Kingston et al., 2009). The Penman-Monteith FAO 56 PM method is recommended by FAO and other studies based on thorough analyses of PET method intercomparisons (Allen et al., 1998; Jian biao et al., 2005; Vörösmarty et al., 1998).

#3 The analyses could be better designed to facilitate understanding of how and why WAYS perform in certain ways, and thus, give more insight into how various components of the model affect the root zone storage and runoff simulation? For example, can the authors show how results are affected by e.g., use of root zone storage capacity derived from uncertain root depth and soil data versus the root zone storage capacity from Wang-Erlandsson et al., 2016? Can the authors perform some sensitivity analyses to highlight model structure and parameter sensitivity?

Thank you for the comment. We agree with the referee that our study could benefit from a better design of the experiment. To facilitate understanding of how RZSC could affect the model simulation, we have additionally conducted a simulation of WAYS with RZSC derived from an uncertain root depth and soil data. The simulated results are then compared between two runs, i.e., one with RZSC from Wang-Erlandsson (2016) and the other with uncertain RZSC. Since this part could support the conclusion of this paper regarding the importance of correct representation of RZSC in models, we include it in the revised manuscript by adding some figures in the SI.

In addition, we have also performed a sensitivity test to highlight the model structure and parameter sensitivity. Since this part is not directly related to the main conclusion of the manuscript but important to demonstrate the model robustness, we have included it in the SI.

Authors' change in the manuscript.

Page 21, Line 26: (the following paragraphs are added)

RZSC is a key parameter of the WAYS model. Therefore, it is important to investigate how RZSC could affect the model simulation. In addition to the model simulated with satellite data-derived RZSC products ($S_{R,CHIRPS-CSM}$ and $S_{R,CRU-SM}$), we have additionally conducted WAYS simulations with RZSC derived from uncertain root depth and soil data. The uncertain RZSC ($S_{R,LOOKUP-TABLE}$) is derived based on literature values of root depth and soil texture data (Müller Schmied et al., 2014; Wang-Erlandsson et al., 2016). Due to the global coverage of the RZSC data ($S_{R,CRU-SM}$), only the simulation with $S_{R,CRU-SM}$ is used for comparison. The spatial distribution of the uncertain RZSC is shown in Figure S17, and the differences between $S_{R,CRU-SM}$ and $S_{R,LOOKUP-TABLE}$ are shown in Figure S18. It can be seen that there are large differences between the two RZSC products. The simulation with uncertain RZSC $S_{R,LOOKUP-TABLE}$ shows overestimation globally except for some regions around low-middle latitudes. The latitudinal averaged RZSC further confirms the overestimation of $S_{R,LOOKUP-TABLE}$ at middle-high latitudes (Figure S19).

The large differences between these two RZSC data sets also introduce differences in simulated hydrological elements. Figure S20 shows the impacts of RZSC on the model simulation, including runoff, evaporation and RZWS. A blue color (decrease of RMSE and increase of the ranked correlation) indicates an improvement of the simulated results by replacing the uncertain RZSC ($S_{R,LOOKUP-TABLE}$) with satellite data-derived RZSC ($S_{R,CRU-SM}$), while a red color implies the opposite. For comparison, reference data are used for different variables. For runoff, evaporation and RZWS, the reference data are ERA-Interim/Land (2001-2010, monthly), LandFluxEVAL (1989-2005, monthly) and NDII (2001-2010, 8-days), respectively. Generally, the model simulations are improved by using the RZSC $S_{R,CRU-SM}$. This result emphasizes the importance of an appropriate representation of RZSC in WAYS. A decline of the model performance is also found in some
regions at high latitudes and low latitudes. This result can be partially explained by the inherent uncertainty in the $S_{R,CRU-SM}$ data, as they are derived from other data sets. The RZSC derivation method itself as well as the input data can also introduce biases (Wang-Erlandsson et al., 2016).

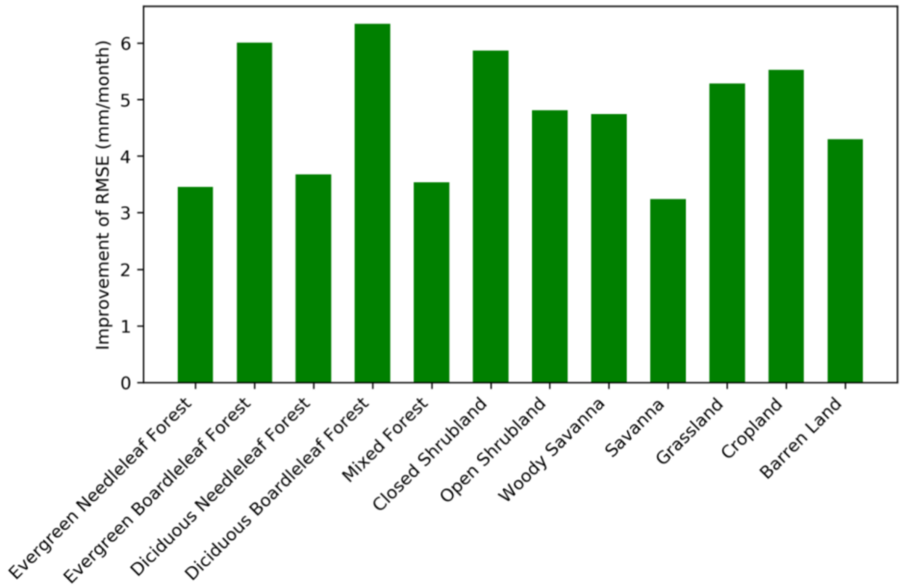

Figure 7. The improvement of RMSE in evaporation simulations for different land covers by using the satellite data-derived RZSC ($S_{R,CRU-SM}$) instead of the uncertain RZSC ($S_{R,LOOKUP-TABLE}$).

Figure 7 shows the RMSE improvements of simulated monthly evaporation for different land covers obtained by implementing the satellite data-derived RZSC ($S_{R,CRU-SM}$) instead of the uncertain RZSC ($S_{R,LOOKUP-TABLE}$). The analysis reveals that the satellite data-derived RZSC ($S_{R,CRU-SM}$) has great potential to improve the evaporation simulation for all kinds of land covers. The largest improvements are found in broadleaf forests. The improvements in the needleleaf forest, mixed forest and savanna are relatively low. The findings also resonate with another work that used a simple terrestrial evaporation to atmosphere model (STEAM) for evaporation simulation (Wang-Erlandsson et al., 2016).

The following figures can be found in the SI of this paper.

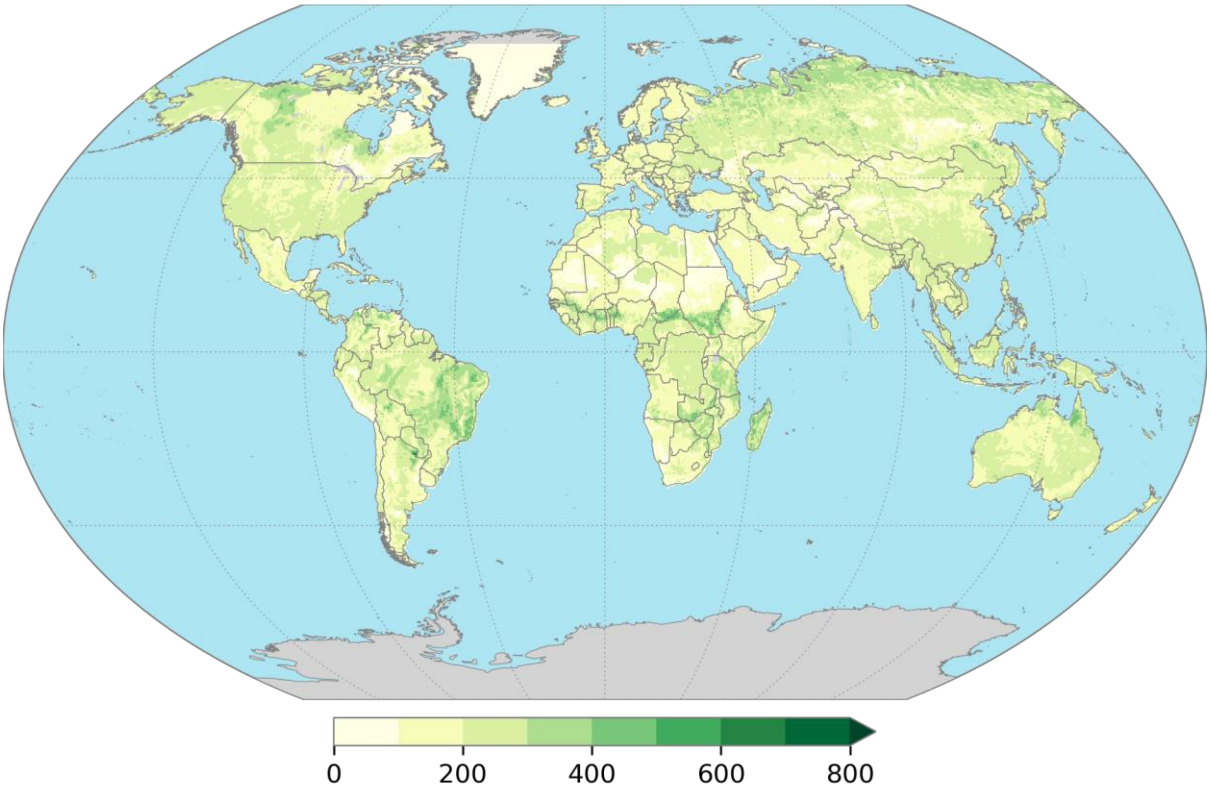

Figure S3. Spatial distribution of uncertain RZSC (SR,LOOKUP-TABLE).

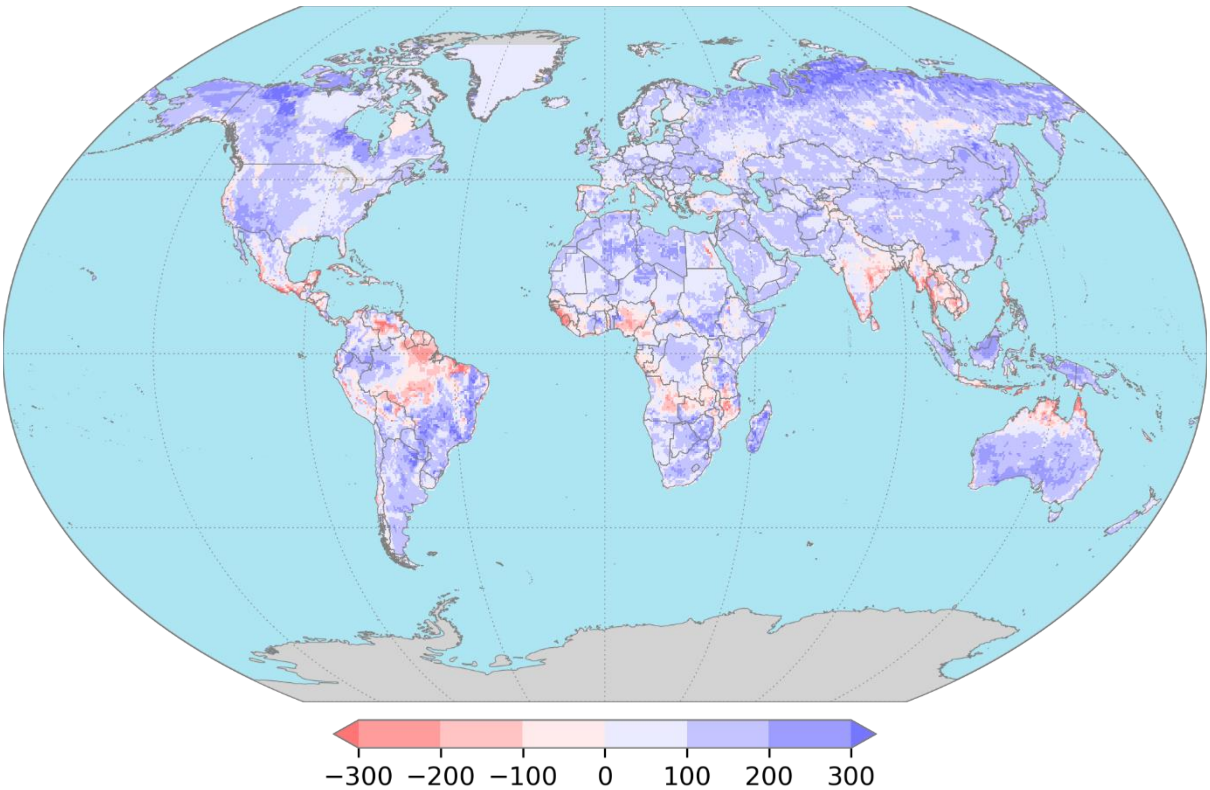

Figure S4. The difference between $S_{R,CRU\text{-}SM}$ and $S_{R,LOOKUP\text{-}TABLE}$ ($S_{R,LOOKUP\text{-}TABLE}$ - $S_{R,CRU\text{-}SM}$).

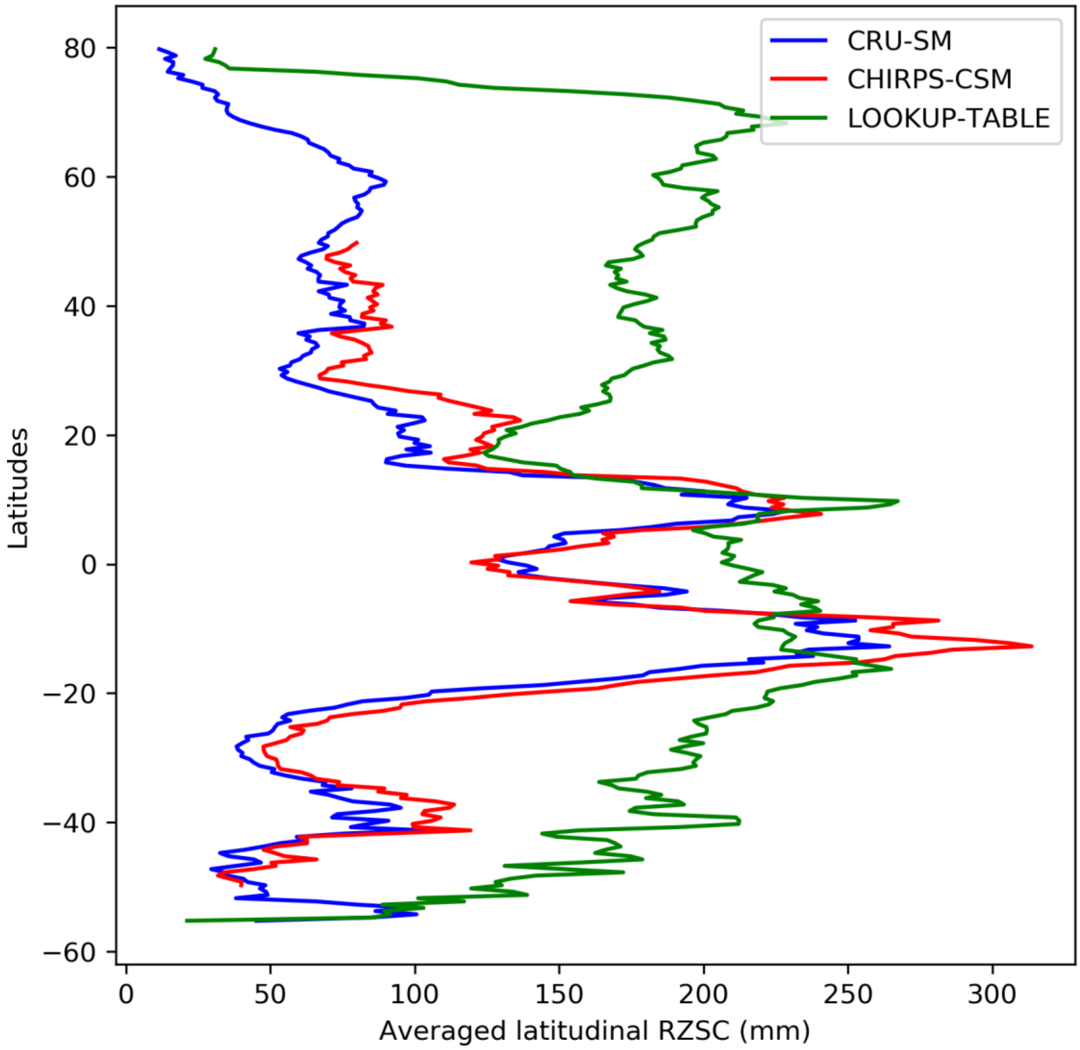

Figure S5. Latitudinal averaged RZSC of different products.

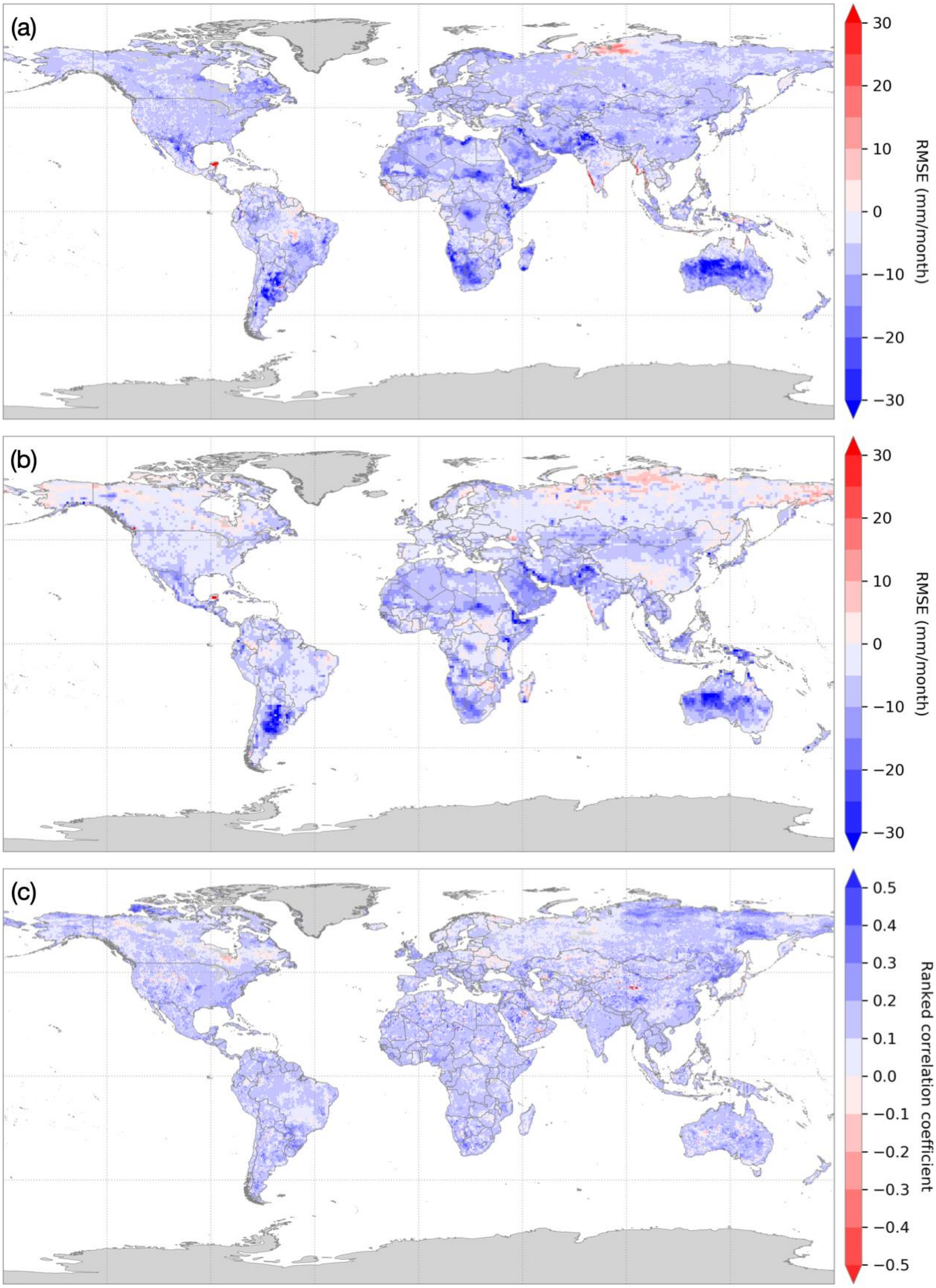

Figure S6. The impacts of RZSC on the model simulation. Blue color indicates the improvement of the simulated results by replacing the uncertain RZSC ($S_{R,LOOKUP\text{-}TABLE}$) with satellite data-derived RZSC ($S_{R,CRU\text{-}SM}$), while red color implies the opposite. (a) The result for runoff and the reference data for comparison is ERA-Interim/Land data (2001-2010, monthly), (b) the result for evaporation and the reference data for comparison is

LandFluxEVAL data (1989-2005, monthly), and (c) the result for RZWS and the reference data is NDII data (2001-2010, 8 days).

The following part is put in the SI.

In the WAYS mode, β and C_e are two crucial parameters that control the partitioning of precipitation into evaporation and runoff, thus affecting the water balance. Due to the incredibly high computation cost, only the sensitivity of the model simulation to these two parameters are tested. First, a pixel is selected randomly from the domain to demonstrate the impacts of parameter perturbation on simulated evaporation, runoff and RZWS. For each experiment, only one parameter is perturbed, and the other one is set to the calibrated value. The calibrated value for β and C_e is 0.17 and 1.67, respectively. The parameter is perturbed within the range randomly 1000 times during the experiment. Simulations are executed from 2009 to 2010 on a daily scale, while the results are shown on a monthly scale (see Figure S7). The model is more sensitive to parameter C_e than parameter β. The uncertainties caused by the parameter C_e are generally larger than those caused by the parameter β, especially for RZWS. These two parameters also have complementary effects on the model simulation, causing larger uncertainties for the simulation than one parameter.

To further investigate the uncertainties stemming from parameters on a global scale, a Monte Carlo simulation of 1000 samples is performed by perturbing the two parameters simultaneously. For both parameters, the normal distribution is used for the Monte Carlo perturbation. Simulations are executed from 2001 to 2010 on a daily scale. The coefficient of variation (CV) for each pixel is then calculated, which reflects the uncertainties (De Graaf et al., 2015). A high value of CV indicates relatively higher uncertainty caused by the parameters, while a low value of CV implies the opposite. Figure S8 shows that parameter-induced uncertainties of evaporation and runoff have similar patterns, while the magnitude is slightly higher for the runoff globally. This finding is consistent with the pixel-based sensitivity test (see Figure S7). The simulated RZWS has the largest uncertainties with the Monte Carlo simulation. Additionally, the uncertainties of RZWS show the opposite trend to the uncertainties of evaporation and runoff. In the northern part of Africa, the Arabian Peninsula, northwest of China and southern part of Australia, the uncertainties in evaporation and runoff are low. However, the uncertainties in RZWS are quite large in these regions.

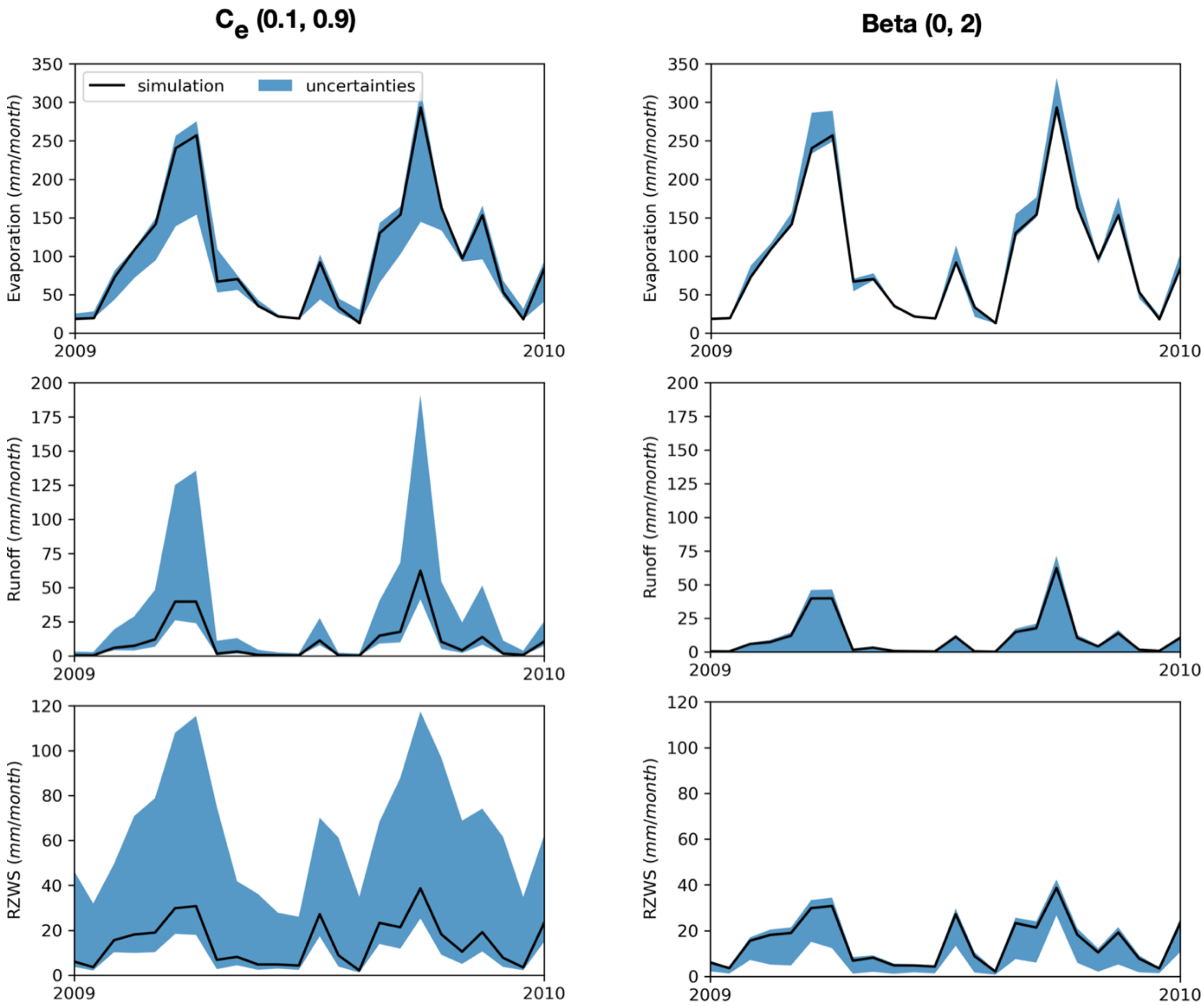

Figure S7. Sensitivity of simulated evaporation (top), runoff (middle) and RZWS (bottom) to parameter β and Ce in a randomly selected pixel within the domain. The black solid line represents the simulation based on the calibrated value. The blue area indicates the uncertainties induced from the perturbation of the parameter 1000 times.

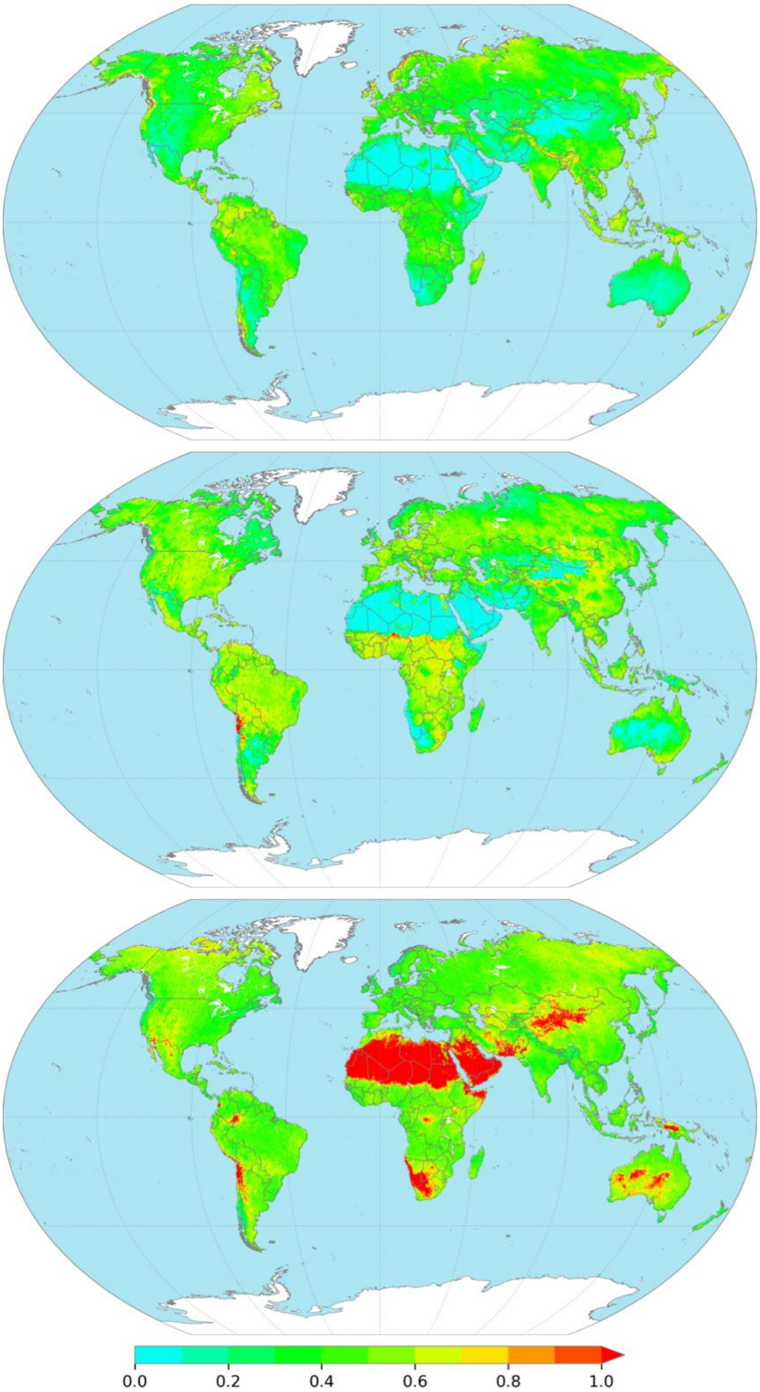

Figure S8. Coefficient of variation of model-simulated evaporation (top), runoff (middle) and RZWS (bottom) from 1000 Monte Carlo simulations with different parameter settings for β and Ce.

#4 The WAYS model is developed based on essential features of the FLEX model (P3L14), and as such I would (1) suggest the authors to present an overview of the similarities and differences between the two and (2) to retain "FLEX" in the model naming (e.g., FLEX-WAYS). Retaining FLEX in the name benefits the model developers that do not need to explain the model roots and will have an easier time communicating the new model developments that builds on an existing well-established mode, and would also be a nice acknowledgement of the earlier FLEX model developments. The practice of name roots

exists in the modelling community, and e.g., the models LPJmL and LPJ-GUESS show through their names that they share the same roots.

Thank you for the comment. To present the similarities and differences between FLEX and WAYS, we have updated Table 1 in the revised manuscript. The last column named "Reference" in Table 1 highlights the sources of equations that are adopted from FLEX or from the literature.

Regarding the model naming, however, we would prefer to keep it as WAYS for the following reasons: (1) WAYS is expected to be further developed by integrating new features, such as a water quality module that allows for environmental impact studies or an economic module to connect the physics of water and virtual water. In this case, WAYS needs its own postfix to identify different features, e.g., WAYS-WQ or WAYS-ECO. A prefix of FLEX will make the model name too complicated. (2) The FLEX model itself actually has different branches, e.g., FLEX-Topo indicates a topography-driven FLEX model, and $FLEX^{D}$ represents a semidistributed FLEX model while $FLEX^{T0}$ stands for FLEX-Topo without constraints (Gao et al., 2014). All the different types of FELX have the same equations for all hydrological processes but with different model structures during the application. WAYS has replaced many equations from FLEX to enhance the capacity of the model for global simulation. A prefix of FLEX could cause confusion as the FLEX branches seldom change the equations. (3) The application of name roots to models is a good strategy for the models that share the core structure and equations but with different features as added functions. For instance, the VIC model is developed based on a small-scale distributed model Xinanjiang (Zhao, 1992). It has its own name and has been further developed by including additional features, e.g., VIC-CropSyst-v2, that simulate the nexus of climate, hydrology, cropping systems, and human decisions.

Authors' change in the manuscript.

Page 8: Table 1 is updated. (the changes are marked as blue)

Table 1. Water balance and constitutive equations used in WAYS

Reservoirs	Water balance equations	Constitutive equations	Reference
Interception reservoir	$\frac{dS_i}{dt} = P_r - E_i - P_{tf}$ (1)	$P_{tf} = max(0, P_r - (S_{i,max} - S_i))$ (2)	-
		$E_i = E_p\left(\frac{S_i}{S_{i,max}}\right)^{2/3}$ (3)	Deardorff (1978)
		$S_{i,max} = m_c L$ (4)	Wang-Erlandsson et al. (2014)
Snow reservoir	$\frac{dS_w}{dt} = \begin{cases} -M & \text{if } T > T_t \\ P_s & \text{if } T \leq T_t \end{cases}$ (5)	$M = \begin{cases} min(S_w, F_{DD}(T - T_t)) & \text{if } T > T_t \\ 0 & \text{if } T \leq T_t \end{cases}$ (6)	Rango and Martinec (1995)
Root zone reservoir	$\frac{dS_{rz}}{dt} = P_e - R - E_a$ (7)	$P_e = P_{tf} + M$ (8)	-
		$\frac{R}{P_e} = 1 - \left(1 - \frac{S_{rz}}{(1+\beta)S_{rz,max}}\right)^{\beta}$ (9)	Sriwongsitanon et al. (2016)
		$E_a = (E_0 - E_i) \cdot min\left(1, \frac{S_{rz}}{C_e S_{rz,max}(1+\beta)}\right)$ (10)	Sriwongsitanon et al. (2016)
Slow response reservoir	$\frac{dS_s}{dt} = R_s - Q_s$ (11)	$R_s = min(f_s R, R_{s,max})$ (12)	Döll and Fiedler (2008)
		$Q_s = S_s / K_s$ (13)	Döll et al. (2003)
Fast response reservoir	$\frac{dS_f}{dt} = R_f - Q_{ff} - Q_f$ (14)	$R_f = R - R_s$ (15)	-
		$Q_{ff} = max(0, S_f - S_{ftr})/K_{ff}$ (16)	-
		$Q_f = S_f / K_f$ (17)	-

Note: all the time scale-dependent parameters need to be divided by Δt to make the equations dimensionally correct and suitable for any other time scales.
- in the reference column indicates that the formula is taken from the FLEX model.

Page 26, Line 9: (the changes are marked as blue)

This study was supported by the National Natural Science Foundation of China (Grant No. 41625001), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA20060402) and the National Natural Science Foundation of China (Grant No. 41571022). We would like to acknowledge the authors of the FLEX model for their great help during the development of WAYS.

#5 The WAYS performance evaluation in terms of root zone storage moisture is highly dependent on the comparison with NDII, which weakens the conclusions, since also further work is still needed to robustly establish the relationship between NDII and soil moisture at the global scale. It is after all only recently suggested by Sriwongsitanon et al. (2016) – a study in a river basin in Thailand – that NDII can have the potential to be used as a proxy for catchment scale root zone storage capacity. The authors could potentially strengthen their conclusions by evaluating model simulation outputs with additional sources of data/methods, such as FLUX-tower, evaporation, EVI etc. Summarizing evaluation figures can be shown in the main manuscript, and others could be included in Supplementary Information. A more detailed list of the equations and calibration process could also be included in Supplementary Information for transparency.

Thank you for the comment. Based on the referee's suggestion, we have performed an additional evaluation on our model simulation to strengthen the conclusions. Since RZWS has close links to the total evaporation, we have compared the WAYS simulated evaporation to FLUX-tower observations (FLUXNET2015) as well as a merged benchmark synthesis product of evaporation (LandFluxEVAL).

The referee also suggested that we compare our model simulation to EVI. However, as we stated in our manuscript (page 2, line 22), EVI as well as NDVI are the most widely used vegetation indices, which have strong links to root zone soil moisture but cannot reflect the dynamics of the water content in the root zone layer (Santos et al. 2014). However, NDII determines the water stress of plants in the root zone by taking advantage of the property of shortwave infrared reflectance, thus possessing the intuitive advantage of reflecting the dynamics of RZWS than EVI (Sriwongsitanon et al. 2016). As we have already compared our model results to NDII, we prefer to skip the comparison between our model simulation with EVI.

Since this evaporation evaluation can support the conclusion of this paper regarding the capacity for hydrological cycle simulation, we include the work of evaporation evaluation against FLUX-tower data in the main text of the revised manuscript and the rest in SI. Please refer to the changes in the revised manuscript.

Regarding "A more detailed list of the equations and calibration process could also be included in Supplementary Information for transparency.", we have further updated the table with model equations by adding necessary references to each equation and one more table to illustrate the model parameters as well as the parameter ranges. Since the model equations and parameters are important to a study on model development, we have retained these two tables in the main text of the manuscript. In addition, the calibrated parameters will be uploaded as supplements in terms of netCDF files.

Authors' change in the manuscript.

Page 20, Line 26: The following paragraphs are inserted
RZWS has a close link to the total evaporation, as RZWS represents the available water that plants can use. In this section, the performance of WAYS in evaporation simulation is evaluated against the FLUXNET2015 data. FLUXNET2015 is a global network of micrometeorological flux measurement sites that measure the exchange of CO_2, water vapor and energy between the biosphere and the atmosphere (Pastorello et al., 2017). The tower-measured latent heat flux (LF, W/m^2) is converted to ET (mm/day) using the proportionality parameter between energy and depth units of ET (Velpuri et al., 2013) as follows:

$$ET = \frac{LE}{\lambda}$$

The results are shown in Figure S15. The background is the annual averaged evaporation from WAYS for the period 1971-2010. The points indicate the comparison results between the flux tower and WAYS simulation. The locations of the points indicate the locations of the flux towers, and the colors indicate the correlation coefficient. WAYS is found to have relatively better performance in America, Europe and China than in Africa and Australia.

However, a few stations near the boundary of America and Europe also show weak correlations between the simulations and flux tower data.

Figure S16 shows the percentage of data points within different intervals of the correlation coefficient. The calculated correlation coefficient is crowded in the interval of 0.6-0.8, while more than half of the stations (56%) show a correlation coefficient of more than 0.6. The relatively poor performance of the model in some regions could be partially explained by the following reason. FLUXNET2015 corresponds to point-based observation data, while WAYS simulates the evaporation on grid cells with a 0.5 degree spatial resolution. For the comparison, the model simulation in a certain pixel is selected based on the distance between the flux tower and the center of the pixel. The model simulation actually represents an averaged value for a 0.5 x 0.5-degree pixel. This averaging will inherently introduce errors when comparing the simulation to station-based data. Similar results are also found in other studies comparing FLUXNET2015 data to either model simulations or remote sensing-derived evaporations (Lorenz et al., 2014; Velpuri et al., 2013).

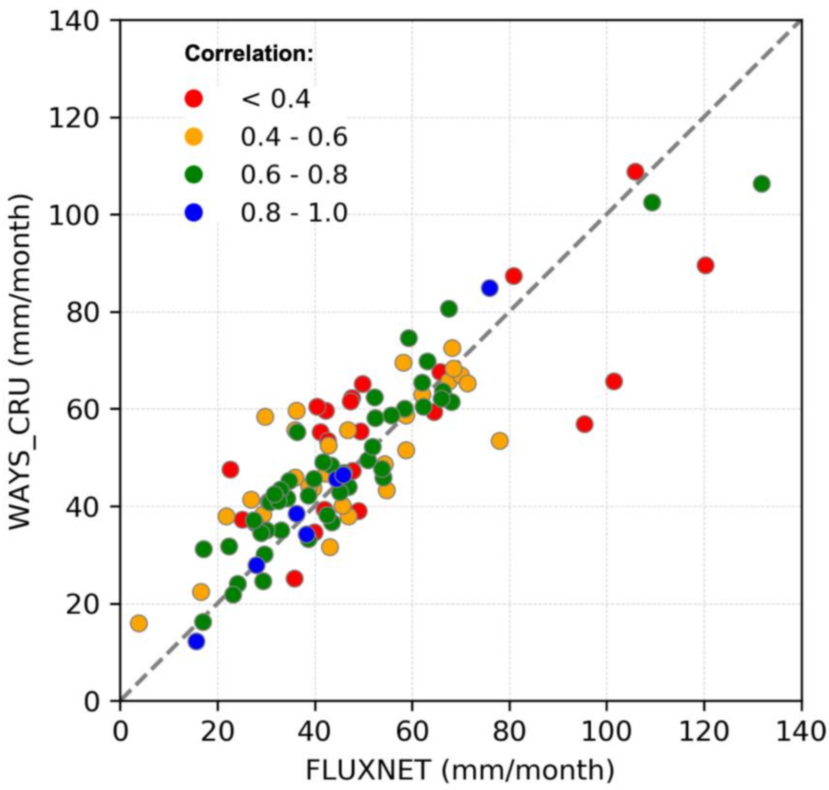

Figure 6. Averaged monthly evaporation of WAYS simulation (WAYS_CRU) against the FLUXNET data.

Furthermore, the average monthly evaporation is compared to the FLUXNET2015 data at each flux tower, and the results are shown in Figure 6. Good correspondence between the model simulation and flux tower data can be found by visual inspection. The points with a higher correlation coefficient show a better relationship between the model simulation and flux tower observation and are distributed closer to the diagonal. The evaluation results confirm the generally good performance of WAYS in monthly evaporation simulation. The detailed results on evaporation evaluation against FLUXNET2015 are provided in the SI as Excel files. In addition, an evaluation of the evaporation simulation is further conducted against LandFluxEVAL, a merged benchmark synthesis product of evaporation at the global scale (Mueller et al., 2013). The results can be found in the SI.

The following part is put in the SI.
The model simulation is further compared to a gridded data set, LandFluxEVAL data, for evaporation evaluation. The LandFluxEVAL data are a merged benchmark synthesis product of evaporation on a global scale and a combination of land-surface model simulations, remote sensing products, reanalysis data and ground observation data (Mueller et al., 2013). The LandFluxEVAL data are used in many studies as reference data for evaporation evaluations (Lorenz et al., 2014; Martens et al., 2017; Wartenburger et al., 2018). Since the LandFluxEVAL data are only available at 1-degree spatial resolution, the WAYS simulated evaporation is aggregated to 1 degree to match the resolution of the reference data. The evaluation is executed for 1989-2005 based on the availability of the LandFluxEVAL data. For the spatial evaluation, the WAYS simulation based on RZSC ($S_{R,CRU-SM}$) is used due to the global coverage of the RZSC product. For latitudinal comparison, both runs of WAYS simulated evaporation are used.

A promising relationship between WAYS simulated evaporation and LandFluxEVAL evaporation is found both in spatial pattern and in latitudinal average (see Figure S9). The generally high correlation coefficient (Figure S9, a) confirms the good performance of the WAYS model. However, relatively poor performance is also found in some regions in Europe, North America and South America (Amazon basin). It can also be seen that the spatial pattern of WAYS simulated annual averaged evaporation follows that of LandFluxEVAL data, while overestimations are found in regions, e.g., the Amazon basin and southeast Asia. The latitudinal evaluation shows that both WAYS simulations (WAYS_CRU and WAYS_CHIRPS) display a slight overestimation.

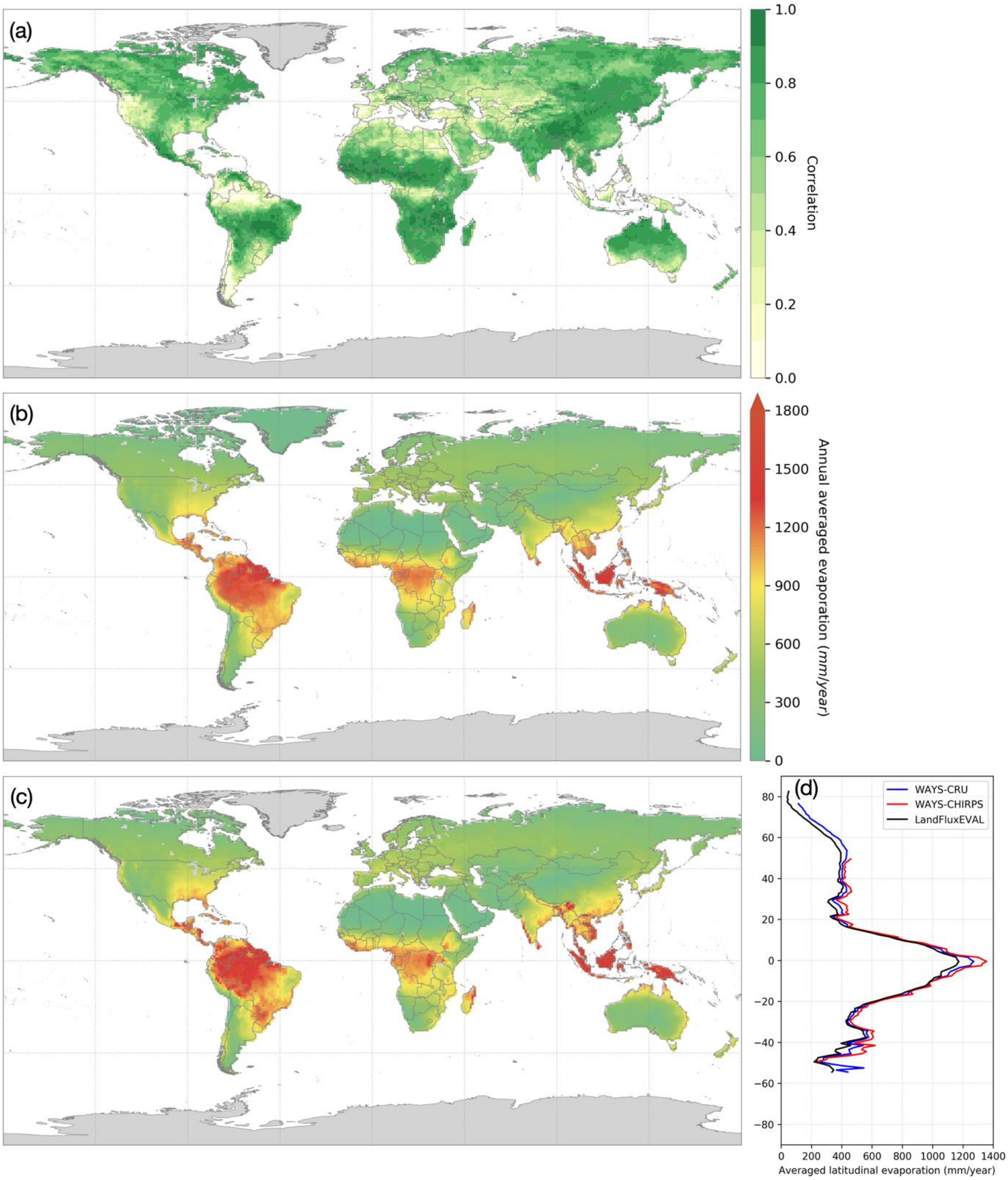

Figure S9. Validation results of the evaporation of WAYS simulation against the LandFluxEVAL data (1989-2005). (a) The calculated correlation coefficient between LandFluxEVAL data and WAYS simulation, (b) the annual averaged evaporation of LandFluxEVAL data, (c) the annual averaged evaporation of WAYS simulation based on RZSC $S_{R,CRU\text{-}SM}$, and (d) the comparison of the averaged latitudinal evaporation for WAYS model runs as well as the LandFluxEVAL data.

#6 Wang-Erlandsson et al., 2016 found that normalizing the root zone storage capacity using the Gumbel distribution by land cover type further improves performance, and recommended the use of Gumbel distribution. Please consider applying the Gumbel normalization to the root zone storage capacity data.

We incorporate the suggestion in the revised manuscript. We have now updated the RZSC data based on the Gumbel normalization. The optimized RZSC is calculated based on the suggested return period for each land cover by Wang-Erlandsson et al. (2016). Figure shows the flow chart of updating the RZSC data based on the Gumbel normalization with a different optimized return period. Since RZSC is a key parameter in the WAYS model, the model is recalibrated, and the simulations are also updated accordingly due to the change of RZSC.

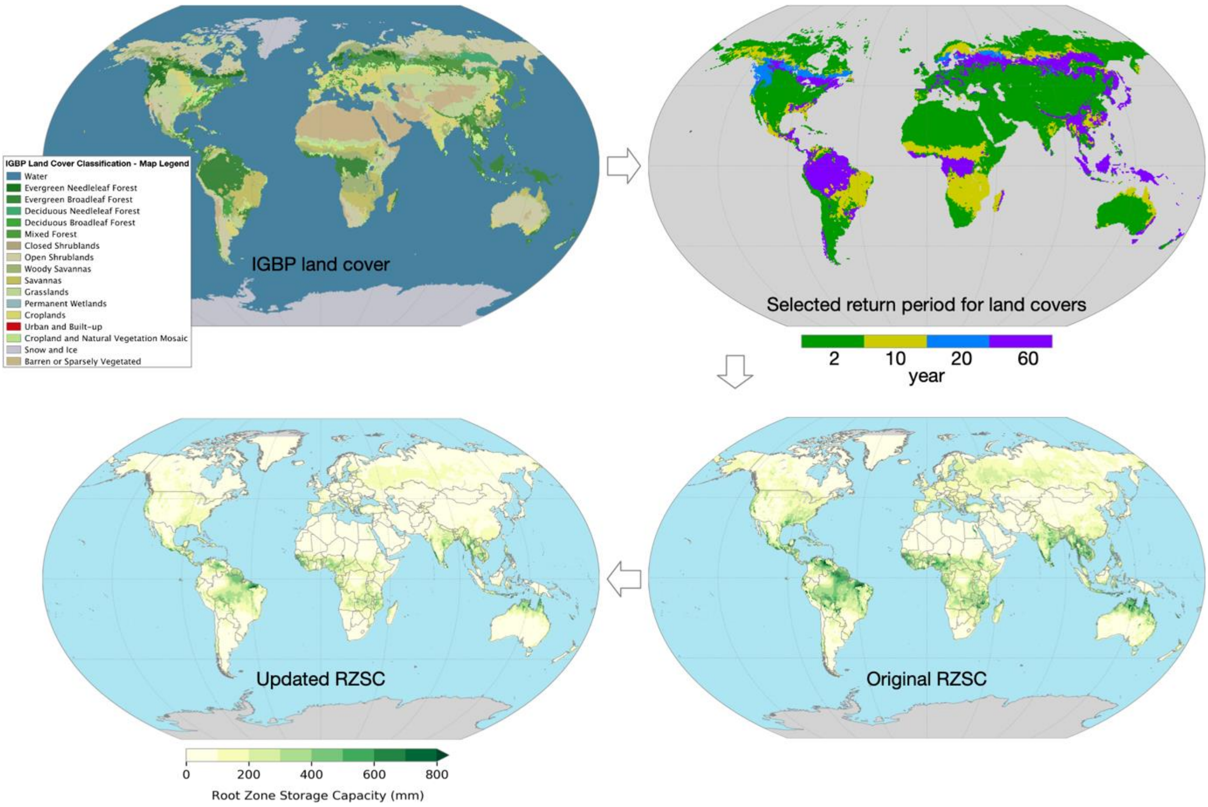

Figure 1. Flow chart of updating RZSC based on the Gumbel normalization

Authors' change in the manuscript.

Page 10, Line 15: (the changes are marked as blue)

Since Wang-Erlandsson et al. (2016) suggested that a Gumbel normalization of RZSC by land cover types with different return periods could further improve the model performance, we have accordingly adjusted the RZSC in this study. The two selected global root zone storage capacity products are shown in Figure S13, and their mean latitudinal values are shown in Figure S14.

#7 Please consider discussing how and where the results might be influenced by groundwater access and irrigation, noting that the root zone storage capacity in Wang-Erlandsson et al., 2016 was adjusted for irrigation but not access to groundwater, while WAYS do not account for either groundwater or irrigation.

Thank you for the comment. Indeed, the WAYS model does not consider the groundwater access and irrigation at the current stage. Although the capillary module is included in

WAYS, it is currently disabled due to the lack of information on the global groundwater table. The same strategy is also applied in other works, especially for hydrological simulation on the global scale (Döll et al., 2003; De Graaf et al., 2015; Hanasaki et al., 2018). Based on the experimental test on the capillary module, activation of the capillary module without groundwater information for capillary flux constrain is found to significantly increase the simulated evaporation. Nevertheless, ignorance of the capillary rise and irrigation are shortcomings of our study. This issue is now discussed in the revised manuscript.

Authors' change in the manuscript.

Page 25, Line 4: The following paragraph is inserted in the discussion part
Moreover, the current study does not consider the groundwater access and irrigation mainly due to the lack of global information. The groundwater table information is crucial for capillary rise simulation (Vergnes et al., 2014). Capillary rise simulation without proper water table information could significantly overestimate the evaporation. Thus, the capillary rise flux is ignored in this study. A similar strategy has also been applied by other works due to the absence of the information on the global water table (Döll et al., 2003; De Graaf et al., 2015; Hanasaki et al., 2018). Observations of irrigation on the global scale are also not available (Leng et al., 2015). Although there are simulated irrigation data available on the global scale, the inherent uncertainties could be propagated in our model simulation. Therefore, irrigation is also not considered at this time. However, this neglect could potentially introduce biases into the model simulation in irrigated areas and deep rooted plant-distributed regions, as both irrigation and capillary rise are an additional supply of soil water recharge. The biases may cause an underestimation of evaporation, especially in the dry summertime (Vergnes et al., 2014). This underestimation could consequently affect the simulation of RZWS and runoff because of the interlinkage of these three elements (Rockström et al., 1999). It is found that ignoring the capillary rise could reduce soil water content in the root zone (RZWS), while the runoff will also be reduced (Vergnes et al., 2014). However, these shortcomings can be simply overcome once the global data are available.

#8 Please provide the source code, and not only by request.

Thank you for the suggestion. We will make the code of the WAYS model, including all the parameters, freely available after the manuscript is accepted.

Specific comments

1. **P1L10: state what was used for evaluating root zone storage (i.e., NDII) in the abstract.**

Thank you. The reference data for RZWS evaluation is stated in the abstract.

Authors' change in the manuscript.
Page 1, Line 10: (the changes is marked as blue)

The results show the ability of the model to mimic RZWS dynamics in most of the regions through comparison with proxy data, the Normalized Difference Infrared Index (NDII).

2. **P1L10: "many applications": please provide concrete examples**.

Thank you. It is addressed accordingly.

Authors' change in the manuscript.
Page 1, Line 11: (the changes is marked as blue)
Compared to existing hydrological models, WAYS's ability to resolve the field-scale spatial heterogeneity of RZSC and simulate RZWS may offer benefits for many applications, e.g., agriculture and land-vegetation-climate interaction investigations.

3. **P1L11: "attention needs to also. . .": hardly the most important limitation, please consider rather listing the more pressing future model developments needs and emphasize the key contribution of this model in comparison to other existing global hydrological models.**

Thank you. We have incorporated the suggestion of the referee and have emphasized the key contribution of this model in comparison to other existing global hydrological models. We have further listed the pressing future research needs in the abstract accordingly.

Authors' change in the manuscript.
Page 1, Line 11: (the changes is marked as blue)
Compared to existing hydrological models, WAYS's ability to resolve the field-scale spatial heterogeneity of RZSC and simulate RZWS may offer benefits for many applications, e.g., agriculture and land-vegetation-climate interaction investigations. However, the results from this study suggest an additional evaluation of RZWS is required for the regions where the NDII might not be the correct proxy.

4. **Please point out that Sriwongsitanon et al. (2016) is a study in a river basin in Thailand and not a global study.**

Thank you. It is addressed accordingly.

Authors' change in the manuscript.
Page 2, Line 26: (the changes is marked as blue)
Recently, Sriwongsitanon et al. (2016) investigated the relation between root zone water storage and the Normalized Difference Infrared Index and found a promising correspondence between them in a river basin in Thailand, especially in the dry seasons, where water stress exists. However, a global scale study has been absent in the literature.

5. **P6L27 "no information is available at the global scale": Please consider including a few more lines describing the issues related to capillary rise modelling in global scale models and include related references, such as (Vergnes, Decharme, and Habets 2014) and references within.**

Thank you. It is addressed accordingly.

Authors' change in the manuscript.
To avoid repetition, please to see the changes in response to comment 7

6. **P8L28, "it has been well-justified (de Boer-Euser et al., 2019)": please consider specifying what is justified and add other relevant sources, e.g. "the method has been shown to increase model performance at both basin and global scale (e.g., de Boer-Euser et al., 2016, 2019, Gao et al. 2014, Wang-Erlandsson et al., 2016, Nijzink et al., 2016)".**

Thank you. It is addressed accordingly.

Authors' change in the manuscript.

Page 9, Line 28: (The changes are marked in blue)
This method has been well justified (de Boer-Euser et al., 2019) and overcomes the shortcomings of the traditional methods (look-up table approach; field observation-based approach) at the global scale, such as data scarcity, location bias, and risks of unlikely vegetation and soil combinations due to data uncertainty (Feddes et al., 2001). The method has been shown to increase the model performance at both the basin and global scales (Gao et al., 2014b; Nijzink et al., 2016; Wang-Erlandsson et al., 2016). Moreover, it has been proven to be able to produce plausible root zone storage capacity in boreal regions by investigating the relationship between RZSC and numerous environmental factors, including climate variables, vegetation characteristics, and catchment characteristics (de Boer-Euser et al., 2019).

7. **P14L11, "reported in his work": please change to "reported in their work".**

Thank you. It is corrected.

8. **P22L6 "DNII", should be NDII.**

Thank you. It is corrected.

References
Vergnes, J.-P., B. Decharme, and F. Habets. 2014. "Introduction of Groundwater Capillary Rises Using Subgrid Spatial Variability of Topography into the ISBA Land Surface Model." Journal of Geophysical Research: Atmospheres 119(19): 11,065-11,086.

Cited in the revised manuscript.

All the references are included in the manuscript.

We would like to thank William Chris for his interest in this topic and for the comments to improve our manuscript. Based on the comments some calculations have been performed. Our point-by-point response to the comments is given in the following (**Comments in black**, Answers in blue and the content related to the changes in the revised manuscript are marked in orange.):

This study tries to develop a 'global' hydrological model. The authors are lack of good understanding on hydrological processes, and the methodology they used are not appropriate at all. The authors overclaimed their contribution. The manuscript is poorly written. Some of the figures are not clear. The current manuscript cannot be accepted, and should be returned to the authors to make it a better work.

Thank you for the comment. In this work, we have extended a widely used lumped model, FLEX, into a distributed model that can be used on a global scale. In addition, a climate-derived root zone storage capacity (RZSC) is integrated into the developed model WAYS to capture the spatial heterogeneity of the rooting systems. We demonstrate the benefit of a climate-derived RZSC to the hydrological model for simulation, especially the capacity of root zone water storage (RZWS) simulation. Thus, we believe the methodology we have used is appropriate and that the hydrological processes conceptualized in WAYS are proper. Based on the comments from the three referees as well as from the short comments, we have further improved the manuscript text as well as the figures and tables.

My comments are as below: 1. The methodology used are not appropriate at all. The authors compared their runoff simulation against some global model simulation and composite runoff data. We all know the global runoff simulation/composite runoff data are designed for global studies, and can have very large uncertainty on each river basin. They cannot use these data to verify their simulation, especially for a study aiming to develop a 'new model'. Thus, the comparison between the authors' simulation and other runoff data that the authors used means nothing: the authors cannot claim their model is good. The authors should compare their simulation against hydrological gauge observation which is not difficult to collect at all. I doubt the authors' results. They may choose to avoid the comparison against hydrological gauge observation purposely because their model is suffering fatal flaws. For a paper developing a hydrological model, comparison against in situ gauge observation is extremely important. The authors should not skip this step. In addition, the authors compare their runoff simulation after calibrating their model, whereas the other models in ISIMIP are not calibrated. Thus, the comparisons are useless because the models in ISIMIP have large uncertainty which have already been unrevealed in several recent studies by the ISIMIP group (perhaps the authors missed these very important publications).

Thank you. In fact, the simulated runoff of WAYS is first compared to the reference data ERA-Interim/Land runoff. The performance of WAYS in runoff simulation is evaluated based on the comparison between ERA-Interim/Land data and WAYS simulation.

Since WAYS uses the same driving data as the ISIMIP2a models and the ISIMIP2a simulations are widely discussed in many studies, an additional comparison between WAYS and the

ISIMIP2a models can provide added-value for evaluating our model. Therefore, the ISIMIP2a simulations are also shown in the results section together with the ERA-Interim/Land data. We do mention the purpose of inclusion of the ISIMIP2a simulations in the results (page 13, line 15: "Since WAYS uses the same driving data as the ISIMIP2a models and the ISIMIP2a simulations have been widely discussed in many studies (Schewe et al., 2014; Müller Schmied et al., 2016; Gernaat et al., 2017; Zaherpour et al., 2018), we also perform a comparison between WAYS and the ISIMIP2a models to further evaluate our model."). However, this is not mentioned in the validation strategy section of the manuscript. We have now further clarified this issue in the revised manuscript (please see "Authors' change in the manuscript.").

Indeed, the ISIMIP2a models are not calibrated. We have mentioned this issue in the manuscript (page 13, line 30: This result occurs partly because some of the ISIMIP2a models are not calibrated at all (Zaherpour et al., 2018), whereas WAYS is calibrated to a Composite Monthly Runoff data set that assimilates the monitored river discharge (Fekete et al., 2011).). We have revised the captions of the related figures (Figures 2 and 3 in the revised manuscript) to note this issue.

To enhance the validation part of this manuscript, we have additionally evaluated our results with observed discharge from the Global Runoff Data Centre (GRDC). Since WAYS does not currently have a native runoff routing module, a third-part runoff routing tool, CaMa-flood, is applied to route the WAYS simulated runoff (Yamazaki et al. 2011). Given that the manuscript is already quite extensive, the discharge comparison is not a direct evaluation of WAYS but of both WAYS and CaMa-Flood. This information has been added in Supplementary Information (SI). Since this comment shares the similar opinion with Referee #3 (comment 2), we would like to refer to the responses to the comments of referee #3 to avoid repetition, as the response is long. The corresponding revision to the manuscript can also be found there.

Authors' change in the manuscript.

Page 11, Line 5: (the changes is marked as blue)

In this study, the ERA-Interim/Land runoff data are used for validation of the runoff simulation, and the Normalized Difference Infrared Index (NDII) is used for the validation of the WAYS model for root zone water storage simulation. Considering the time period of coverage of both data sets (ERA-Interim/Land: 1979-2010, NDII: 2000-present) and the study period (1971-2010) of this work, the period 2001-2010 is selected as the validation period. For runoff evaluation, ISIMIP2a simulations are also included, as they use the same climate forcing as our study in the same period. The purpose of inclusion of the ISIMIP2a simulations for comparison can be found in the model evaluation section (see Section 4).

2. The authors are lack of basic knowledge about remote sensing. The root zone can be more than 10 meters in depth. The sensors used in the NDII studies cannot penetrate the earth ground up to 10 meters, and even one or two meters are suffering large uncertainty because the attenuations of signals with increase in depth. This is why the most state-of-

the-art soil moisture products just provide data in the surface 5/10 cm. Thus, the comparison against NDII based data is not appropriate at all. Because this paper is to develop a model, the authors should use in situ observation which is not difficult to collect. I don't understand why the authors choose to skip the comparison against gauge observation.

Thank you for the comment. As we stated in the manuscript (page 2, line 8 in the revised manuscript), remote sensing itself can only detect the soil water in the surface layer. However, NDII is not a direct observation from the satellite but a Normalized Difference Index, similar to NDWI, NDVI, and so on. It is calculated based on infrared reflectance (NIR) and shortwave infrared reflectance, and it reflects the water stress in the root zone layer and, thus, can be used as proxy data for RZWS rather than RZWS itself. The NDII-related information is interpreted in detail in Section 3.3.2 in the manuscript.

We do not compare the situ observations because there are no observations available for RZWS (Sriwongsitanon et al., 2016). The observation you mentioned is probably the soil moisture at a certain depth, which differs from RZWS.

3. The authors do not have a good understanding on hydrological processes. i). Vegetation plays a vital role in runoff variations especially in densely vegetated regions (e.g., the Amazon, Congon and some regions in the Yangtze, Mekong, Ganges, Mississippi Rivers et.al.) through the transpiration processes. At the leaf and canopy scales, the mechanisms of transpiration are also different. LAI, fPAR, CO2, wind, solar radiation, stomatal conductance all are influencing transpiration. The authors did not consider the stomatal influence at all (as shown in the Figure 1 and Table 1). Without comprehensively considering the transpiration processes, how the model developed can predict water resources availability, especially many recent studies have unravelled that the earth is greening and CO2 concentration is increasing. Thus, the model developed by the authors has fatal flaws, and this paper cannot be accepted.

Thank you for the comment. We agree with the reviewer that vegetation plays a vital role in runoff variations, especially in densely vegetated regions, and the mechanisms of transpiration are also different at the leaf and canopy scales. However, the model we developed in this study is a conceptual hydrological model with a conceptualized structure to mimic the hydrological cycle. This design differs from land surface models, dynamic vegetation models or physically based hydrological models, which could have more functions with physical meanings (Bierkens, 2015). The conceptual hydrological model, however, has its own advantages in practicability and computation efficiency (Devia et al., 2015). The transpiration is of course considered by conceptual models, while some of them calculated the total evaporation without separating the evaporation into different fluxes. Moreover, conceptual models are widely applied for water related applications, e.g., runoff simulation and water scarcity analysis, especially on a global scale (Döll et al., 2003; Döll and Fiedler, 2008; Hanasaki et al., 2008; Wang-Erlandsson et al., 2014). Thus, a well-developed conceptual model, such as WAYS, should be proper for predicting water resource availability.

In addition, the continuous greening of the earth as well as the increased CO_2 concentration are indeed important issues. However, they are beyond the scope of this study as they are more related to climate change analysis.

ii). The infiltration capacity of soil plays an important role in controlling the volume of surface runoff and subsurface runoff, and also influences root zone water storage. The infiltration capacity of soil is related to soil type, and has clear physical meaning. The authors considered the infiltration as shown in the Figure 1. However, the authors did not report how they determine this important parameter value. If the authors used the values related each soil type, they did not report which soil map distribution data and which hydraulic property datasets of the soil types are used. If the authors calibrated the parameter values, the authors should be aware of that if it is appropriate to calibrate because the results may be wrong after calibrating some parameters with clear physical meaning. The authors are afraid of reporting the calibrated parameter values and the parameter ranges used in the calibration. The authors stated they calibrated their model for good runoff simulation. I am afraid that they calibrated their model for good runoff simulation with the cost of losing the physical meaning of important parameters. Perhaps the authors choose to not show the important information purposely in order to get their paper published. No, absolutely no. The authors have to show which parameters are calibrated, the parameter ranges used in calibration and calibrated parameter values.

Thank you for the comment. The precipitation partitioning function in the WAYS model is based on a widely used beta function of the Xinanjiang model (Zhao, 1992). It is a conceptualized runoff generation function that consists of empirical parameters. The model is a conceptual model and is different from the physically based model. The model parameter must be calibrated before simulation. Indeed, the physically based model is usually run without calibration as the parameters it uses have corresponding physical meanings. However, the physical model and conceptual model are two different methods without any conflicts between each other.

Moreover, we have added a table to illustrate the parameters used as well as the parameter ranges if calibration is needed. Please refer to the changes in the revised manuscript (page 11, Table 2). We will share the calibrated parameters together with the code for the model after the paper is accepted for publication.

Since the calibrated parameters are spatially distributed and are not appropriate to show in tables, we provide the spatial patterns of two key parameters (β, C_e) that are calibrated, as these two parameters mostly affect the partitioning of precipitation (see Figure S21 and Figure S22). The rest of the calibrated parameters are uploaded to the response thread in a netCDF file as a supplementary document.

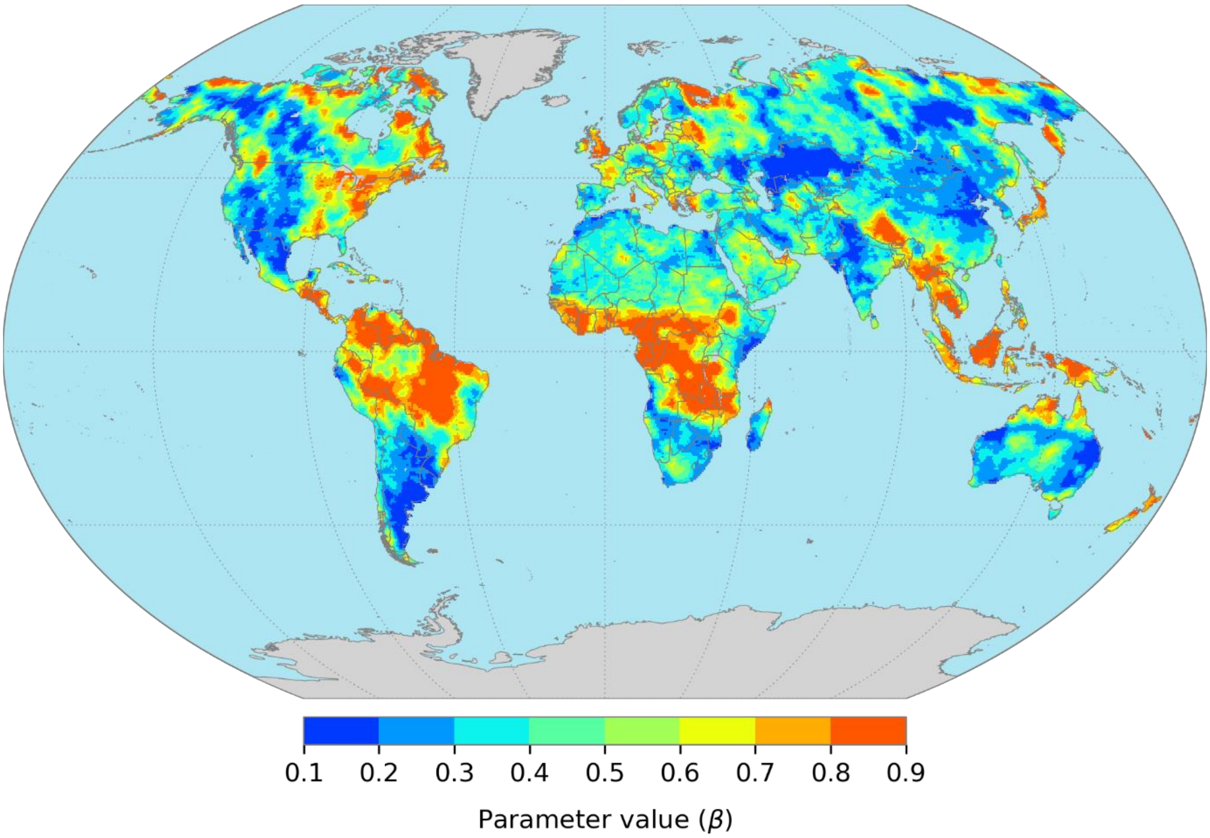

Figure S21. The spatial distribution of the model parameter β

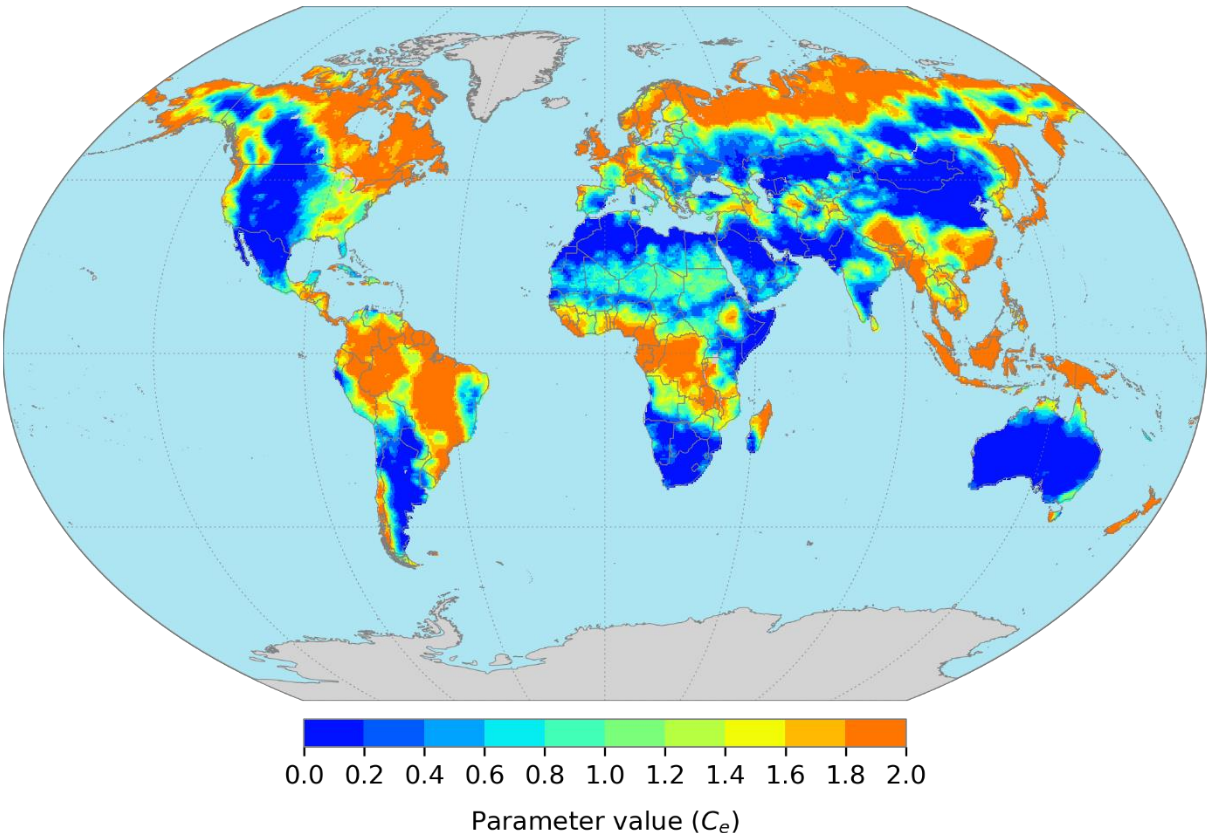

Figure S22. The spatial distribution of the model parameter C_e

Authors' change in the manuscript.

Page 12: (the following table is added)

Table 2. Parameter ranges of the WAYS model

Parameter	Range	Literature	Parameter	Range
$S_{i,max}$	distributed	Wang-Erlandsson et al. (2014)	β	(0, 2)
$S_{rz,max}$	distributed	Wang-Erlandsson et al. (2016)	C_e	(0.1, 0.9)
$R_{s,max}$	7/4.5/2/5 (Sand/Loam/Clay)	Döll and Fiedler (2008)	K_f	(1, 40)
K_s	100	Döll et al. (2003)	K_{ff}	(1, 9)
f_s	distributed	Döll and Fiedler (2008)	S_{ftr}	(10, 200)
F_{DD}	distributed	Müller Schmied et al. (2014)	T_{lag}	(0, 5)
T_t	0	Müller Schmied et al. (2014)		

4. The model developed is not a global scale model at all. Because the authors did not use soil map and related soil hydraulic parameter values, the use of the model must rely on calibration to determine some of its parameter values on river basin scales. Therefore, it cannot be a global scale model. It is still a river basin scale model, and the authors just applied the model in several large-scale river basins (without any river basins in most of the regions of Canada, Europe, Middle East, Russia, Mongolia). The used river basins just cover a small proportion of global land surface.

Thank you for the comment. The WAYS model actually uses many global parameters for hydrological simulation, e.g., RZSC, land cover, DEM, digital maps of the slope, soil texture, geology and permafrost information (see page 6, line 5 in the revised manuscript).

Based on the comments from the referees as well as from the short comments, additional evaluations covering large areas are included in the revised manuscript. These include discharge comparison to GRDC observation, evaporation comparison to FLUXNET2015 and LandFluxEVAL data. The results of the discharge evaluation can be found in responses to comments of referee #3 (comment 2). For the evaporation evaluation, we would like to refer to the responses to the comments of referee #3 (comment 5) to avoid repetition, as the response is long. The corresponding revision to the manuscript can also be found there.

5. The authors claimed they used 2000 iterations to calibrate their model. However, the authors did not explain the reason. Why 2000 iterations were used?

Thank you. In fact, the number of iterations is recommended by the author of Dynamically Dimensioned Search (DDS) algorithm (Tolson and Shoemaker, 2009). We have clarified this in the revised manuscript.

Authors' change in the manuscript.

Page 13, Line 6: (the changes is marked as blue)

The criterion of fit for calibration is the Nash-Sutcliffe efficiency coefficient (NSE), and the DDS optimization algorithm is run with 2000 iterations for each grid cell for parameter estimation, as suggested by the author of DDS (Tolson and Shoemaker, 2007).

6. The root zone storage variations are related to ground water level dynamics. Did the model simulate the ground water level changes? Please show the simulation results.

Thank you. The current work did not consider the groundwater level changes as well as the capillary rise due to the lack of groundwater table information. We have discussed this issue in the revise manuscript.

Authors' change in the manuscript.

Page 25, Line 4: The following paragraph is inserted in the discussion part
Moreover, the current study does not consider the groundwater access and irrigation mainly due to the lack of global information. The groundwater table information is crucial for capillary rise simulation (Vergnes et al., 2014). Capillary rise simulation without proper water table information could significantly overestimate the evaporation. Thus, the capillary rise flux is ignored in this study. A similar strategy has also been applied by other works due to the absence of the information on the global water table (Döll et al., 2003; De Graaf et al., 2015; Hanasaki et al., 2018). Observations of irrigation on the global scale are also not available (Leng et al., 2015). Although there are simulated irrigation data available on the global scale, the inherent uncertainties could be propagated in our model simulation. Therefore, irrigation is also not considered at this time. However, this neglect could potentially introduce biases into the model simulation in irrigated areas and deep rooted plant-distributed regions, as both irrigation and capillary rise are an additional supply of soil water recharge. The biases may cause an underestimation of evaporation, especially in the dry summertime (Vergnes et al., 2014). This underestimation could consequently affect the simulation of RZWS and runoff because of the interlinkage of these three elements (Rockström et al., 1999). It is found that ignoring the capillary rise could reduce soil water content in the root zone (RZWS), while the runoff will also be reduced (Vergnes et al., 2014). However, these shortcomings can be simply overcome once the global data are available.

7. Please use scientific languages. The sub-titles of Section 2.4 and 2.5 are not appropriate in such as a scientific paper. The statements 'Fast- and Slow-' are vague.

Thank you. We have now changed the Fast- and Slow- flow to preferential flow and matrix flow based on the related literature (Ali et al., 2018; Gao et al., 2019).

Authors' change in the manuscript.
The fast flow and slow flow are replaced by preferential flow and matrix flow in the entire manuscript.

8. I agree with the reviewer 1 about the capillary mechanism which is missed by the authors. This indicates the authors are lack of good understanding on hydrological processes from another perspective. When we develop a new model, we try to incorporate new hydrological mechanism to advance our understanding on hydrological processes. However, the authors missed several very important hydrological processes which have already been recognised to be very important. Therefore, the 'developed' model cannot provide any new understanding on hydrology to us. I am afraid that the authors just copy other models' code, delete several important parts, replace a few equations and change computer language used in original code, and then the authors claim they develop a new model. No, this is not the right way to do research. I also wonder why the authors delete the capillary mechanism part from the original code. The authors should realize that they cannot just delete some codes of other's model, and make it look like a 'new model' in order to get the manuscript published. This is not real science. The authors must work hard to consider the capillary and vegetation transpiration mechanisms and using gauge data to validate their simulation. Otherwise, their model cannot be better (based on the physical processes considered) than other hundreds/thousands of models that already exist.

Thank you. In fact, WAYS does include the capillary module from Gao et al. (2014a), a key publication on the FLEX model. At the current stage, it is, however, disabled due to the lack of global information on the groundwater table. A detailed explanation could be found in the responses to comment 6 of referee #1. The corresponding revision in the manuscript can also be found there.

9. The manuscript is poorly written and needs to be largely reworked. There are many typos and grammar mistakes. Many sentences are vague and lack of support. The figures are not clear, e.g., Figure 4 and Figure 5, and one cannot distinguish the lines.

Thank you. We have carefully checked the manuscript and corrected typos and grammatical mistakes. The revised manuscript has been edited by a professional academic language and manuscript service company. We have also further improved the manuscript as well as the figures and tables. Figure 4 and Figure 5 are reproduced with high resolution, and the lines are clearer now. Since short comment 10 suggested us to move some figures from the main text of the manuscript. Thus, the figures in the revised manuscript are re-sorted.

10. Figure 2 is not your result. Please remove Figure 2. Using related references in the manuscript to refer to the data is ok.

Thank you. Indeed, Figure 2 shows the spatial distribution of RZSC, which is obtained from Wang-Erlandsson et al. (2016). Since it a key parameter for the model we developed and spatial distribution information would be useful, we have move them to SI rather just placed them in the references. In addition, Figure 3, which shows the latitudinal averaged RZSC, has also been moved from the main text of the manuscript to SI, as it is also based on the results from Wang-Erlandsson et al. (2016).

It is also important to note that the RZSC is now updated based on the comment of Referee #3. Referee #3 suggested that RZSC should be updated by applying the Gumbel normalization, as Wang-Erlandsson et al. (2016) found that normalizing the RZSC using the Gumbel distribution by land cover type further improves performance.

Authors' change in the manuscript.
The Figures 2 and 3 are moved to the SI.

All the references are included in the manuscript.

We would like to thank Astrid Kerkweg, the Executive editor of GMD, for his constructive comments on our manuscript regarding to the basic requirements of papers submitted in GMD. Our point-by-point response to the comments is given in the following (**Comments in black**, Answers in blue and the content related to the changes in the revised manuscript are marked in orange.):

Dear authors,
in my role as Executive editor of GMD, I would like to bring to your attention our Editorial version 1.1:
http://www.geosci-model-dev.net/8/3487/2015/gmd-8-3487-2015.html
This highlights some requirements of papers published in GMD, which is also available on the GMD website in the 'Manuscript Types' section:
http://www.geoscientific-model-development.net/submission/manuscript_types.html
In particular, please note that for your paper, the following requirements have not been met in the Discussions paper:

Thank you for the notes. We have carefully read the information of Editorial version 1.1. We will follow the requirements of papers published in GMD.

1 "The main paper must give the model name and version number (or other unique identifier) in the title."// Accordingly, add the acronym WAYS including a version number to the title.

Thank you. We have changed the title accordingly.

Authors' change in the manuscript.
The title of the manuscript is changed from
"A hydrological model for root zone water storage simulation on a global scale"
to "WAYS v1: A hydrological model for root zone water storage simulation on a global scale"

2 GMD is encouraging authors to upload the program code of models (including relevant data sets) as a supplement or make the code and data of the exact model version described in the paper accessible through a DOI (digital object identifier). In case your institution does not provide the possibility to make electronic data accessible through a DOI you may consider other providers (eg. zenodo.org of CERN) to create a DOI. Please note that in the code accessibility section you can still point the reader how to obtain the newest version.

If for some reason the code and/or data cannot be made available in this form (e.g. only via e-mail contact) the "Code Availability" section need to clearly state the reasons for why access is restricted (e.g. licensing reasons). Consequently, you need to provide a reason in the code availability section, why the code can not be made publicly available. Without a proper reason, it is not acceptable that the code is not made public available before the final publication of the article.

Thank you for the comment, we will make the code including the parameters public accessible.

We would like to thank H.M. Jones for his interest in this topic and for the comments to improve our manuscript. Based on the comments some calculations have been performed. Our point-by-point response to the comments is given in the following (**Comments in black**, Answers in blue and the content related to the changes in the revised manuscript are marked in orange.):

1. After reading the manuscript, I do not think the results can support the research objective. First, the WAYS is calibrated and the runoff simulation is compared with others after that. Therefore, the better performance of WAYS (let's assume it is better first, and actually I do not think so) could be due to the calibration, not because of the consideration of root zone water storage changes. Second, the NDII data were used as a surrogate of root zone water storage changes. The NDII is just suggested in a river basin in Thailand. However, it is still not clear if it is appropriate to do so on large scales with different climate and hydrological regimes. Therefore, the simulated root zone water storage is not actually verified.

Thank you. In fact, the simulated runoff of WAYS is first compared to the reference data ERA-Interim/Land runoff. The performance of WAYS in runoff simulation is evaluated based on the comparison between ERA-Interim/Land data and WAYS simulation. Since WAYS uses the same driving data as the ISIMIP2a models and the ISIMIP2a simulations are widely discussed in many studies, an additional comparison between WAYS and the ISIMIP2a models can provide added-value for evaluating our model. Therefore, the ISIMIP2a simulations are also shown in the results section together with the ERA-Interim/Land data.

Moreover, to investigate the impacts of RZSC on model simulation, we have additionally conducted the simulation of WAYS with the root zone storage capacity derived from uncertain root depth and soil data. The simulated results are then compared with the two runs, i.e., one with RZSC from Wang-Erlandsson (2016) and the other with uncertain RZSC. The uncertain RZSC ($S_{R,UNCERTAIN}$) is derived based on the literature values of root depth and soil texture data (Müller Schmied et al. 2014; Wang-Erlandsson et al. 2016). For details of related changes, we refer to the response to the comments of Referee #2 (comment 5) to avoid repetition, as the response is long. The corresponding revision in the manuscript can also be found there.

We agree with the reviewer that the NDII is just investigated in a river basin in Thailand, thus the evaluation could weaken the conclusions. Thus, additional evaluations covering large areas have been conducted to further strengthen conclusions. Since this comment shares the similar opinion with Referee #3 (comment 5), we would like to refer to the responses to the comments of referee #3 to avoid repetition, as the response is long. The corresponding revision to the manuscript can also be found there.

2. I also feel it is not rigorous that without in situ hydrological gauge and flux tower data to verify simulations of ET, runoff, soil moisture etc. Comparison with ISIMIP model runoff simulation is not convincing. The spatial distribution of simulation is also important. Please show the spatial distribution.

Thank you. In the revised manuscript, we have substantially improved the model evaluation by conducting additional simulations, validations and comparisons, following the comments by reviewers and the short comments. In brief, we have compared the discharge with GRDC observations and evaluated evaporation simulation against FLUXNET2015 and LandFluxEVAL data. Please refer to our responses to comments 2 and 5 of Reviewer 3 for details.

Regarding the comment on comparing our model simulation with soil moisture, we have stated in the manuscript (page 2, line 16: However, all these studies estimated the root zone soil moisture up to a certain depth, e.g., 100 cm, thus still retaining drawbacks to the accurate calculation of the water stored in the entire root zone layer. Since the root depth is location-dependent and could reach a depth of more than 30 meters (Fan et al. 2017).). The soil moisture in the top 100 cm cannot reflect the water content in the entire root zone layer. Evaluating the model performance against soil moisture would not necessarily contribute to improving the model robustness. Therefore, we did not verify the model with the soil moisture.

3. As shown in Figure 1 and the manuscript descriptions, the soil layer is separated into vadose zone (includes the root zone) and saturated zone, which is similar to many existing models. In addition, in this manuscript, the NDII is not justified to represent root zone water storage changes on large scales with different climate and hydrological regimes. Therefore, the novelty of this manuscript is not enough.

Thank you. We agree with the reviewer that NDII is not justified to represent root zone water storage changes on large scales, which could weaken the conclusions. Referee #3 shares a similar opinion in his comments. We have addressed this issue in detail in the response to the comments of Referee #3 (comment 5). The corresponding revision in the manuscript can also be found there.

4. Because the soil is separated into different zones, at every grid, each zone must have a certain depth (or a percentage value) at a moment and the depth or percentage will change with rainfall-runoff processes. The manuscript failed to report the changes of the depth of each zone or what percentage of soil is saturated/unsaturated at different time. Please also show the spatial distribution. This is important to see if the simulation is reasonable.

Thank you. One of the motivations of our work is to simulate root zone water storage on a global scale, without constraining the quantification to a certain depth. In fact, RZWS is simulated in terms of the water equivalent depth. Based on the comment, we have analyzed the spatial pattern of the simulated RZWS as well as the dynamics of RZWS in different latitudes in different months. Due to the length of the manuscript, this information has been included in Supplementary Information (SI).

The following part is put in the SI.

Figure S1 shows the spatial distribution of the annual averaged RZWS simulated by WAYS in the 1971-2010 period. It shows that RZWS is high in low-middle latitudes, while RZWS in middle-high regions is relatively low. RZWS represents the water content that is stored in the root zone as well as the available water for plants. Therefore, for lower or middle latitudes, the available water for plants is relative higher than for high-latitude areas.

To further investigate the soil water condition, we have calculated the root zone soil wetness by dividing RZWS by RZSC, and the results are shown in Figure S2. The root zone soil wetness follows the spatial patterns of RZWS in general. However, differences can also be found in regions such as Europe, South America and the eastern part of North America.

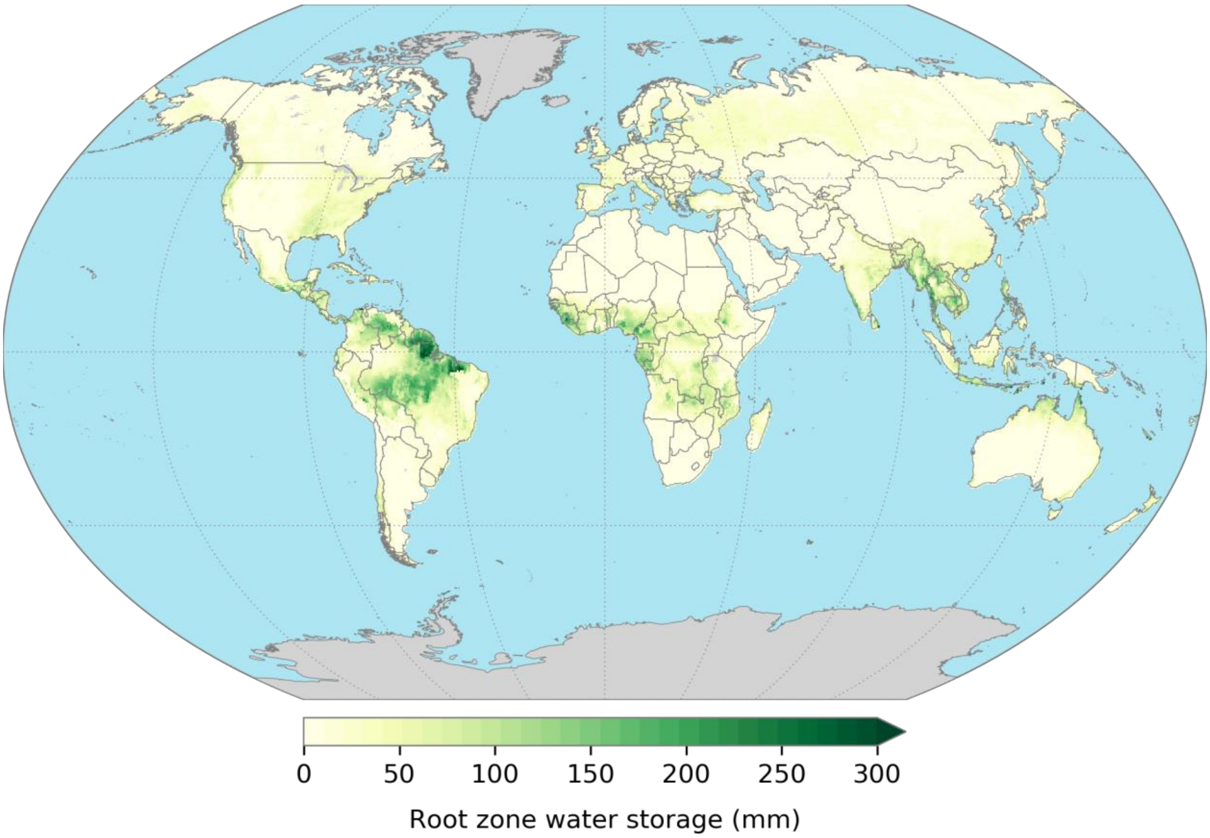

Figure S1. The spatial distribution of the annual averaged RZWS simulated by WAYS in the 1971-2010 period.

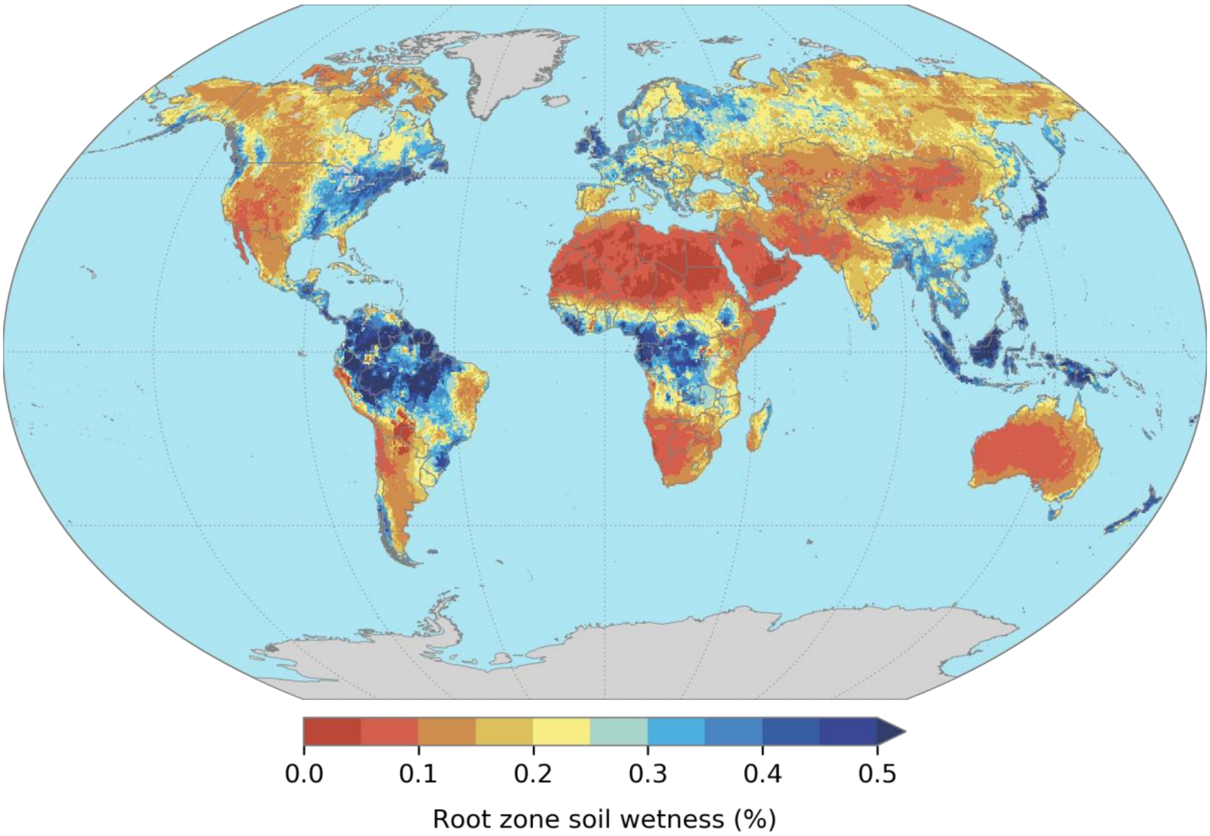

Figure S2. The spatial distribution of the annual averaged root zone soil wetness in the 1971-2010 period.

The simulated RZWS is shown in Figure S3 to reveal dynamics in different latitudes and in different months. The latitudinal averaged RZWS again confirms that the RZWS are relatively plentiful compared with the high latitudes. However, a decreasing trend can also be found by moving from a low latitude to the equator. Two simulations of the WAYS model show similar fluctuation along the latitudes, while the simulation with $S_{R,CHIRPS}$ is slightly higher. Figure S3 shows that RZWS in low-middle latitudes has a larger monthly variation than in other regions, while the Northern Hemisphere and Southern Hemisphere show opposite changing trends. In the low latitudes in Northern Hemisphere, the RZWS peak occurs in May-June and the off-peak in October-November. In the Southern Hemisphere, the RZWS off-peak occurs in May-June and the peak in October-November.

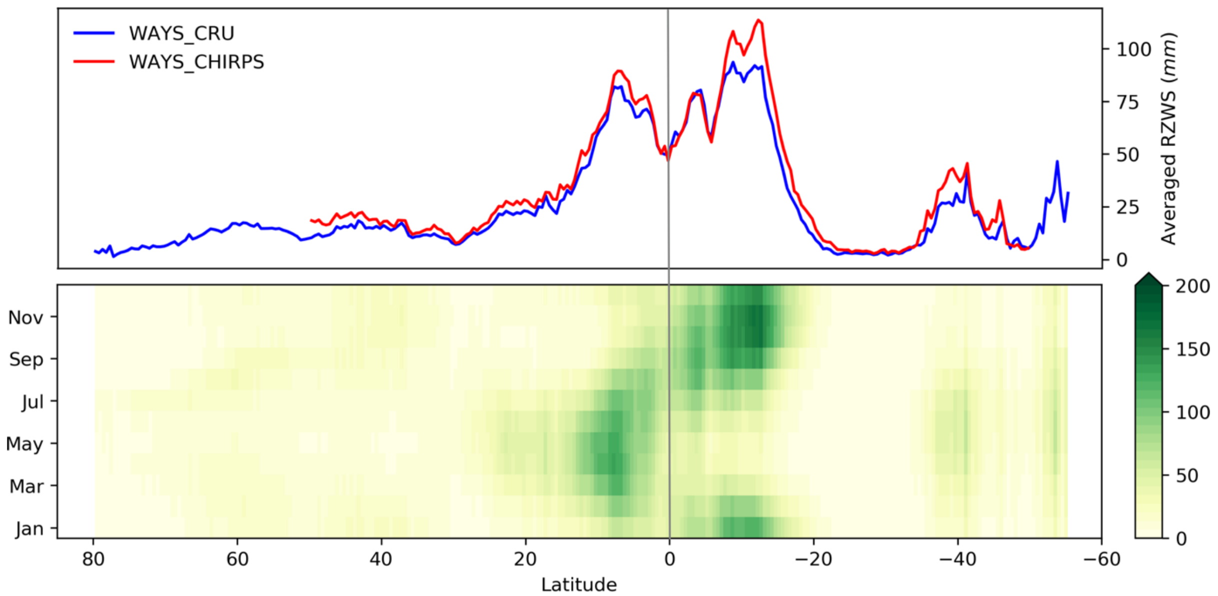

Figure S3. The dynamics of the simulated RZWS for different latitudes in different months.

5. I don't think the WAYS is a new hydrological model because it only changed several equations and replaced a few parameters compared to the FLEX model. It is not an improvement of the FLEX model either, because it removed several important components of the original FLEX model and the manuscript failed to prove that the WAYS is better compared to FLEX after doing that.

Thank you. In this work, we have extended a widely used lumped model, FLEX, into a distributed model that can be applied on a global scale. In addition, a climate-derived root zone storage capacity (RZSC) is integrated into WAYS to capture the spatial heterogeneity of the rooting systems. We have demonstrated the benefits of a climate-derived RZSC to the hydrological model for simulation, especially the capacity of root zone water storage (RZWS) simulation.

In fact, we did not remove any important components from the original FLEX model. Only the capillary module is disabled due to the lack of global information on the groundwater table. A detailed explanation can be found in the responses to the comments of Referee #1 (comment 6) and Referee #3 (comment 2). The corresponding revision in the manuscript can also be found there.

6. When I saw the root zone water storage, I thought the manuscript would study vegetation. However, I did not find how they deal with vegetation transpiration. Because root zone water storage changes are largely controlled by vegetation transpiration, I don't believe the WAYS can simulate root zone water storage changes properly without considering vegetation transpiration. I share the similar concerns as other reviewers that WAYS has fatal flaws regarding this. In addition, WAYS means 'Water And ecosYstem Simulator' according to the manuscript. Without considering vegetation transpiration, WAYS cannot represent ecosystem and cannot simulate ecosystem influence on water

either. Thus, I believe that the manuscript title, the statement in the manuscript, and the model name are misleading and not suitable.

Thank you. Like most of the conceptual models, WAYS considers the vegetation transpiration. It simulates the total evaporation, which consists of interception, soil evaporation and transpiration. A detailed list of all the model equations is shown in Table 1 in the manuscript. WAYS simulates the water stored in the root zone, which is a critical variable connecting the hydrology and ecology. Thus, the extension name of WAYS, i.e., 'Water And ecosYstem Simulator', will not mislead readers.

7. The manuscript failed to report how many parameters the model has, which parameters need to be calibrated, what are the calibrated parameter values, which parameters use default values. The physical meanings of the parameters should be reported. Some parameters have their physical meanings and cannot be calibrated.

Thank you for the comment. This comment shares the same opinion with comment 2 of Referee #1, to which a detailed interpretation and response to the comment can be found. The corresponding revision in the manuscript can also be found there.

In sum, I am not convinced by the methodology and results, and several key issues of the study objective are not solved. I feel that this manuscript should be rejected.

We have further improved our manuscript based on all the comments from referees and the short commenters. We believe that the manuscript has now been greatly improved.

All the references are included in the manuscript.

WAYS v1: A hydrological model for root zone water storage simulation on a global scale

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Abstract. The soil water stored in the root zone is a critical variable for many applications, as it plays a key role in several hydrological and atmospheric processes. Many studies have been conducted to obtain reliable information on soil water in the root zone layer. However, most of them are mainly focused on the soil moisture within a certain depth rather than the water stored in the entire rooting system. In this work, a hydrological model named WAYS is developed to simulate the root zone water storage (RZWS) on a global scale. The model is based on a well validated lumped model and has now been extended to a distribution model. To reflect the natural spatial heterogeneity of the plant rooting system across the world, a key variable that influences RZWS, i.e., root zone storage capacity (RZSC), is integrated into the model. The newly developed model is first evaluated based on runoff and RZWS simulations across ten major basins. The results show the ability of the model to mimic RZWS dynamics in most of the regions through comparison with proxy data, the Normalized Difference Infrared Index (NDII). The model is further evaluated against station observations, including flux tower and gauge data. Despite regional differences, generally good performances are found for both the evaporation and discharge simulation. Compared to existing hydrological models, WAYS's ability to resolve the field-scale spatial heterogeneity of RZSC and simulate RZWS may offer benefits for many applications, e.g., agriculture and land-vegetation-climate interaction investigations. However, the results from this study suggest an additional evaluation of RZWS is required for the regions where the NDII might not be the correct proxy.

1 Introduction

Soil moisture is one of the critical variables in earth system dynamics (Sheffield and Wood, 2008) and is claimed an Essential Climate Variable by the World Meteorological Organization due to its key role in several hydrological and atmospheric processes (Legates et al., 2011). The soil water stored in the plant root zone is of great importance in some fields of application, e.g., agriculture, as it represents the reservoir of the plant available water and mediates numerous subsurface processes (Sabater et al., 2007; Wang et al., 2015; Cleverly et al., 2016). A fundamental limiting factor that constrains crop yields is the water resources in the root zone (Tobin et al., 2017). The water stored in the root zone is also directly linked with one of the important water resources for ecosystems, i.e., green water resources, as green water is defined as the water that originates from precipitation that is stored in the unsaturated soil and eventually consumed by plants through evapotranspiration (Falkenmark and Rockström, 2006; Liu and Yang, 2010).

There are several methods for soil moisture estimation, including in situ measurements, satellite-based approaches and model simulation (Paulik et al., 2014; Dumedah et al., 2015; Colliander et al., 2017; Zhang et al., 2017; Berg et al., 2017). Especially in recent years, a variety of specific sensors and systems have been built for global soil moisture measurement, e.g., the Advanced Microwave Sounding Radiometer for Earth Observation System (AMSR-E) as well as the AMSR-2 (Njoku et al., 2003) and the Soil Moisture Ocean Salinity (SMOS) (Kerr et al., 2010) and Soil Moisture Active Passive (SMAP) missions (Entekhabi et al., 2010). These sensors are able to provide continuous estimations of soil moisture worldwide.

Obtaining reliable root zone water storage is still challenging, as it cannot be directly observed (González-Zamora et al., 2016). Satellite remote sensing itself can only detect the soil water at the surface layer (in most cases with a depth of 5 cm) and has the shortcoming that it cannot look at the deep soil profile (Petropoulos et al., 2015). Considerable effort has been made recently by researchers to retrieve root zone soil moisture (RZSM), a variable that is very close to RZWS. Tobin et al. (2017) developed an exponential filter to leverage the remotely sensed surface soil moisture to produce RZSM. Faridani et al. (2017) and Baldwin et al. (2017) applied a soil moisture analytical relationship (SMAR) model to generate RZSM, where the surface soil moisture is the input. Apart from remote sensing-based approaches, hydrological models and land surface models are important tools for moisture simulation, as they work both in the past and in future scenarios (Xia et al., 2014; Sheikh et al., 2009; Albergel et al., 2018; Samaniego et al., 2018). Additionally, many studies estimate RZSM by combining remotely sensed soil moisture with different models using data assimilation techniques (Rebel et al., 2012; Renzullo et al., 2014a, b). However, all these studies estimated the root zone soil moisture until a certain depth, e.g., 100 cm, thus still retaining the drawback of being unable to accurately calculate the water stored in the entire root zone layer. Moreover, the root depth is location dependent and can reach a depth of more than 30 meters (Fan et al., 2017).

Alternatively, RZSM can also be obtained by investigating and applying the relationship between RZSM and different vegetation indices derived from MODIS or Landsat satellites, e.g., the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) (Santos et al., 2014; Wang et al., 2007; Schnur et al., 2010; Liu et al., 2012). Nevertheless, their work either stays at a certain soil depth assuming a consistent rooting depth or estimates only the water content ratio assuming a homogeneous soil profile, rather than the water amount covering the entire spatially heterogeneous rooting system (Fan et al., 2017). To date, studies that directly focus on root zone water storage are still rare.

Recently, Sriwongsitanon et al. (2016) investigated the relation between root zone water storage and the Normalized Difference Infrared Index and found a promising correspondence between them in a river basin in Thailand, especially in the dry seasons, where water stress exists. However, the NDII is an index value that reflects only the dynamics of RZWS rather than the absolute value. Moreover, remote sensing-based approaches only allow historical analyses. While the ability to predict RZWS, usually by employing models, is still missing, which is crucial for impact studies, e.g., agricultural drought analysis (Keyantash and Dracup, 2002), the work of Sriwongsitanon et al. (2016) provided enlightenment for future RZWS-related studies, as their findings support NDII as a potential proxy for RZWS. This is critical for mitigating the major challenge, i.e., the lack of direct observation of root zone water storage for evaluation, in the field of hydrological modeling.

In this study, a global hydrological model is developed to simulate root zone water storage, a key variable for ecohydrological studies. Though many global hydrological models (GHMs) have already been developed, most of them are similar regarding the general hydrological component simulations (Sood and Smakhtin, 2015), and the developed model has its unique scheme for root zone process depiction; thus, it enables RZWS simulations with the ability to consider the global spatially heterogeneous rooting systems. The model has input requirements similar to most of the existing GHMs and can also generate general hydrological variables in addition to RZWS. Since it simulates RZWS, which is of great importance for both hydrology and ecology, it will be further developed in the future for water and ecosystem-related applications. The newly developed model is named the Water And ecosYstem Simulator (WAYS). The ultimate goal of this study is to test the feasibility of WAYS for RZWS simulation on a global scale, an added-value feature useful for many applications.

2 Model Description

2.1 General Overview

WAYS is a hydrological model implementation in Python. It is a process-based model that assumes water balance at the grid cell level. The development of WAYS is based on a lumped conceptual model with an HBV-like model structure, called the FLEX model (Fenicia et al., 2011; Gao et al., 2014a). The FLEX model has been widely used and validated at the basin scale to simulate the soil moisture content and root zone water storage (Gao et al., 2014b; Nijzink et al., 2016; de Boer-Euser et al., 2016; Sriwongsitanon et al., 2016). Benefiting from its flexible modeling framework, we have now extended it to a spatially distributed global hydrological model. In addition, some improvements have been made to increase the model capacity at the global scale, e.g., a more sophisticated soil water storage capacity strategy and more land cover support.

WAYS is a raster-based model that calculates the water balance and simulates the hydrological processes in a fully distributed way. It works on a daily time step, and the model structure consists of five conceptual reservoirs: the snow reservoir S_w (mm) representing the surface snow storage, the interception reservoir S_i (mm) expressing the water intercepted in the canopy, the root zone reservoir S_r (mm) describing the root zone water storage in the unsaturated soil, the fast response reservoir S_f (mm), and the slow response reservoir S_s (mm). Two lag functions are applied to describe the lag time from the storm to peak flow (T_{lagF}) and the lag time of recharge from the root zone to the groundwater (T_{lagS}). In addition to the water balance equation, each reservoir also has process functions to connect the fluxes entering or leaving the storage compartment (so-called constitutive functions). Figure 1 provides a schematic representation of how the vertical water balance is modeled in WAYS, and the basic equations are shown in Table 1. In Figure 1, the flowchart represents the conceptualized hydrological cycle in the model, and the schematic drawing shows the corresponding water fluxes and stocks in the real world. Since some of the fluxes are intermediate variables, they are shown in the flowchart but not visualized in the schematic drawing. For instance, R_f is the generated preferential runoff in the root zone layer before the split of the runoff into surface runoff and subsurface runoff. The effective precipitation P_e is the sum of snowmelt and precipitation throughfall. The conceptualized hydrological cycle of the model can be briefly described as follows. The precipitation that can drop as rainfall or snowfall depends on the temperature. The snowfall will be stored in the snow reservoir, and the rainfall will be intercepted by the canopy before it reaches the surface. After the interception, the rainfall penetrates the canopy and reaches the surface as precipitation throughfall. The effective precipitation that consists of the throughfall and the snowmelt will partially infiltrate into the soil, and the rest runs away as runoff. The runoff is then split into surface runoff and subsurface runoff depending on the texture. A part of the infiltration will be stored in the soil for plants, and the rest will percolate into the deep soil and reach the groundwater table as groundwater recharge. The parameters that regulate the different simulation steps are described below, and the changes we made to the original FLEX model are highlighted. The original lumped model FLEX has 28 parameters in total that consider four land use types in the basin (Gao et al., 2014a). To reduce the computation cost of calibration and avoid overfitting issues at the global scale, some calibrated parameters are replaced by the empirical values from the literature, e.g., the snowmelt ratio F_{DD}, the capacity of the interception reservoir $S_{i,max}$, the groundwater recharge factor f_s and the maximum value of groundwater recharge $R_{s,max}$.

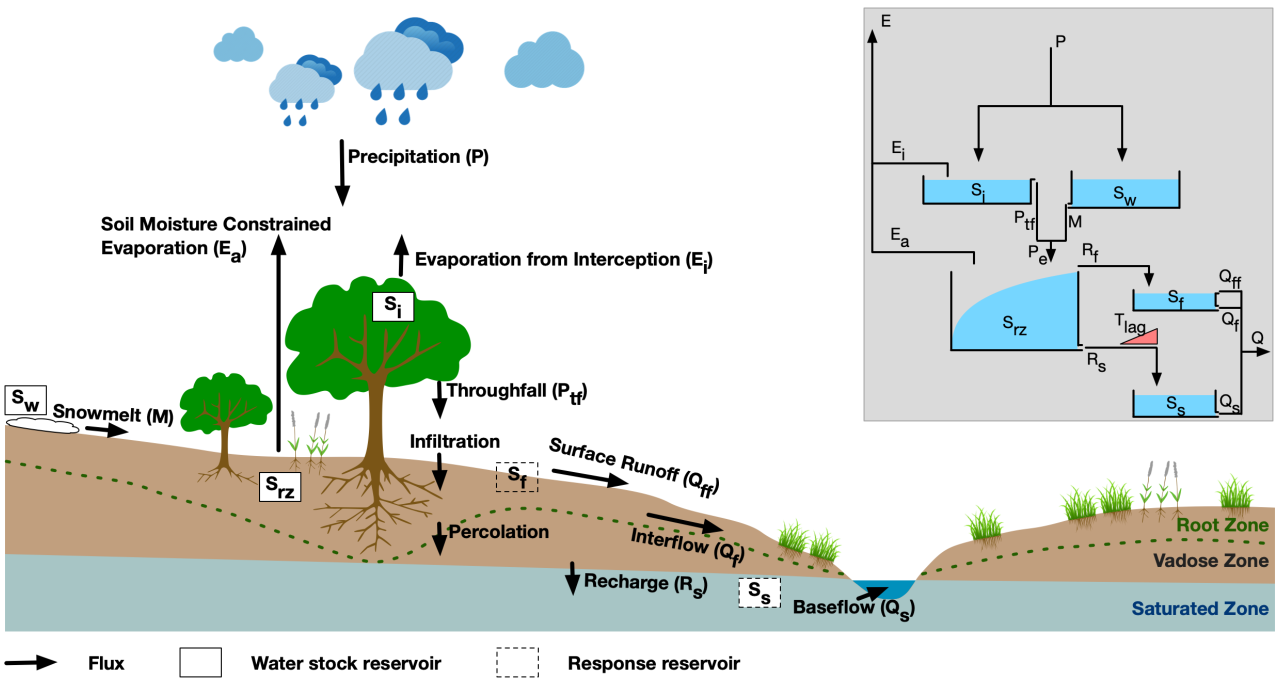

Figure 1. Model structure of WAYS

2.2 Interception and Snow Routine

In the WAYS model, the precipitation is allowed to be intercepted by the canopy or stored as snow before entering into the root zone reservoir.

Interception occurs during the days with rain when the temperature is above the threshold temperature T_t. The interception reservoir stores the precipitation intercepted by the canopy before it reaches the soil that will directly evaporate back into the atmosphere. The canopy water balance equation is shown in Eq. (1), where the precipitation P (mm/day) is the inflow, and the precipitation throughfall P_{tf} (mm/day) and the interception evaporation E_i (mm/day) are the outflows. The calculation of the precipitation throughfall P_{tf} is simply based on comparing the rainfall P_r (mm/day) to the water already stored in the interception reservoir S_i (mm) and the capacity of the interception reservoir $S_{i,max}$ (mm) (Eq. (2)). In the FLEX model, the interception evaporation E_i is assumed to be the potential evaporation, and the interception capacity is a calibrated parameter. In WAYS, the interception evaporation E_i is calculated based on the potential evaporation E_0 (mm/d), the storage of the interception reservoir S_i (mm) and the interception reservoir storage capacity $S_{i,max}$ (Eq. (3)) following Deardorff (1978). The interception capacity $E_{i,max}$ is calculated by using Eq. (4), where m_c is 0.3 mm and L is the leaf area index, which is calculated based on a modified phenology model in Jolly et al. (2005) obtained by replacing the original vapor pressure stress function with the soil moisture in the model (Wang-Erlandsson et al., 2014).

The snow simulation is based on a simple degree-day algorithm (Rango and Martinec, 1995) that has been successfully applied in hydrological models in many studies (Comola et al., 2015; Bair et al., 2016; Krysanova and Hattermann, 2017). The water balance in the snow reservoir is described in Eq. (5), and the constitutive equations are shown in Eq. (6) in Table 1. Below the threshold temperature T_t (°C), the precipitation P (mm/day) falls as snow P_s (mm/day) and is added to the snow storage S_w (mm). Above the threshold temperature T_t, snow melts if it is available at a certain ratio per degree (F_{DD}). Both the threshold temperature T_t and the snowmelt ratio F_{DD} are parameters calibrated in the FLEX model. Following Müller Schmied et al. (2014), T_t is set to 0 °C, and F_{DD} is set for different land cover classifications from 1.5 mm/d per degree to 6 mm/d per degree in WAYS. It is also important to be aware that the snowmelt water is conceptualized in the model as directly infiltrating into the soil in the model, thus effectively bypassing the interception reservoir.

2.3 Root Zone Routine

The effective root zone routine is the core of the WAYS model. It controls both the evapotranspiration and the runoff generation by precipitation partitioning. Similar to the interception and snow routine, the change of root zone water storage S_{rz} (mm) over time t (day) is described in Eq. (7), with effective precipitation P_e (mm/day) as the inflow and soil moisture constrained evaporation E_a (mm/day) and runoff R (mm/day) as outflows. In the FLEX model, the runoff generation is calculated based on the widely used beta function of the Xinanjiang model (Zhao, 1992), which is a function of the relative soil moisture in the unsaturated soil layer. The beta function for calculation of runoff in WAYS is replaced by a modified version from the work of Sriwongsitanon et al. (2016) to link the function to the water storage in the root zone layer. Depending on the root zone water storage S_{rz}, a part of the effective precipitation turns into runoff, and the rest infiltrates into the soil and recharges the root zone layer. The runoff coefficient is determined by both the relative soil water content $S_{rz}/S_{rz,max}$ in the root zone and the shape parameter β describing the spatial process heterogeneity over pixels at the global scale. The root zone storage capacity used in WAYS is derived by applying the method in Wang-Erlandsson et al. (2016), which calculates the soil moisture deficit based on satellite-based evaporation and precipitation, while it is a calibrated parameter in FLEX.

The soil moisture constrained evaporation, sometimes also known as actual evapotranspiration, is calculated as a function of the potential evaporation leftover $E_0 - E_i$ (mm/day), the relative soil water content $S_{rz}/S_{rz,max}$, the shape parameter β and the scale parameter C_e, which indicates the fraction of $S_{rz,max}$ above which the transpiration is no longer limited by soil moisture stress. Since the root zone routine connects both the runoff and evapotranspiration and the runoff generation function has been modified, the actual evapotranspiration function in WAYS is also accordingly revised from the original one in the

FLEX model (Sriwongsitanon et al., 2016). The scale parameter C_e is set to 0.5 in the FLEX model when applied at the basin scale, and it becomes a calibrated parameter in WAYS at the global scale.

2.4 Slow Response Routine

The water balance in the slow response reservoir S_s (mm) is simple, with the groundwater recharge R_s (mm/day) as the inflow and baseflow Q_s (mm/day) as the outflow (Eq. (11)). The groundwater recharge R_s is depicted in WAYS by applying the splitter function described in Eq. (12). It separates the runoff into preferential flow and groundwater recharge based on the groundwater recharge factor f_s, which ranges between 0 and 1. In WAYS, the amount of groundwater recharge is also limited by the maximum groundwater recharge $R_{s,max}$ (mm/day) for each grid cell, which is specified by the soil texture, while there is no constraint on the maximum value for groundwater recharge in the FLEX model. The values of $R_{s,max}$ used in this study are 7, 4.5 and 2.5 for sandy soil, loamy soil and clayey soil, respectively, following Döll and Fiedler (2008).

The groundwater recharge factor f_s is a calibrated parameter in the FLEX model, while in WAYS, it is now determined by applying the approach developed by Döll and Fiedler (2008), in which it is a function of global digital maps of the slope, soil texture, geology, and permafrost. The method is simple and computationally inexpensive, and it was validated at the global scale in many subsequent publications, e.g., Döll et al. (2012) and Döll et al. (2014). All the related parameters are provided in look-up tables in the work of Döll and Fiedler (2008), and the only changes we made are that the input data of the groundwater recharge method, e.g., the global relief data and the global soil texture map, have been accordingly updated based on the newly available data (Hanasaki et al., 2018). The outflow of the slow response reservoir, i.e., the baseflow, is modeled with the function described in Eq. 13, where the baseflow coefficient K_s is set to 100 globally following the work of Döll et al. (2003).

2.5 Fast Response Routine

The preferential flow R_f (mm/day) is routed directly into the fast response reservoir S_f (mm), and it is divided into surface runoff Q_{ff} (mm/day) and interflow Q_f (mm/day). The water balance in the fast response reservoir is shown in Eq. (14). In the FLEX model, it is assumed that the preferential flow is routed into the fast response reservoir based on a lag-function that represents the time lag between a storm and preferential runoff generation. In WAYS, we have assumed that the preferential flow will route into the fast response reservoir directly without any delay globally, as it is run at the daily time scale.

Similar to the slow response reservoir, the fast response reservoir is also set as a linear-response reservoir, representing a linear relationship between water storage and water release. The surface runoff generation is only active when the storage of the fast response reservoir exceeds the specified threshold S_{ftr}, with a generation ratio K_{ff} (Eq. (16)), while the interflow Q_f is simply calculated in proportion to the already stored water in the fast response reservoir using the fraction of $1/K_f$ (Eq. (17)).

2.6 Additional Model Adaptation

In addition to the abovementioned model description, some modifications and assumptions are necessary to adapt the model to the global scale. In WAYS, the actual evaporation from open water bodies is assumed to be the potential evapotranspiration, and the freezing of open water bodies is not considered in the model. Potential evapotranspiration is derived by the Hamon equation (Hamon, 1961) in the FLEX model, and it is now replaced by the using the Penman-Monteith FAO 56 PM method (Allen et al., 1998) for the following reason. The Hamon method is found to have less robustness in different climatic conditions as well as drawbacks in the daily variability of the PET simulation due mainly to the relatively simple equation in the Hamon method, as it only employs the average air temperature as an input (Bai et al., 2016; Droogers and Allen, 2002). In contrast, the Penman-Monteith FAO 56 PM method is based on fundamental physical principles and is found to be the most reliable method for potential evapotranspiration estimation when sufficient meteorological data exist (Chen et al., 2005; Kingston et al., 2009). The Penman-Monteith FAO 56 PM method is recommended by FAO and other studies based on thorough analyses of PET method intercomparisons (Allen et al., 1998; Jian biao et al., 2005; Vörösmarty et al., 1998). In the FLEX model, capillary rise from groundwater is also considered. However in WAYS, the feature for capillary rise simulation is currently disabled, as it cannot be taken into account when no information is available at the global scale. The WAYS model is written in Python version 3.6. To benefit from a supercomputer, the model is designed with full support for parallel computation.

Table 1. Water balance and constitutive equations used in WAYS

Reservoirs	Water balance equations		Constitutive equations		Reference
Interception reservoir	$\frac{dS_i}{dt} = P_r - E_i - P_{tf}$	(1)	$P_{tf} = max(0, P_r - (S_{i,max} - S_i))$	(2)	-
			$E_i = E_p\left(\frac{S_i}{S_{i,max}}\right)^{2/3}$	(3)	Deardorff (1978)
			$S_{i,max} = m_c L$	(4)	Wang-Erlandsson et al. (2014)
Snow reservoir	$\frac{dS_w}{dt} = \begin{cases} -M & \text{if } T > T_t \\ P_s & \text{if } T \leq T_t \end{cases}$	(5)	$M = \begin{cases} min(S_w, F_{DD}(T - T_t)) & \text{if } T > T_t \\ 0 & \text{if } T \leq T_t \end{cases}$	(6)	Rango and Martinec (1995)
Root zone reservoir	$\frac{dS_{rz}}{dt} = P_e - R - E_a$	(7)	$P_e = P_{tf} + M$	(8)	-
			$\frac{R}{P_e} = 1 - \left(1 - \frac{S_{rz}}{(1+\beta)S_{rz,max}}\right)^{\beta}$	(9)	Sriwongsitanon et al. (2016)
			$E_a = (E_0 - E_i) \cdot min\left(1, \frac{S_{rz}}{C_e S_{rz,max}(1+\beta)}\right)$	(10)	Sriwongsitanon et al. (2016)
Slow response reservoir	$\frac{dS_s}{dt} = R_s - Q_s$	(11)	$R_s = min(f_s R, R_{s,max})$	(12)	Döll and Fiedler (2008)
			$Q_s = S_s / K_s$	(13)	Döll et al. (2003)
Fast response reservoir	$\frac{dS_f}{dt} = R_f - Q_{ff} - Q_f$	(14)	$R_f = R - R_s$	(15)	-
			$Q_{ff} = max(0, S_f - S_{ftr}) / K_{ff}$	(16)	-
			$Q_f = S_f / K_f$	(17)	-

Note: all the time scale-dependent parameters need to be divided by Δt to make the equations dimensionally correct and suitable for any other time scales.

- in the reference column indicates that the formula is taken from the FLEX model.

3 Model Setup

For the assessment of model performance, the WAYS model is applied at the global scale with a spatial resolution of 0.5 degrees for the historical period from 1971 to 2010. Two simulations are conducted based on two products of the global root zone storage capacity from Wang-Erlandsson et al. (2016). The model is calibrated in the period 1986-1995 and validated in the period of 2001-2010 depending on the availability of the reference data.

3.1 Driving Data

3.1.1 Meteorological Data

The model is driven by the climate data set from the Global Soil Wetness Project 3 (Kim, 2017), GSWP3 (http://hydro.iis.u-tokyo.ac.jp/GSWP3/), for the historical period from 1971 to 2010. The GSWP3 data set is generated based on the Twentieth Century Reanalysis Project (Compo et al., 2011). It has been proven to be able to represent realistic submonthly variability over the entire 20*th* century (1901-2010) and has been used as a forcing data set in several other hydrological modeling studies (Veldkamp et al., 2017; Masaki et al., 2017; Liu et al., 2017; Tangdamrongsub et al., 2018). The climate variables used in this study include precipitation, minimum temperature, maximum temperature, relative humidity, surface downwelling longwave radiation, surface downwelling shortwave radiation and wind speed at 10 meters. All the variables are on a daily scale and have a 0.5 degree spatial resolution; in addition, the wind speed at 10 meters is converted to the wind speed at 2 meters based on the conversion function in Allen et al. (1998), as it is required by the Penman-Monteith FAO 56 PM method for potential evapotranspiration calculations.

3.1.2 Land Use Data

The land cover data that we used are the Global Mosaics of the standard MODIS land cover type data product (MCD12Q1) with a spatial resolution of 0.5 degrees in the year of 2001, which are derived from the IGBP Land Cover Type Classification (17 classes) and are reprojected into geographic coordinates of latitude and longitude on the WGS 1984 coordinate reference system (Friedl et al., 2010).

3.1.3 Root Zone Storage Capacity

The root zone storage capacity (RZSC) data are a crucial parameter in WAYS. The global root zone storage capacity data used in this study are from Wang-Erlandsson et al. (2016), derived by using the "Earth observation-based" method. This method determines the soil moisture deficit at the global scale by using the state-of-the-art observation-based precipitation data and satellite-based evaporation data, under the assumption that vegetation optimizes its root zone storage capacity to bridge critical dry periods and does not invest more in its roots than necessary. This method has been well justified (de Boer-Euser et al., 2019) and overcomes the shortcomings of the traditional methods (look-up table approach; field observation-based approach) at the global scale, such as data scarcity, location bias, and risks of unlikely vegetation and soil combinations due to data uncertainty

(Feddes et al., 2001). The method has been shown to increase the model performance at both the basin and global scales (Gao et al., 2014b; Nijzink et al., 2016; Wang-Erlandsson et al., 2016). Moreover, it has been proven to be able to produce plausible root zone storage capacity in boreal regions by investigating the relationship between RZSC and numerous environmental factors, including climate variables, vegetation characteristics, and catchment characteristics (de Boer-Euser et al., 2019).

Since there are two global root zone storage capacity products ($S_{R,CHIRPS-CSM}$ and $S_{R,CRU-SM}$) presented by Wang-Erlandsson et al. (2016) based on different precipitation and evaporation data sets and there is no preference for either product, in this study, both RZSC products are used. $S_{R,CHIRPS-CSM}$ covers the latitudes from 50°N to 50°S and is derived based on the United States Geological Survey (USGS) Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) precipitation data (Funk et al., 2014) and the ensemble mean of three satellite-based global-scale evaporation data sets: the Commonwealth Scientific and Industrial Research Organization (CSIRO) Moderate Resolution Imaging Spectroradiometer (MODIS) Reflectance Scaling EvapoTranspiration (CMRSET) data (Guerschman et al., 2009), the Operational Simplified Surface Energy Balance (SSEBop) data (Senay et al., 2013), and the MODIS evapotranspiration (MOD16) data (Mu et al., 2011). $S_{R,CRU-SM}$ covers the latitudes from 80°N to 56°S and is derived by using the Climatic Research Unit Time Series version 3.22 precipitation data (Harris et al., 2014) together with the ensemble mean of only SSEBop and MOD16 because CMRSET overestimates evaporation at high latitudes (Wang-Erlandsson et al., 2016). Since Wang-Erlandsson et al. (2016) suggested that a Gumbel normalization of RZSC by land cover types with different return periods could further improve the model performance, we have accordingly adjusted the RZSC in this study. The two selected global root zone storage capacity products are shown in Figure S13, and their mean latitudinal values are shown in Figure S14. Similar patterns and magnitudes of RZSC can be found, and there is good agreement between the two products at different latitudes, especially at low latitudes around the equator, where the products reflect the fluctuation with high consistency. A large difference is seen mainly in the northern midlatitude area, where the absolute difference in percentage is still less than 20%.

3.2 Calibration Data

The WAYS model has a few parameters, and while some of them are obtained independently from the literature, some have to be determined by model calibration (see Table 2). The WAYS model is calibrated against the ISLSCP II UNH/GRDC Composite Monthly Runoff data (Fekete et al., 2011) from 1986 to 1995 at a 0.5 degree resolution, which are composite runoff data that combine simulated water balance model runoff estimates and monitored river discharge. The ISLSCP II UNH/GRDC Composite Monthly Runoff data also comprise a standard data set in the second phase of ISIMIP (Inter-Sectoral Impact Model Inter-comparison Project) (ISIMIP2a) (Warszawski et al., 2014) for calibration and validation, as it assimilates discharge measurements at gauge stations and preserves the spatial specificity of the water balance while being constrained by the station observations. The data can be downloaded from The Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=994).

Table 2. Parameter ranges of the WAYS model

Parameter	Range	Literature	Parameter	Range
$S_{i,max}$	distributed	Wang-Erlandsson et al. (2014)	β	(0, 2)
$S_{rz,max}$	distributed	Wang-Erlandsson et al. (2016)	C_e	(0.1, 0.9)
$R_{s,max}$	7/4.5/2/5 (Sand/Loam/Clay)	Döll and Fiedler (2008)	K_f	(1, 40)
K_s	100	Döll et al. (2003)	K_{ff}	(1, 9)
f_s	distributed	Döll and Fiedler (2008)	S_{ftr}	(10, 200)
F_{DD}	distributed	Müller Schmied et al. (2014)	T_{lag}	(0, 5)
T_t	0	Müller Schmied et al. (2014)		

3.3 Validation Data

In this study, the ERA-Interim/Land runoff data are used for validation of the runoff simulation, and the Normalized Difference Infrared Index (NDII) is used for the validation of the WAYS model for root zone water storage simulation. Considering the time period of coverage of both data sets (ERA-Interim/Land: 1979-2010, NDII: 2000-present) and the study period (1971-2010) of this work, the period 2001-2010 is selected as the validation period. For runoff evaluation, ISIMIP2a simulations are also included, as they use the same climate forcing as our study in the same period. The purpose of inclusion of the ISIMIP2a simulations for comparison can be found in the model evaluation section (see Section 4).

3.3.1 ERA-Interim/Land Runoff Data

ERA-Interim/Land is a global land surface reanalysis data set produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Balsamo et al., 2015). The gridded data set ERA-Interim/Land is selected for model evaluation mainly because the current version of the WAYS model does not include a runoff routing model on the global scale. Therefore, the results are not comparable with observed gauge data. Since the ERA-Interim/Land data set is well assessed with a quality check through comparison with ground-based and remote sensing observations, it has been used as reference data for many studies (Xia et al., 2014; Dorigo et al., 2017). ERA-Interim/Land runoff data are one of the variables in the ERA-Interim/Land reanalysis data set and are widely used as benchmark data (Alfieri et al., 2013; Orth and Seneviratne, 2015; Reichle et al., 2017) due to their good agreement with the Global Runoff Data Centre (GRDC) data set and large improvement compared to the ERA-Interim runoff reanalysis data, which were used as one of the reference data sets (Wang-Erlandsson et al., 2014; Balsamo et al., 2015). The ERA-Interim/Land runoff data used in this study were downloaded from the ECMWF website (http://apps.ecmwf.int/datasets/) at a 0.5 degree resolution and a daily scale from 2001 to 2010.

It should be noted that there are other reanalysis runoff data available, such as ERA-Interim, GLDAS and NECP. However, they show low robustness based on the available research results. For instance, GLDAS v1.0-CLM was found to overestimate runoff globally, and GLDAS v1.0-Noah generated more surface runoff over the northern middle-high latitudes (Lv et al., 2018). GLDAS v2.0-Noah showed a significant underestimation trend in exorheic basins (Wang et al., 2016). The snowmelt-runoff peak magnitude simulated by GLDAS v2.1-Noah was found to be excessively high in June and July (Lv et al., 2018). NECP runoff was found to be too high during the winter and too low during the summer in the Mississippi River Basin (Roads and Betts, 2000). ERA-Interim was found to be less close to the observed stream flows compared with ERA-Interim/Land data (Balsamo et al., 2015).

3.3.2 NDII Data

NDII was developed by Hardisky et al. (1983) for satellite imagery analysis based on calculations of the ratios of different values between infrared reflectance (NIR) and shortwave infrared reflectance (SWIR). NDII has been found to have a strong correlation with the vegetation water content and canopy water thickness (Serrano et al., 2000; Jackson et al., 2004; Hunt and Yilmaz, 2007; Wilson and Norman, 2018). It can also be used to effectively determine the water stress of plants by taking advantage of the property of shortwave infrared reflectance, which has a negative relationship with leaf water content because of the large absorption by leaves (Steele-Dunne et al., 2012; Friesen et al., 2012; van Emmerik et al., 2015). Recently, Sriwongsitanon et al. (2016) found a promising linkage between NDII and the root zone water storage. Even though NDII reflects the dynamics of RZWS better in moisture stress periods than in moisture stress-free periods, the general good correspondence between NDII and RZWS indicates that NDII has potential as a proxy for RZWS. Therefore, in this study, NDII is used as the benchmark to assess the performance of the model in RZWS depiction.

NDII is calculated by applying the following equation from Hardisky et al. (1983):

$$NDII = \frac{\rho_{0.85} - \rho_{1.65}}{\rho_{0.85} + \rho_{1.65}} \tag{18}$$

where $\rho_{0.85}$ is the reflectance at the $0.85\,\mu\mathrm{m}$ wavelength and $\rho_{1.65}$ is the reflectance at the $1.65\,\mu\mathrm{m}$ wavelength. NDII is a normalized index that ranges between -1 and 1. A low value of NDII indicates high canopy water stress, which also reflects that there is less water content in the root zone (Sriwongsitanon et al., 2016).

In our work, NDII is computed based on the satellite data MODIS level 3 surface reflectance product (MOD09A1) (Vermote, 2015), which provides an estimate of the surface spectral reflectance of Terra MODIS Bands 1 through 7 corrected for atmospheric conditions such as gases, aerosols, and Rayleigh scattering in the sinusoidal projection. The MOD09A1 product is available on an 8-day temporal scale with a $500\,\mathrm{m}$ spatial resolution globally from 2000-02-24 until the present. Each MOD09A1 pixel contains the value selected from all the acquisitions within the 8-day composite on the basis of high observation coverage, low viewing angle, the absence of clouds or cloud shadow, and aerosol loading. The satellite image processing and NDII calculation are performed by using the Google Earth Engine platform (http://earthengine.google.com). Some of the MOD09A1 images are missing. In total, 452 NDII rasters are generated for the validation period (2001-2010).

3.4 Calibration Strategy

A global parameter optimization algorithm (Tolson and Shoemaker, 2007), dynamically dimensioned search (DDS), has been applied in this study for model parameter calibration. DDS is designed for computationally expensive optimization problems and has been used in many studies related to distributed hydrological model calibration at global and regional scales (Moore et al., 2010; Kumar et al., 2013; Rakovec et al., 2016; Nijzink et al., 2018; Smith et al., 2018).

Since the reference data, i.e., ISLSCP II UNH/GRDC data, are at a monthly temporal scale, the runoff simulated by WAYS in the calibration period (1986-1995) is also averaged to the monthly scale for consistency. The criterion of fit for calibration is the Nash-Sutcliffe efficiency coefficient (NSE), and the DDS optimization algorithm is run with 2000 iterations for each grid cell for parameter estimation, as suggested by the author of DDS (Tolson and Shoemaker, 2007).

4 Model Evaluation

To evaluate model performance, simulated runoff and root zone water storage values are compared to the reference data (see Section 3.3) for the validation period (2001-2010) in ten major river basins of the world considering the coverage of the root zone storage capacity products ($S_{R,CHIRPS-CSM}$ covers only the latitudes from 50°N to 50°S).

4.1 Runoff Evaluation

WAYS simulated runoff values are compared to the ERA-Interim/Land runoff as well as to the multimodel global runoff simulations from ISIMIP2a. ISIMIP is a community-driven global platform that supports model intercomparison studies at both global and regional scales, while ISIMIP2a focuses on the historical period, and all the models are driven by four state-of-the-art climate forcing factors (Warszawski et al., 2014). Since WAYS uses the same driving data as the ISIMIP2a models and the ISIMIP2a simulations have been widely discussed in many studies (Schewe et al., 2014; Müller Schmied et al., 2016; Gernaat et al., 2017; Zaherpour et al., 2018), we also perform a comparison between WAYS and the ISIMIP2a models to further evaluate our model. To make the climate forcing consistent with the WAYS model, only the GSWP3-driven simulations are used for comparison. The evaluation is performed at the monthly scale, even though the WAYS model simulates the runoff at the daily scale, because only monthly runoff data are available for some of the ISIMIP2a models (Warszawski et al., 2014).

Figure 2 shows the time series of runoff from reference data and different models. WAYS_CRU in the legend indicates the runoff simulated by the WAYS model with root zone storage capacity product $S_{R,CRU-SM}$, and WAYS_CHIRPS denotes the simulation with RZSC product $S_{R,CHIRPS-CSM}$. First, it can be seen that the two WAYS simulations with different RZSC products show extremely good correspondence in all selected basins. This result is consistent with the investigation of RZSC data sets in Section 3.1.3, where there is a high consistency in the two used products, which even show that RZSC itself naturally exhibits high variability along the latitudes (see Figure S13 and S14). This result confirms the robustness of the RZSC products that we used in our WAYS model for runoff simulation. The results show good agreements between WAYS simulations and the reference data, i.e., ERA-Interim/Land in the selected basins, while the ISIMIP2a models present stark differences in the simulated runoff. For example, the ISIMIP2a models show a clear trend of overestimation in some of the basins (Mississippi, Ganges, Yangtze, Parana and Murray Darling), where the spread of the runoff ensembles is also large. This result occurs partly because some of the ISIMIP2a models are not calibrated at all (Zaherpour et al., 2018), whereas WAYS is calibrated to a Composite Monthly Runoff data set that assimilates the monitored river discharge (Fekete et al., 2011).

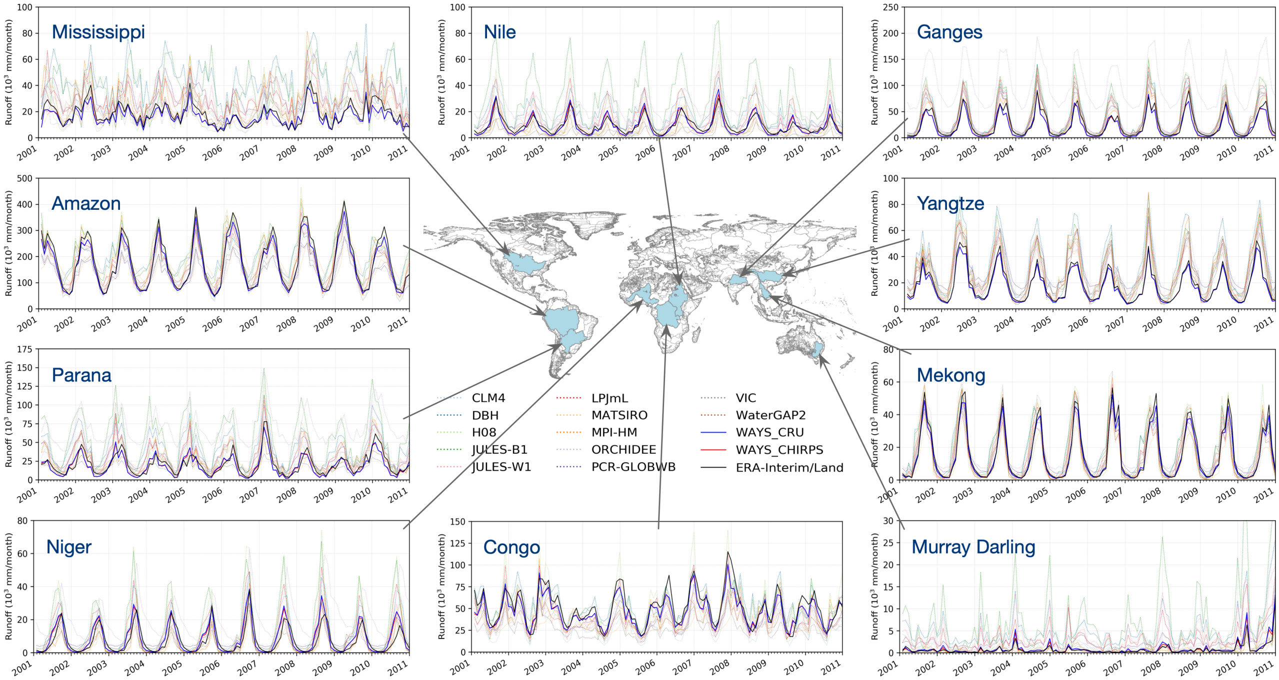

Figure 2. Time series of monthly runoff simulated by WAYS and the ISIMIP2a models, as well as the reference data. The basins highlighted in the world map indicate the selected catchments for model evaluation. The solid lines in blue and red indicate the WAYS simulations with two different RZSC products. The solid line in black indicates the ERA-Interim/Land data, and dashed lines represent the ISIMIP2a model simulations. In some plots, the red line is not visible and is covered by the blue line due to the small differences between the two WAYS runs. WAYS is calibrated using Composite Monthly Runoff data, while the ISIMIP2a models are not calibrated for the simulation.

In the Mekong River basin, all the models show a high consistency in monthly runoff generation, with a narrow spread of the ensemble. This result may be due to the natural characteristics of the Mekong River, i.e., highly predictable timing and size of the wet-season peak. In addition, precipitation in this region is concentrated in an extremely regular wet-season peak under the impact of tropical monsoons (Adamson et al., 2009). The manner in which WAYS outperforms the other models is also observed in the northernmost (Mississippi) and southernmost (Murray Darling) catchments of our selected basins, while the ISIMIP2a models show extremely large differences in the runoff simulations with large uncertainties. The good performance is particularly highlighted in the Murray Darling basin, where the monthly runoffs are extremely low, due mainly to the anthropogenic climate impacts (Cai and Cowan, 2008; Potter and Chiew, 2011), which is extremely difficult for other models to capture without overestimation (see Figure 2). A slight overestimation is found in the WAYS model in two African basins, i.e., the Nile and Niger. This result can be explained by the general overestimation of the precipitation value in climate forcing data GWSP3 in these regions (Muller Schmied et al., 2016). In these two regions, the ISIMIP2a simulations also show dramatic overestimations. In contrast, the models show a trend of underestimation in another African basin, the Congo. This result might be caused by both the quality of precipitation and the complexity of natural processes here (Tshimanga and Hughes, 2014).

Wang-Erlandsson et al. (2014) reported in their work that Congo precipitation and runoff estimates are particularly uncertain in general. It is worth highlighting that the WAYS model can still capture the monthly variability of runoff in this basin well.

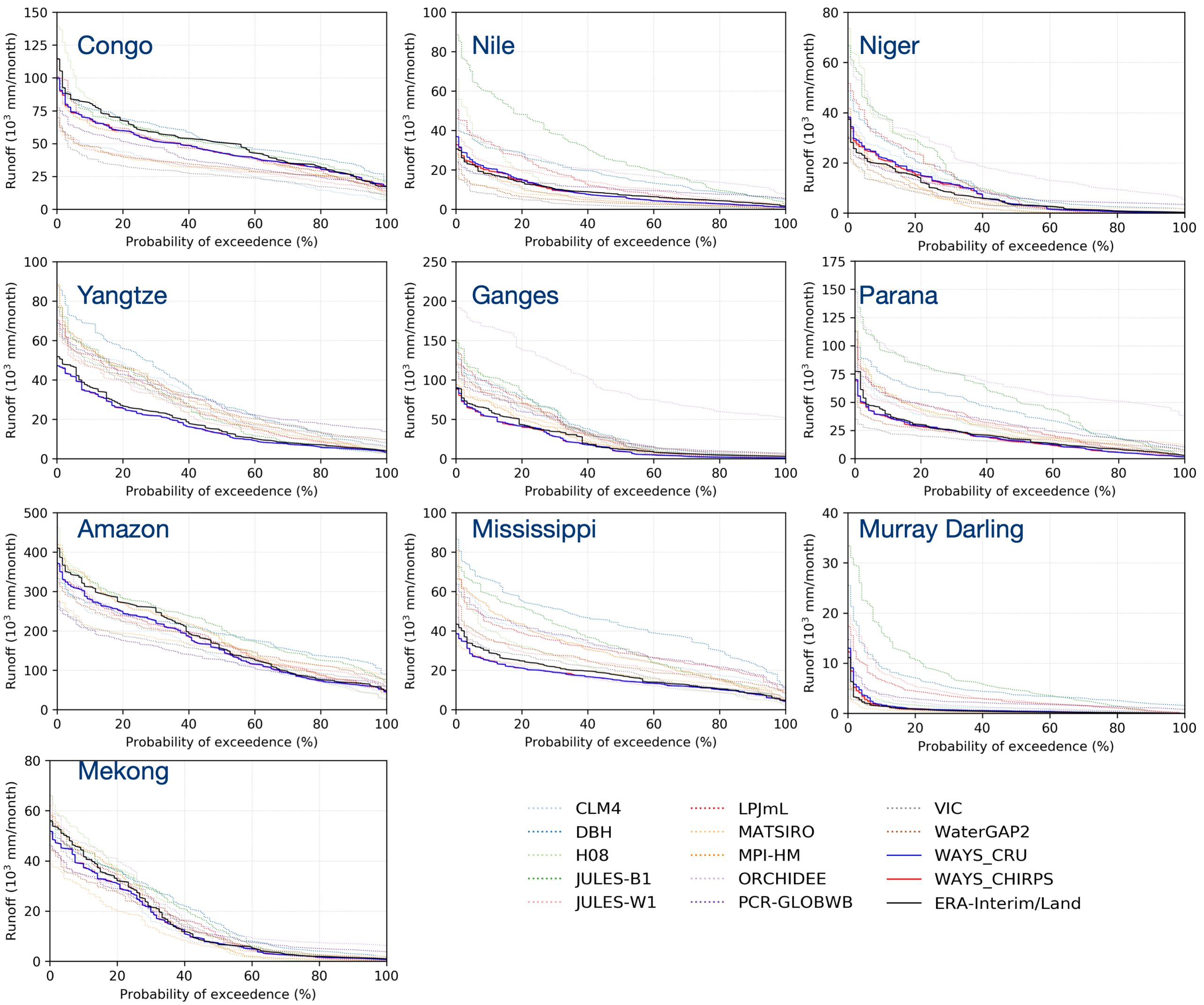

Figure 3. The probability of exceedance for monthly runoff simulated by different models as well as the reference data in ten selected basins. The solid lines in blue and red indicate WAYS simulations with two different RZSC products. The solid line in black indicates the ERA-Interim/Land data, and dashed lines represent the ISIMIP2a model simulations. In some plots, the red line is not visible and is covered by the blue line due to the small differences between the two WAYS runs. WAYS is calibrated using Composite Monthly Runoff data, while the ISIMIP2a models are not calibrated for the simulation.

To evaluate the ability of the WAYS model to replicate the distribution, a comparison study on the probability of exceedance is conducted, and the result is shown in Figure 3. The probability of exceedance reveals the model performance at different magnitudes. With a visual inspection, we can see that WAYS is able to reproduce the runoff distribution well with a good match to the ERA-Interim/Land data, especially in the Congo, Parana and Mississippi basins, while the ISIMIP2a model simulated runoff is skewed differently than that of the ERA-Interim/Land runoff distribution. In a few basins (Nile, Ganges, Parana and Mississippi), some of the ISIMIP2a models even show a bear-sized shift of distribution relative to the reference data, highlighting that these models struggle to simulate the monthly runoff at all different magnitudes. In the Nile and Niger basins, WAYS also shows a slight offset for both simulations, but it still lies within the uncertainty range. The results also show a large uncertainty in the runoff simulations in the upper tails, which reflects the larger deviation in the high values produced than in the middle- and low-value simulations for the models. Such biases in reproducing the runoff distribution in the ISIMIP2a models, in turn, deliver large ensemble spreads in the time series.

To further assess the performance of the WAYS model, three general metrics for runoff comparison are selected for the evaluation, i.e., the Nash-Sutcliffe Efficiency (NSE), root mean squared error (RMSE) and percent bias (PBIAS). The estimated scores from the monthly runoff time series for WAYS and the ISIMIP2a models are presented in Figure 4. For better comparison, the NSE values are converted to the 1-NSE values; thus, numbers closer to 0 indicate better performance. The model performance of WAYS is generally better than that of the ISIMIP2a models, and the estimated scores based on different criteria are also close to the benchmarks. The 1-NSE comparison (Figure 4 (a)) indicates that the model performance of WAYS in the selected basins, except for the Niger and Nile, is particularly favorable compared to the ISIMIP2a models. In these basins, both of the WAYS simulations (WAYS_CRU and WAYS_CHIRPS) are ranked in the top five (14 model simulations in total in the comparison). In six basins, both of the WAYS simulations have 1-NSE metric scores less than 0.3, resulting in a value of NSE of greater than 0.7. In the Yangtze, Amazon and Mekong, the WAYS model is even ranked as the best one, with both of the simulations outperforming the others. The relatively low performance of WAYS in the Niger and Nile is the result of the model slightly overestimating the middle and high runoff values (Figure 3). The RMSE comparison (Figure 4 (b)) delivers information similar to the 1-NSE comparison, in which WAYS shows generally better performance. In the Amazon, all the model simulations show large RMSE due to the large value of monthly runoff in this catchment. By examining the percent bias (Figure 4 (c)), it is evident that the WAYS model performs well in most of the basins, as the scores of the two WAYS simulations are close to the benchmark. A relatively poor performance of the WAYS model in the percent bias assessment is found in the Murray Darling basin, with PBIAS values of approximately 100%, but they are still within the uncertainty range based on a check with other models. This large value may be caused by the extremely low runoff-induced low value of the benchmark, in which a slight difference in the absolute value will cause a large difference in the percentage.

Combining the time series analysis, most commonly used metric examination in hydrology and probability of exceedance assessment, our results show a comprehensive assessment of the model performance in runoff simulation. The strong performance of WAYS with the subtle difference between the runoff simulation and reference data in all the tests indicates the particularly favorable applicability of WAYS in runoff simulation across major basins. Even though relatively poor performances are found in two African basins, the biases are still within the uncertainty range based on investigations of other models. Such a trend of overestimation could also be explained by the overestimation of the precipitation value in the forcing data in these regions (Muller Schmied et al., 2016). In addition, it is worth acknowledging that global hydrological models show large differences in runoff simulations across basins. Previous studies emphasized that large ensemble spreads from GHMs could be caused by

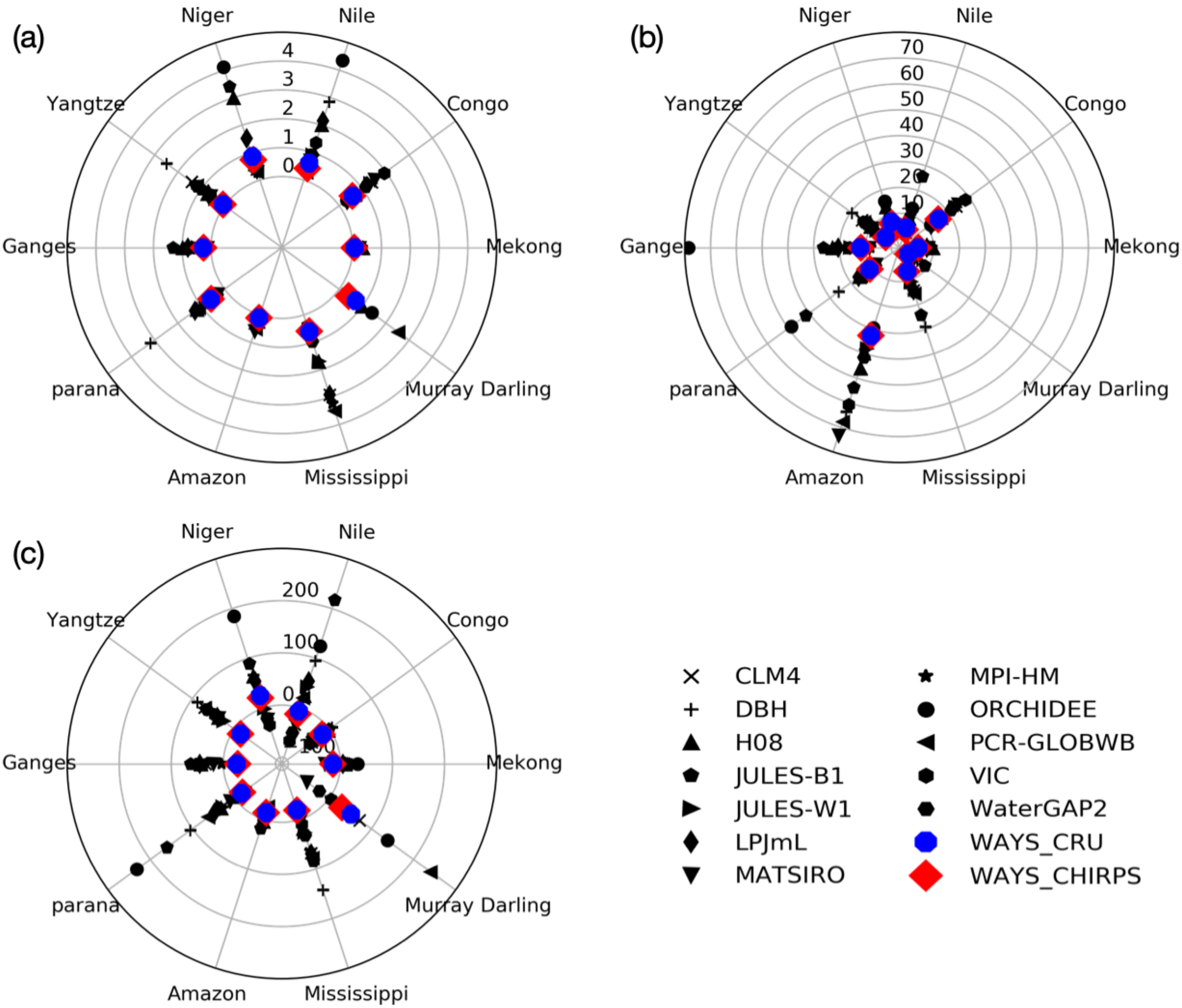

Figure 4. The catchment clockwise pole plot according to different metrics, (a) 1-NSE, (b) RMSE, and (c) PBIAS. Colored markers indicate the score for the WAYS model with two different simulations, and black markers represent the score for ISIMIP2a models. For all the metrics, the value of 0 is the benchmark.

model structural uncertainties (Haddeland et al., 2011; Gudmundsson et al., 2012). The lack of physical process representations, e.g., transmission loss, in the hydrological models can also explain some of the biases between the simulated runoff and the reference data (Gosling and Arnell, 2011).

The performance of WAYS is further evaluated against the gauge observations. Since WAYS does not have a native runoff routing module at the moment, a third-part runoff routing tool, CaMa-flood, is applied to route the WAYS simulated runoff (Yamazaki et al., 2011). The evaluation results can be found in the Supplementary Information (SI).

4.2 Validation of Root Zone Water Storage

Similar to the runoff evaluation, the performance of the simulation of root zone water storage by the WAYS model is also evaluated at ten major river basins in the period from 2001 to 2010. The spatial pattern as well as the RZWS dynamics at different latitudes and in different months can be found in the SI of the paper. Since the NDII is a normalized index and on an 8-day temporal scale, the WAYS simulated root zone water storage is first averaged over an 8-day temporal scale and then normalized to the range between 0 and 1 before the comparison. A few time steps are missing in the NDII data set. To keep the compared data sets consistent, only pair-wised RZWS data are selected for the model evaluation.

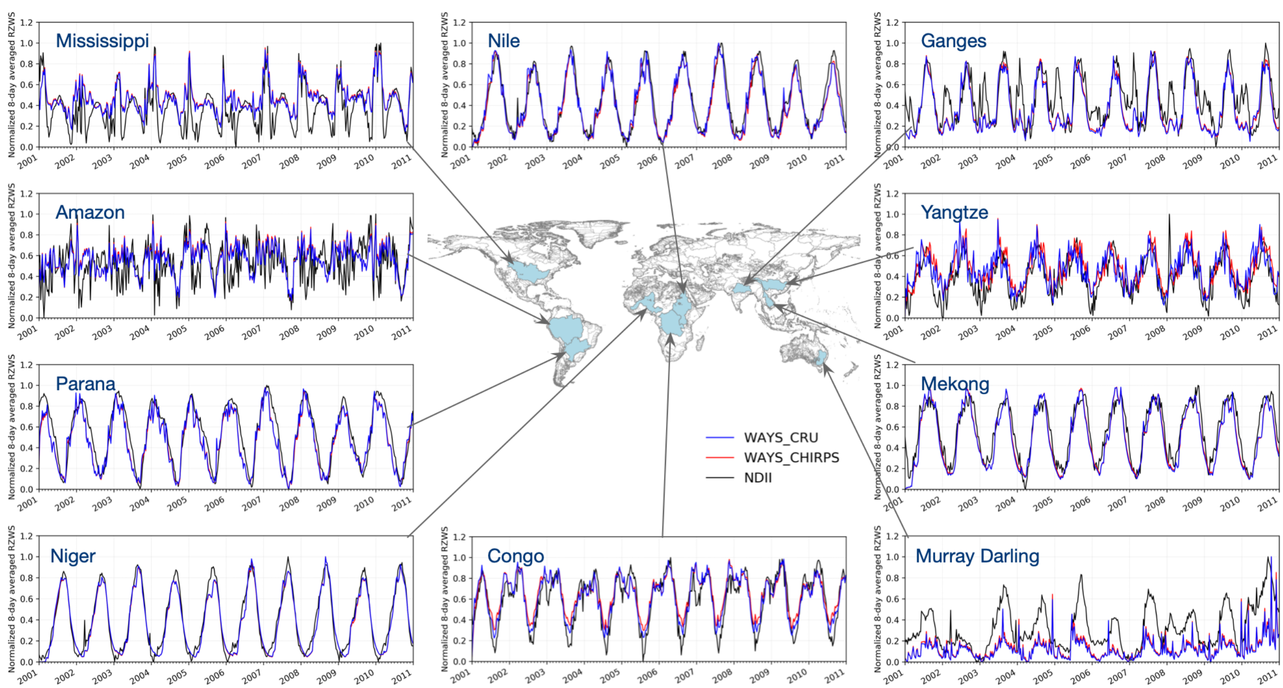

Figure 5. Time series of 8-day normalized RZWS simulated by the WAYS model and NDII value.

The 8-day NDII values are compared to the 8-day averaged root zone water storage values of the WAYS model, and the results are shown in Figure 5 and Table 3. Figure 5 shows a comparison of the time series of NDII and simulated RZWS in the selected basins, and Table 3 presents the corresponding rank correlation (Spearman's rho) between NDII and RZWS. The

Table 3. The rank correlation of NDII and WAYS-simulated RZWS in ten selected basins

Selected River Basins	Models	
	WAYS_CRU	WAYS_CHIRPS
Congo	0.872	0.871
Nile	0.951	0.967
Niger	0.975	0.975
Yangtze	0.713	0.764
Ganges	0.803	0.817
Parana	0.931	0.934
Amazon	0.593	0.552
Mississippi	0.689	0.677
Murray Darling	0.614	0.636
Mekong	0.936	0.938

RZWS simulated by GEPCI-hydro is not compared to the other model, as the RZWS variable is not available in other GHMs. For ISIMIP2a, some models produced the root zone soil moisture within a fixed depth of the soil profile in the model structure. However, this is still a different variable compared with the root zone water storage.

First, it is clear that NDII shows totally different patterns in different basins. Clear seasonal cycles are shown in the Nile, Mekong, and Niger river basins and so on. Camel-like structures are observed in the Ganges and Congo basins, and relatively complex patterns are represented in the Mississippi, Murray Darling and Amazon basins. The simulated RZWS shows good agreement in the time series with NDII in most of the selected basins. High values of rank correlation are also detected in these regions. Seven catchments of ten have a rank correlation value higher than 0.7, especially in the Nile, Niger, Parana and Mekong, where the correlation coefficients are even higher than 0.9, indicating the strong model performance of WAYS in these basins for root zone water storage simulation, as the NDII reflects the soil water content in the root zone (Sriwongsitanon et al., 2016). The two simulated RZWS time series with different root zone storage capacity products also show identical behavior with subtle differences, except in the Yangtze River basin due to the relatively larger differences in the averaged RZSC of the two products ($S_{R,CRU-SM}$: 135 mm, $S_{R,CHIRPS-CSM}$: 163 mm) in this basin. In the Ganges and Congo, the NDII time series show a two-humped structure, which the WAYS model can still capture, even though underestimations are detected in some years. The rank correlation coefficients in these two catchments are higher than 0.8. In the Yangtze, a suddenly high value of NDII is found on the 25th of August in 2008. By investigating the NDII values a few days before and after this date and the precipitation amount in this period, the unrealistic high value might be caused by the quality of satellite data MOD09A1 on that day, as it can be affected by many issues, including clouds, shadow, viewing angle, aerosol loading and so on (Vermote, 2015).

Relatively large differences between NDII and simulated RZWS are also found in some catchments. In the Mississippi, WAYS shows a good performance in large-value simulations, while it struggles to simulate low values, with considerable overestimation of them. Therefore, the rank correlation is also relatively low in this catchment, with values of approximately 0.67. The Mississippi river basin is the northernmost catchment of our selected basins. The NDII here shows a totally different pattern compared to the others, while the WAYS-simulated RZWS can barely show a clear seasonal variation. There could be multiple reasons for this overestimation: our model has a relatively simple snowmelt module (degree-day method), which could consequently introduce biases into the simulation, especially in relatively cold regions. Additionally, the relatively uncertain forcing data could contribute to the mismatches between NDII and RZWS, as the largest uncertainties in precipitation occur mainly at the higher latitudes (Vinukollu et al., 2011). Some studies also reported that precipitation-induced spurious seasonal and interannual variations also exist in the soil moisture in this basin (Yang et al., 2015). In contrast, WAYS shows a trend of underestimation in the Murray Darling. A possible reason could be that deep rooted plants are widespread across the Murray Darling basin and can tap into groundwater (Runyan and D'Odorico, 2010; Lamontagne et al., 2014); thus, the NDII may not be the correct proxy for moisture stress in this region. A vast amount of groundwater drawing from the saturated zone to the root zone could explain such underestimation of RZWS (Leblanc et al., 2011). Other reasons behind these findings could be the underestimated RZSC in this region as well as the intensive human activities, including dam construction, a water diversion system and river management, which will impact both the RZSC estimation and RZWS simulation (Reid et al., 2002; Kingsford, 2000). In the Amazon, the model can only capture a few downward troughs but shows difficulty in representing the complete complex dynamics of NDII, resulting in the lowest value of the rank correlation (0.593 and 0.552) among all the selected basins. The primary reason for this low performance could be the inability of NDII to represent RZWS in relatively wet regions where water stress for plants is low (Sriwongsitanon et al., 2016). Among our selected basins, the Amazon has the highest averaged annual precipitation amount, with a value of 2201 mm/year in the validation period. In this case, the performance of WAYS in the RZWS simulation of such regions cannot be justified.

Overall, these model validation results over the ten selected river basins deliver generally good evaluated values that suggest the capability of the WAYS model for RZWS simulation, especially for interannual variability simulation. However, attention should also be paid to some regions, e.g., the basins at high latitudes in the Northern Hemisphere as well as the regions with plenty of precipitation where moisture stress might be low and NDII may not correctly reflect the RZWS dynamics (Sriwongsitanon et al., 2016).

4.3 Evaporation Evaluation

RZWS has a close link to the total evaporation, as RZWS represents the available water that plants can use. In this section, the performance of WAYS in evaporation simulation is evaluated against the FLUXNET2015 data. FLUXNET2015 is a global network of micrometeorological flux measurement sites that measure the exchange of CO_2, water vapor and energy between the biosphere and the atmosphere (Pastorello et al., 2017). The tower-measured latent heat flux (LF, W/m^2) is converted to ET (mm/day) using the proportionality parameter between energy and depth units of ET (Velpuri et al., 2013) as follows:

$$ET = \frac{LE}{\lambda} \tag{19}$$

where λ is the latent heat of vaporization (2.45 MJ/kg). In total, 108 stations are selected based on the data availability in the period 1971-2010. The flux tower latent heat is converted to evaporation before the comparison. The correlation coefficients between simulated evaporation and the FLUXNET2015-derived evaporation are then calculated on the monthly scale.

The results are shown in Figure S15. The background is the annual averaged evaporation from WAYS for the period 1971-2010. The points indicate the comparison results between the flux tower and WAYS simulation. The locations of the points indicate the locations of the flux towers, and the colors indicate the correlation coefficient. WAYS is found to have relatively better performance in America, Europe and China than in Africa and Australia. However, a few stations near the boundary of America and Europe also show weak correlations between the simulations and flux tower data.

Figure S16 shows the percentage of data points within different intervals of the correlation coefficient. The calculated correlation coefficient is crowded in the interval of 0.6-0.8, while more than half of the stations (56%) show a correlation coefficient of more than 0.6. The relatively poor performance of the model in some regions could be partially explained by the following reason. FLUXNET2015 corresponds to point-based observation data, while WAYS simulates the evaporation on grid cells with a 0.5 degree spatial resolution. For the comparison, the model simulation in a certain pixel is selected based on the distance between the flux tower and the center of the pixel. The model simulation actually represents an averaged value for a 0.5 x 0.5-degree pixel. This averaging will inherently introduce errors when comparing the simulation to station-based data. Similar results are also found in other studies comparing FLUXNET2015 data to either model simulations or remote sensing-derived evaporations (Lorenz et al., 2014; Velpuri et al., 2013).

Furthermore, the average monthly evaporation is compared to the FLUXNET2015 data at each flux tower, and the results are shown in Figure 6. Good correspondence between the model simulation and flux tower data can be found by visual inspection. The points with a higher correlation coefficient show a better relationship between the model simulation and flux tower observation and are distributed closer to the diagonal. The evaluation results confirm the generally good performance of WAYS in monthly evaporation simulation. The detailed results on evaporation evaluation against FLUXNET2015 are provided in the SI as Excel files. In addition, an evaluation of the evaporation simulation is further conducted against LandFluxEVAL, a merged benchmark synthesis product of evaporation at the global scale (Mueller et al., 2013). The results can be found in the SI.

4.4 The Effect of Root Zone Storage Capacity on Hydrological Simulation

RZSC is a key parameter of the WAYS model. Therefore, it is important to investigate how RZSC could affect the model simulation. In addition to the model simulated with satellite data-derived RZSC products ($S_{R,CHIRPS-CSM}$ and $S_{R,CRU-SM}$), we have additionally conducted WAYS simulations with RZSC derived from uncertain root depth and soil data. The uncertain RZSC ($S_{R,LOOKUP-TABLE}$) is derived based on literature values of root depth and soil texture data (Müller Schmied et al., 2014; Wang-Erlandsson et al., 2016). Due to the global coverage of the RZSC data ($S_{R,CRU-SM}$), only the simulation with $S_{R,CRU-SM}$ is used for comparison. The spatial distribution of the uncertain RZSC is shown in Figure S17, and the differences between $S_{R,CRU-SM}$ and $S_{R,LOOKUP-TABLE}$ are shown in Figure S18. It can be seen that there are large differences between the two RZSC products. The simulation with uncertain RZSC $S_{R,LOOKUP-TABLE}$ shows overestimation globally

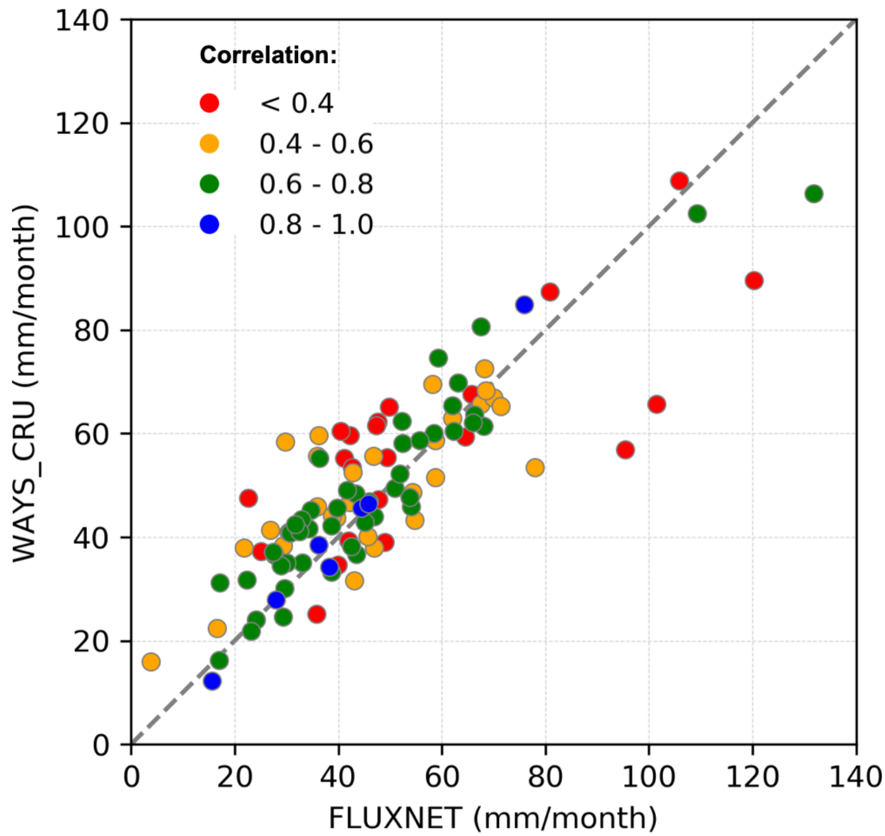

Figure 6. Averaged monthly evaporation of WAYS simulation (WAYS_CRU) against the FLUXNET data.

except for some regions around low-middle latitudes. The latitudinal averaged RZSC further confirms the overestimation of $S_{R,LOOKUP-TABLE}$ at middle-high latitudes (Figure S19).

The large differences between these two RZSC data sets also introduce differences in simulated hydrological elements. Figure S20 shows the impacts of RZSC on the model simulation, including runoff, evaporation and RZWS. A blue color (decrease of RMSE and increase of the ranked correlation) indicates an improvement of the simulated results by replacing the uncertain RZSC ($S_{R,LOOKUP-TABLE}$) with satellite data-derived RZSC ($S_{R,CRU-SM}$), while a red color implies the opposite. For comparison, reference data are used for different variables. For runoff, evaporation and RZWS, the reference data are ERA-Interim/Land (2001-2010, monthly), LandFluxEVAL (1989-2005, monthly) and NDII (2001-2010, 8-days), respectively. Generally, the model simulations are improved by using the RZSC $S_{R,CRU-SM}$. This result emphasizes the importance of an appropriate representation of RZSC in WAYS. A decline of the model performance is also found in some regions at high latitudes and low latitudes. This result can be partially explained by the inherent uncertainty in the $S_{R,CRU-SM}$ data, as they are derived from other data sets. The RZSC derivation method itself as well as the input data can also introduce biases (Wang-Erlandsson et al., 2016).

Figure 7 shows the RMSE improvements of simulated monthly evaporation for different land covers obtained by implementing the satellite data-derived RZSC ($S_{R,CRU-SM}$) instead of the uncertain RZSC ($S_{R,LOOKUP-TABLE}$). The analysis reveals that the satellite data-derived RZSC ($S_{R,CRU-SM}$) has great potential to improve the evaporation simulation for all kinds of land covers. The largest improvements are found in broadleaf forests. The improvements in the needleleaf forest, mixed forest and savanna are relatively low. The findings also resonate with another work that used a simple terrestrial evaporation to atmosphere model (STEAM) for evaporation simulation (Wang-Erlandsson et al., 2016).

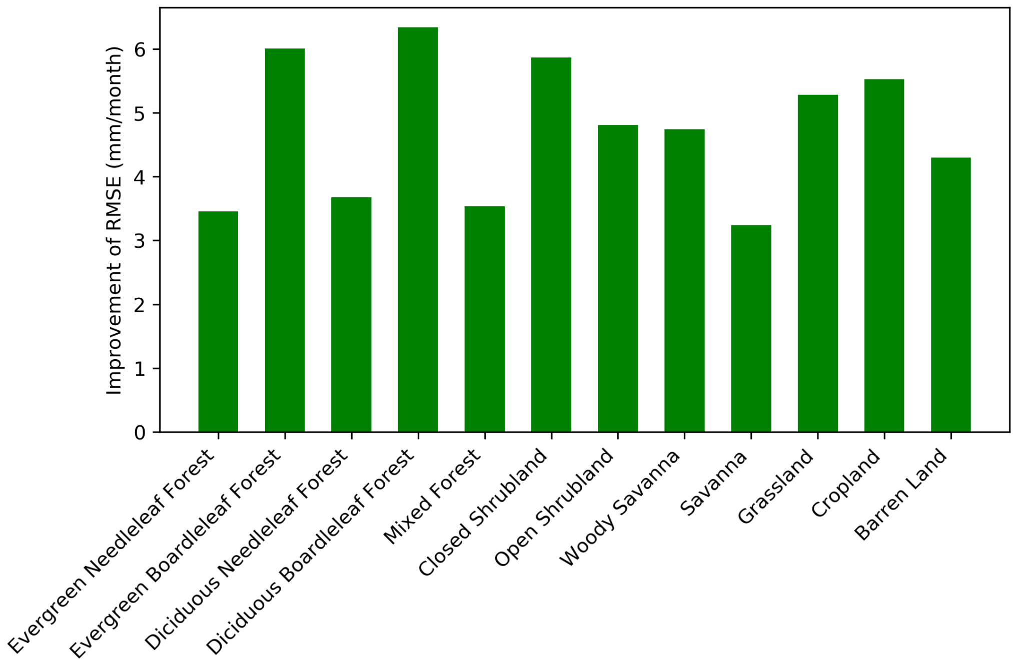

Figure 7. The improvement of RMSE in evaporation simulations for different land covers by using the satellite data-derived RZSC ($S_{R,CRU-SM}$) instead of the uncertain RZSC ($S_{R,LOOKUP-TABLE}$).

5 Discussion and conclusion

In this study, a global hydrological model has been developed that aims to simulate the soil water volume stored in the entire root zone, a critical variable for ecohydrology-related studies, by considering the global spatial heterogeneity of the plant rooting system. The primary motivation behind the development of WAYS is to improve the integrality of soil water simulation in hydrological models by acknowledging the key role played by RZWS in many applications, as it connects the climate, hydrology and earth surface systems (Savenije and Hrachowitz, 2017). Existing models represent the soil profile with different schemes (Devia et al., 2015). However, they still suffer from the structure limitations of the models in reflecting the soil water dynamics for the entire rooting system (Bierkens, 2015; Sood and Smakhtin, 2015). A persistent weakness in the RZWS simulation in the hydrological models is the lack of direct observations for model evaluation (Sriwongsitanon et al., 2016).

Benefiting from recent progress made in the field of hydrology and remote sensing, the WAYS model is developed based on an advanced lumped model, FLEX (Fenicia et al., 2011; Gao et al., 2014a), and evaluated with a proxy of RZWS, the remote sensing-based index NDII (Hardisky et al., 1983). NDII is not new, but strong linkage between NDII and RZWS found by Sriwongsitanon et al. (2016) enlightened our work. This potential candidate as a proxy of RZWS bridges the gaps in the field, where RZWS cannot be directly observed at large scales. The model FLEX is widely used and has been validated for root zone water dynamics simulation, but at the basin scale (Gao et al., 2014b; Nijzink et al., 2016; de Boer-Euser et al., 2016; Sriwongsitanon et al., 2016). A variety of modifications and extensions are made based on FLEX that allow WAYS to simulate the hydrological cycles at the global scale with an advanced schema in the root zone system. Another key parameter that allows appropriate RZWS simulation in WAYS is the global RZSC recently produced by Wang-Erlandsson et al. (2016). Before that, it was usually obtained by look-up approaches with inherently large uncertainty. RZSC reveals the spatial heterogeneity of the plant rooting system and has a direct relation to RZWS. Moreover, RZSC is produced under the assumption that plants do not invest more in their roots than necessary to bridge a dry period. Thus, this assumption is also held by our work, and the root zone reservoir (Section 2.3) actually defines the part of the unsaturated zone that determines the dynamics of the runoff regime (Sriwongsitanon et al., 2016; Savenije and Hrachowitz, 2017).

The major goal of this study is to test the feasibility of WAYS for reliable RZWS simulation. The newly developed model is first validated for runoff and RZWS simulation in ten major basins across the world and is then further evaluated against station observations, including flux tower and gauge data. Despite regional differences, general good performances are found for runoff and evaporation simulation. In addition, the WAYS model also shows a good representation of RZWS, with high values of rank correlation in most of the validated regions. The evaluation results confirm the capacity of WAYS as a useful tool to simulate hydrological elements, particularly RZWS, at the global scale. However, we have to highlight that the model shows lower performance in some regions, e.g., the Amazon, in the RZWS simulation, where the reference data NDII may have shortcomings in reflecting RZWS. In these regions where NDII might not be a correct proxy for RZWS, an additional data set could be helpful for evaluation, e.g., the solar-induced fluorescence (SIF), which reflects photosynthesis and thus has a close relationship to the available water in the root zone. A combination of vegetation index data, such as EVI and NDVI, could also be alternatives, as they represent different characteristics of plants. However, further investigations need to be performed before this combination can be applied. It is also important to note that the high latitude regions are not covered by one of the key parameters, i.e., root water storage capacity, used by the WAYS model, and only major river basins at middle and low latitudes are investigated. Thus, the performance of the model in the other regions is not justified. This is one of the limitations of this work, and further investigations are needed.

It should also be noted that during the evaluation of RZWS, the reference data NDII represent a normalized index based on surface reflectance and can reflect only the dynamics of RZWS rather than the absolute value (Sriwongsitanon et al., 2016). Therefore, a real value-based evaluation could be much more helpful for the model application. This could be another limitation of the work. However, this fact also emphasizes the importance and necessity of this work from the following two aspects: 1) The remote sensing-based approach, e.g., NDII, is thus far one of the best available methods for root zone information retrieval (Tobin et al., 2017). However, it is still limited in its ability to reflect the real value, which urges model development, as the model has the ability for absolute value simulation. 2) The remote sensing-based approach works only for historical analysis, which limits its ability to be used in future impact studies. This issue also motivates model development, as the model can work for both past and future studies after appropriate evaluation.

Moreover, the current study does not consider the groundwater access and irrigation mainly due to the lack of global information. The groundwater table information is crucial for capillary rise simulation (Vergnes et al., 2014). Capillary rise simulation without proper water table information could significantly overestimate the evaporation. Thus, the capillary rise flux is ignored in this study. A similar strategy has also been applied by other works due to the absence of the information on the global water table (Döll et al., 2003; De Graaf et al., 2015; Hanasaki et al., 2018). Observations of irrigation on the global scale are also not available (Leng et al., 2015). Although there are simulated irrigation data available on the global scale, the inherent uncertainties could be propagated in our model simulation. Therefore, irrigation is also not considered at this time. However, this neglect could potentially introduce biases into the model simulation in irrigated areas and deep rooted plant-distributed regions, as both irrigation and capillary rise are an additional supply of soil water recharge. The biases may cause an underestimation of evaporation, especially in the dry summertime (Vergnes et al., 2014). This underestimation could consequently affect the simulation of RZWS and runoff because of the interlinkage of these three elements (Rockström et al., 1999). It is found that ignoring the capillary rise could reduce soil water content in the root zone (RZWS), while the runoff will also be reduced (Vergnes et al., 2014). However, these shortcomings can be simply overcome once the global data are available.

In summary, the newly developed global hydrological model WAYS improves the integrality of soil water simulation in hydrological models, as it simulates the water stored in the entire root zone. This added-value feature could benefit many applications related to the root zone processes. For instance, the correct representation of RZWS could help researchers in the investigation of land-vegetation-climate-water integration, where RZWS plays a key role. The capability for RZWS simulation could also benefit the field of agriculture, as RZWS represents the plant available water, which is closely linked to the crop yields. Moreover, this can also advance the hydrological model itself, as the water stored in the root zone controls the partitioning of the precipitation into evaporation, infiltration and runoff in the model (Liang et al., 1994). The precise simulation of variables in the root zone could benefit the simulation of other elements in the model, thus advancing the model simulation toward an advanced philosophy, i.e., obtaining the right answers for the right reasons rather than simply obtaining the right answers (Kirchner, 2006). In addition, the WAYS model can be further improved by integrating a more sophisticated evaporation module, e.g., the STEAM model developed by Wang-Erlandsson et al. (2014), which separates the evaporation fluxes in a more detailed way. Finally, a runoff generation module recently developed by Gao et al. (2019), HSC-MCT, could provide another possibility to improve the WAYS model, as it offers another venue for determining one of the key parameters in WAYS (β) independently without calibration. This calibration-free module could actually benefit any conceptual hydrological model.

Code and data availability. The source code will be available after the paper is accepted. The meteorological data used in this work are available at the data center of the "Global Soil Wetness Project 3" (http://hydro.iis.u-tokyo.ac.jp/GSWP3/). The land use data are available at the Global Land Cover Facility (http://www.landcover.org). The root zone storage capacity is collected from the work of Wang-Erlandsson et al. (2016). The runoff data for model calibration are available at the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=994). The runoff data for model evaluation are available at the European Centre for Medium-Range Weather Forecasts (ECMWF) website (http://apps.ecmwf.int/datasets/). The NDII data and simulated hydrological data are available upon request from the corresponding author.

Author contributions. GM and JL contributed equally to the paper. GM and JL designed the study, analyzed the data and wrote the paper. JL designed the model structure, and GM wrote the model code.

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

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WAYS v1: A hydrological model for root zone water storage simulation on a global scale

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Abstract. The soil water stored in the root zone is a critical variable for many applications, as it plays a key role in several hydrological and atmospheric processes. Many studies have been ~~done~~ conducted to obtain reliable ~~soil water information~~ information on soil water in the root zone layer. However, most of them are mainly focused on the soil moisture ~~in~~ within a certain depth rather than the water stored in the entire rooting system. In this work, a hydrological model named WAYS is developed to simulate the root zone water storage (RZWS) on a global scale. The model is based on a well validated lumped model and has ~~been extended now~~ now been extended to a distribution model. To reflect the natural spatial heterogeneity of the plant rooting system across the world, a key variable that ~~influencing the~~ influences RZWS, i.e., root zone storage capacity (RZSC), is integrated into the model. The newly developed model is ~~evaluated~~ first evaluated based on runoff and RZWS ~~simulation~~ simulations across ten major basins. The ~~evaluation of runoff indicates the strong capacity of the model for monthly simulation with a good performance on time series and distribution depiction. Results also~~ results show the ability of the model ~~for RZWS dynamics mimicing~~ to mimic RZWS dynamics in most of the regions ~~. This model~~ through comparison with proxy data, the Normalized Difference Infrared Index (NDII). The model is further evaluated against station observations, including flux tower and gauge data. Despite regional differences, generally good performances are found for both the evaporation and discharge simulation. Compared to existing hydrological models, WAYS's ability to resolve the field-scale spatial heterogeneity of RZSC and simulate RZWS may offer benefits for many applications~~due to its ability for RZWS simulation.However, attentions need to also be paid for application as the high latitude regions are not investigated by this work due to the incomplete latitudinal coverage of~~ , e.g., agriculture and land-vegetation-climate interaction investigations. However, the ~~RZSC. Therefore, the performance of the model in such regions is not justified~~results from this study suggest an additional evaluation of RZWS is required for the regions where the NDII might not be the correct proxy.

1 Introduction

Soil moisture is one of the critical variables in earth system dynamics (Sheffield and Wood, 2008) and is claimed an Essential Climate Variable by the World Meteorological Organization due to its key role ~~played in several hydrologic~~ in several hydrological and atmospheric processes (Legates et al., 2011). The soil water stored in the plant root zone is of great importance in some fields of application, e.g., agriculture, as it represents the reservoir of the plant available water and mediates numerous ~~sub-surface~~ subsurface processes (Sabater et al., 2007; Wang et al., 2015; Cleverly et al., 2016). A fundamental limiting factor that constrains crop yields is the water resources in the root zone (Tobin et al., 2017). The water stored in the root zone is also directly linked with one of the ~~importance~~ important water resources for ecosystems, i.e., green water resources, as ~~the~~ green water is defined as the water that originates from precipitation that is stored in the unsaturated soil and eventually consumed by plants through evapotranspiration (Falkenmark and Rockström, 2006; Liu and Yang, 2010).

There are several methods for soil moisture estimation~~including~~ , including in situ measurements, satellite-based approaches and model simulation (Paulik et al., 2014; Dumedah et al., 2015; Colliander et al., 2017; Zhang et al., 2017; Berg et al., 2017). Especially in recent years, a variety of specific sensors and systems have been built for ~~soil moisture measuring globally~~global soil moisture measurement, e.g., the Advanced Microwave Sounding Radiometer for Earth Observation System (AMSR-E) ~~and~~ as well as the AMSR-2 (Njoku et al., 2003) ~~,~~ and the Soil Moisture Ocean Salinity (SMOS) (Kerr et al., 2010) ~~,~~ and Soil Moisture Active Passive (SMAP) ~~mission~~ missions (Entekhabi et al., 2010). These sensors are able to provide continuous estimations of soil moisture worldwide.

Obtaining reliable root zone water storage is still challenging, as it cannot be directly observed (González-Zamora et al., 2016). Satellite remote sensing itself can only detect the soil water at the surface layer (in most ~~of~~ cases with a depth of 5 cm) and has the shortcoming ~~to look into~~ that it cannot look at the deep soil profile (Petropoulos et al., 2015). ~~A lot of~~ Considerable effort has been ~~done~~ made recently by researchers to retrieve root zone soil moisture (RZSM), a variable that is very close to ~~the~~ RZWS. Tobin et al. (2017) developed an exponential filter to leverage the ~~remote~~ remotely sensed surface soil moisture to produce RZSM. Faridani et al. (2017) and Baldwin et al. (2017) applied a soil moisture analytical relationship (SMAR) model to generate RZSM, where the surface soil moisture is the input. Apart from remote ~~sensing based~~ sensing-based approaches, hydrological models and land surface models are important tools for moisture simulation, as they work both in the past and ~~future~~ in future scenarios (Xia et al., 2014; Sheikh et al., 2009; Albergel et al., 2018; Samaniego et al., 2018). Additionally, many studies estimate ~~the~~ RZSM by combining remotely sensed soil moisture with different models using data assimilation techniques (Rebel et al., 2012; Renzullo et al., 2014a, b). However, all these studies estimated the root zone soil moisture until a certain depth, e.g., 100 cm, thus still ~~hold the drawbacks~~ retaining the drawback of being unable to accurately calculate the water stored in the entire root zone layer. ~~Since the rooting~~ Moreover, the root depth is location dependent and ~~could reach an~~ can reach a depth of more than 30 meters (Fan et al., 2017).

Alternatively, RZSM can also be obtained by investigating and applying the relationship between RZSM and different vegetation indices derived from MODIS or Landsat satellites, e.g., the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) (Santos et al., 2014; Wang et al., 2007; Schnur et al., 2010; Liu et al., 2012). Nevertheless, their work either ~~stick~~ stays at a certain soil depth assuming ~~the~~ a consistent rooting depth or estimates only the water content ratio assuming ~~the~~ a homogeneous soil profile, rather than the water amount covering the entire ~~spatial~~ spatially heterogeneous rooting system (Fan et al., 2017). ~~So far~~To date, studies that directly focus on ~~the~~ root zone water storage are still rare.

Recently, Sriwongsitanon et al. (2016) investigated the relation between root zone water storage and the Normalized Difference Infrared Index and found a promising correspondence between them in a river basin in Thailand, especially in the dry seasons, where water stress exists. However, the NDII is an index value that reflects only the dynamics of RZWS rather than the absolute value. Moreover, remote ~~sensing based~~ sensing-based approaches only allow ~~us for the historical analysis~~historical analyses. While the ability ~~for predicting the~~ to predict RZWS, usually ~~hold by~~ by employing models, is still missing, which is crucial for impact studies, e.g., agricultural drought analysis (Keyantash and Dracup, 2002)~~. But~~ , the work of Sriwongsitanon et al. (2016) provided ~~enlightenments for future RZWS related~~ enlightenment for future RZWS-related studies, as their findings support NDII ~~to be~~ as a potential proxy for RZWS. This is critical for mitigating the major challenge, i.e.~~there is no~~ , the lack of direct observation of root zone water storage for evaluation, in the field of hydrological ~~modelling~~modeling.

In this study, a global hydrological model is developed to simulate root zone water storage, a key variable for ~~eco-hydrological~~ ecohydrological studies. Though many ~~of~~ global hydrological models (GHMs) have already been developed~~and most of the~~ , most of them are similar ~~in general hydrological components simulation (Sood and Smakhtin, 2015),~~ regarding the general hydrological component simulations (Sood and Smakhtin, 2015), and the developed model has its unique scheme for root zone ~~processes depiction, thusit allows for RZWS simulation~~ process depiction; thus, it enables RZWS simulations with the ability ~~for considering the global spatial heterogeneous rooting system~~to consider the global spatially heterogeneous rooting systems. The model has ~~the similar input requirements~~ input requirements similar to most of the existing GHMs and can also generate general hydrological variables in addition to ~~the~~ RZWS. Since it simulates ~~the RZWS~~RZWS, which is of great importance for both hydrology and ecology, ~~and~~ it will be further developed in the future for water and ~~ecosystem related~~ ecosystem-related applications. The newly developed model is named ~~as~~ the Water And ecosYstem Simulator (WAYS). The ultimate goal of this study is to test the feasibility of WAYS for RZWS simulation on a global scale, an added-value feature useful for many applications.

2 Model Description

2.1 General Overview

WAYS is a hydrological model implementation in Python. It is a process-based model that ~~assums~~ assumes water balance at the grid cell level. The development of WAYS is based on a lumped conceptual model with an HBV-like model structure, called the FLEX model (Fenicia et al., 2011; Gao et al., 2014a). The FLEX model has been widely used and validated at the basin scale to simulate the soil moisture content and root zone water storage (Gao et al., 2014b; Nijzink et al., 2016; de Boer-Euser et al., 2016; Sriwongsitanon et al., 2016). ~~Benefit~~ Benefiting from its flexible ~~modelling~~ modeling framework, we have now extended it to a spatially distributed global hydrological model. In addition, some improvements ~~are~~ have been made to increase the model capacity at the global scale, e.g., a more sophisticated soil water storage capacity strategy and ~~supports of~~ more land cover support.

WAYS is a raster-based model that calculates the water balance and simulates the hydrological processes in a fully distributed way. It works on a daily time step, and the model structure consists of five conceptual reservoirs: the snow reservoir S_w (mm) representing the surface snow storage, the interception reservoir S_i (mm) expressing the ~~intercepted water in~~ water intercepted in the canopy, the root zone reservoir S_r (mm) describing the root zone water storage in the unsaturated soil, the fast response reservoir S_f (mm), and the slow response reservoir S_s (mm). Two lag functions are applied to describe the lag time from the storm to peak flow (T_{lagF}) and the lag time of recharge from the root zone to the groundwater (T_{lagS}). In addition to the water balance equation, each reservoir has also also has process functions to connect the fluxes entering or leaving the storage compartment (so-called constitutive functions). Fig. Figure 1 provides a schematic representation of how the vertical water balance is modelled in WAYSmodeled in WAYS, and the basic equations are shown in Table 1. The parameters that regulates In Figure 1, the flowchart represents the conceptualized hydrological cycle in the model, and the schematic drawing shows the corresponding water fluxes and stocks in the real world. Since some of the fluxes are intermediate variables, they are shown in the flowchart but not visualized in the schematic drawing. For instance, R_f is the generated preferential runoff in the root zone layer before the split of the runoff into surface runoff and subsurface runoff. The effective precipitation P_e is the sum of snowmelt and precipitation throughfall. The conceptualized hydrological cycle of the model can be briefly described as follows. The precipitation that can drop as rainfall or snowfall depends on the temperature. The snowfall will be stored in the snow reservoir, and the rainfall will be intercepted by the canopy before it reaches the surface. After the interception, the rainfall penetrates the canopy and reaches the surface as precipitation throughfall. The effective precipitation that consists of the throughfall and the snowmelt will partially infiltrate into the soil, and the rest runs away as runoff. The runoff is then split into surface runoff and subsurface runoff depending on the texture. A part of the infiltration will be stored in the soil for plants, and the rest will percolate into the deep soil and reach the groundwater table as groundwater recharge. The parameters that regulate the different simulation steps are described below, and the changes we made to the original FLEX model are highlighted. The original lumped model FLEX has 28 parameters in total that considers consider four land use types in the basin (Gao et al., 2014a). In order to To reduce the computation cost of calibration and avoid overfitting issues at the over-fitting issues at global scale, some calibrated parameters are replaced by the empirical values from literaturesthe literature, e.g.the snow melt , the snowmelt ratio F_{DD}, the capacity of the interception reservoir $S_{i,max}$, the groundwater recharge factor f_s and the maximum value for of groundwater recharge $R_{s,max}$.

2.2 Interception and Snow Routine

In the WAYS model, the precipitation is allowed to be intercepted by the canopy or stored as snow before enter entering into the root zone reservoir.

Interception happens during the rain days occurs during the days with rain when the temperature is above the threshold temperature T_t. Interception The interception reservoir stores the intercepted precipitation by precipitation intercepted by the canopy before it reaches the soil and will directly evaporated that will directly evaporate back into the atmosphere. The canopy water balance equation is shown in Eq. (1). Where , where the precipitation P (mm/day) is the inflow, and the precipitation throughfall P_{tf} (mm/day) and the interception evaporation E_i (mm/day) are the outflows. The calculation of the precipitation throughfall P_{tf} is simply based on comparing the rainfall P_r (mm/day) to the water already stored in the interception reservoir S_i (mm) and the capacity of the interception reservoir $S_{i,max}$ (mm) (Eq. (2)). In the FLEX model, the interception evaporation E_i is assumed to be the potential evaporation, and the interception capacity is a calibrated parameter. In WAYS, the interception evaporation E_i is calculated based on the potential evaporation E_0 (mm/d), the storage of the interception reservoir S_i (mm) and the interception reservoir storage capacity $S_{i,max}$ (Eq. (3)) by following Deardorff (1978). The interception capacity $E_{i,max}$

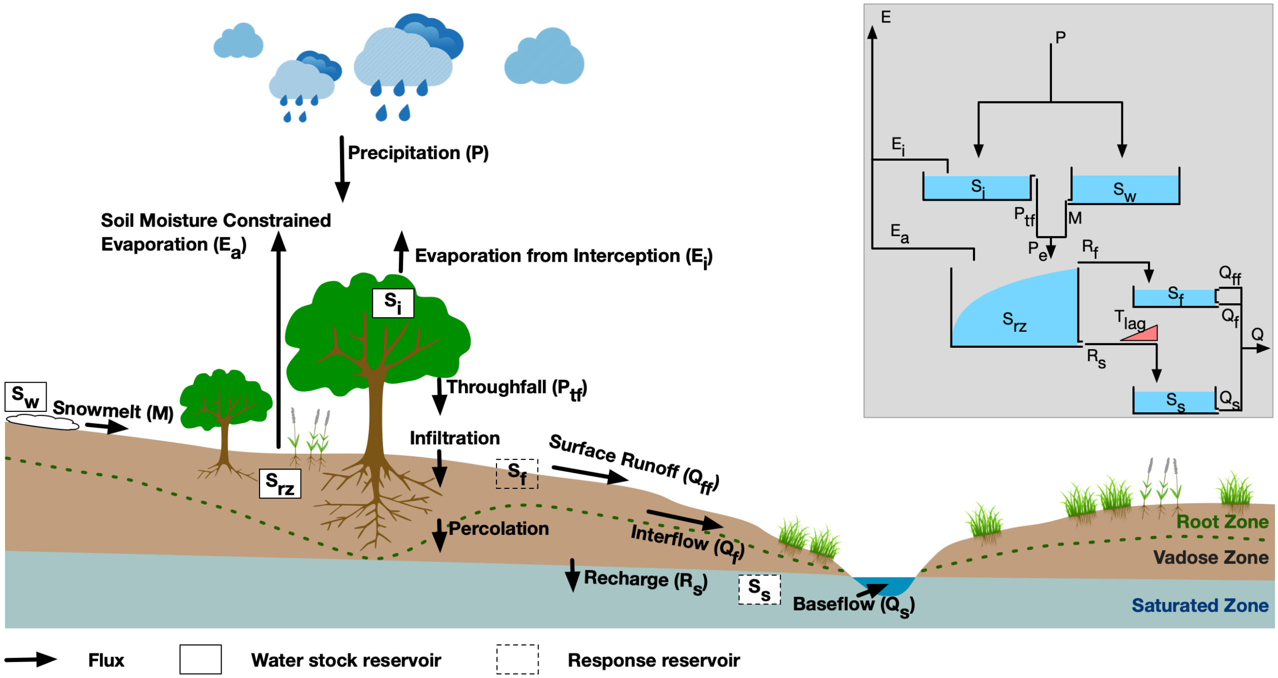

Figure 1. Model structure of ~~the~~ WAYS

is calculated by using ~~the equation~~ Eq. (4), where m_c is 0.3 mm and L is the leaf area index, which is calculated based on a modified phenology model in Jolly et al. (2005) obtained by replacing the original ~~vapour~~ vapor pressure stress function with the soil moisture in the model (Wang-Erlandsson et al., 2014).

The snow simulation is based on a simple degree-day algorithm (Rango and Martinec, 1995) ~~which is~~ that has been successfully applied in hydrological models in many studies (Comola et al., 2015; Bair et al., 2016; Krysanova and Hattermann, 2017). The water balance in the snow reservoir is described in Eq. (5), and the constitutive equations ~~is~~ are shown in Eq. (6) in Table 1. Below the threshold temperature T_t (°C), the precipitation P (mm/day) falls as snow P_s (mm/day) and is added to the snow storage S_w (mm). Above the threshold temperature T_t, snow melts if it is available ~~with~~ at a certain ratio per degree (F_{DD}). Both the threshold temperature T_t and the ~~snow melt~~ snowmelt ratio F_{DD} are parameters ~~that calibrated in~~ calibrated in the FLEX model. Following Müller Schmied et al. (2014), T_t is set to 0 °C, and F_{DD} is set for different land cover classifications ~~ranging~~ from 1.5 mm/d per degree to 6 mm/d per degree in WAYS. It is also important to be aware that the ~~snow melt~~ snowmelt water is conceptualized in the model ~~to directly infiltrate~~ as directly infiltrating into the soil in the model, thus effectively bypassing the interception reservoir.

2.3 Root Zone Routine

The effective root zone routine is the core of the WAYS model. It controls both the evapotranspiration and the runoff generation by precipitation partitioning. Similar to the interception and snow routine, the change of root zone water storage S_{rz} (mm) over time t (day) is described in Eq. (7), with effective precipitation P_e (mm/day) as the inflow and soil moisture constrained evaporation E_a (mm/day) and runoff R (mm/day) as outflows. In the FLEX model, the runoff generation is calculated based on the widely used beta function of the Xinanjiang model (Zhao, 1992)that , which is a function of the relative soil moisture in the unsaturated soil layer. The beta function for calculation of runoff in WAYS is replaced by a modified version from the work of Sriwongsitanon et al. (2016) to link the function to the water storage in the root zone layer. Depending on the root zone water storage S_{rz}, a part of the effective precipitation turns into runoff, and the rest are infiltrated into infiltrates into the soil and recharges the root zone layer. The runoff coefficient is determined by both the relative soil water content $S_{rz}/S_{rz,max}$ in the root zone and the shape parameter β that describing the spatial process heterogeneity over pixels at the global scale. The root zone storage capacity used in WAYS is derived by applying the method in Wang-Erlandsson et al. (2016), which calculates the soil moisture deficit based on satellite-based evaporation and precipitation, while it is a calibrated parameter in FLEX.

The soil moisture constrained evaporation, sometime sometimes also known as actual evapotranspiration, is calculated as a function of potential evaporation left-over the potential evaporation leftover $E_0 - E_i$ (mm/day), the relative soil water content $S_{rz}/S_{rz,max}$, the shape parameter β and the scale parameter $C_e$that , which indicates the fraction of $S_{rz,max}$ above which the transpiration is no longer limited by soil moisture stress. Since the root zone routine connects both the runoff and evapotranspiration and the runoff generation function is has been modified, the actual evapotranspiration function in WAYS is also revised accordingly accordingly revised from the original one in the FLEX model (Sriwongsitanon et al., 2016). The scale parameter C_e was is set to 0.5 in the FLEX model when applying at basin scale applied at the basin scale, and it becomes a calibrated parameter in WAYS at the global scale.

2.4 Slow Response Routine

The water balance in the slow response reservoir S_s (mm) is simple, with the groundwater recharge R_s (mm/day) as the inflow and baseflow Q_s (mm/day) as the outflow (Eq. (11)). The groundwater recharge R_s is depicted in WAYS by applying a splitter function that is the splitter function described in Eq. (12). It separates the runoff into preferential flow and groundwater recharge based on the groundwater recharge factor $f_s$that is ranging , which ranges between 0 and 1. In WAYS, the amount of groundwater recharge is also limited by a the maximum groundwater recharge $R_{s,max}$ (mm/day) for each grid cells cell, which is specified by the soil texture, while there is no constrain of constraint on the maximum value for groundwater recharge in the FLEX model. The values of $R_{s,max}$ used in this study are 7, 4.5 and 2.5 for sandy soil, loamy soil and clayey soilby , respectively, following Döll and Fiedler (2008).

The groundwater recharge factor f_s is a calibrated parameter in FLEX model the FLEX model, while in WAYS, it is now determined by applying the approach developed by Döll and Fiedler (2008)which , in which it is a function of global digital maps of the slope, soil texture, geology, and permafrost. The method is simple and computationally inexpensiveand it has been validated at , and it was validated at the global scale in many subsequent publications, e.g., Döll et al. (2012) and Döll et al. (2014). All the related parameters are provided by in look-up tables in the work of Döll and Fiedler (2008), and the only changes we made is are that the input data of the groundwater recharge method, e.g., the global relief data and the global soil texture map, has been updated accordingly have been accordingly updated based on the newly available data (Hanasaki et al., 2018). The outflow of the slow response reservoir, i.e., the baseflow, is modelled modeled with the function described in Eq. 13, where the baseflow coefficient K_s is set to 100 globally followed by following the work of Döll et al. (2003).

2.5 Fast Response Routine

The preferential flow R_f (mm/day) is routed directly into the fast response reservoir S_f (mm), and it is divided into surface runoff Q_{ff} (mm/day) and interflow Q_f (mm/day). The water balance in the fast response reservoir is shown in Eq. (14). In the FLEX model, it is assumed that the preferential flow is routed into the fast response reservoir based on a lag-function that represents the time lag between storm and fast a storm and preferential runoff generation. In WAYS, we have assumed that the preferential flow will route into the fast response reservoir directly without any delay globally, as it is run at the daily time scale.

Similar to the slow response reservoir, the fast response reservoir is also set as a linear-response reservoir, representing a linear relationship between water storage and water release. The surface runoff generation is only active when the storage of the fast response reservoir exceeds the specified threshold S_{ftr}, with a generation ratio K_{ff} (Eq. (16)), while the interflow Q_f is simply calculated in proportion to the already stored water in the fast response reservoir with using the fraction of $1/K_f$ (Eq. (17)).

2.6 Additional Model Adaptation

In addition to above-mentioned the abovementioned model description, some modifications and assumptions are necessary to adapt the model to the global scale. In WAYS, the actual evaporation from open water bodies is assumed to be the potential evapotranspiration, and the freezing of open water bodies is not considered in the model. Potential evapotranspiration is derived by the Hamon equation (Hamon, 1961) in the FLEX model, and it is now replaced by the using the Penman-Monteith FAO 56 PM method (Allen et al., 1998) . In the for the following reason. The Hamon method is found to have less robustness in different climatic conditions as well as drawbacks in the daily variability of the PET simulation due mainly to the relatively simple equation in the Hamon method, as it only employs the average air temperature as an input (Bai et al., 2016; Droogers and Allen, 2002). In contrast, the Penman-Monteith FAO 56 PM method is based on fundamental physical principles and is found to be the most reliable method for potential evapotranspiration estimation when sufficient meteorological data exist (Chen et al., 2005; Kingston et al., 2009). The Penman-Monteith FAO 56 PM method is recommended by FAO and other studies based on thorough analyses of PET method intercomparisons (Allen et al., 1998; Jian biao et al., 2005; Vörösmart . In the FLEX model, capillary rise from groundwater is also considered. However in WAYS, the feature for capillary rise simulation is removed currently disabled, as it cannot be taken into account when no information is available at the global scale. The WAYS model is written in Python version 3.6. In order to benefit from To benefit from a supercomputer, the model is designed with full support for parallel computation.

Table 1. Water balance and constitutive equations used in WAYS

Reservoirs	Water balance equations		Constitutive equations		Reference
Interception reservoir	$\frac{dS_i}{dt} = P_r - E_i - P_{tf}$	(1)	$P_{tf} = max(0, P_r - (S_{i,max} - S_i))$	(2)	-
			$E_i = E_p\left(\frac{S_i}{S_{i,max}}\right)^{2/3}$	(3)	Deardorff (1978)
			$S_{i,max} = m_c L$	(4)	Wang-Erlandsson et al. (2014)
Snow reservoir	$\frac{dS_w}{dt} = \begin{cases} -M & \text{if } T > T_t \\ P_s & \text{if } T \leq T_t \end{cases}$	(5)	$M = \begin{cases} min(S_w, F_{DD}(T - T_t)) & \text{if } T > T_t \\ 0 & \text{if } T \leq T_t \end{cases}$	(6)	Rango and Martinec (1995)
Root zone reservoir	$\frac{dS_{rz}}{dt} = P_e - R - E_a$	(7)	$P_e = P_{tf} + M$	(8)	-
			$\frac{R}{P_e} = 1 - \left(1 - \frac{S_{rz}}{(1+\beta)S_{rz,max}}\right)^{\beta}$	(9)	Sriwongsitanon et al. (2016)
			$E_a = (E_0 - E_i) \cdot min\left(1, \frac{S_{rz}}{C_e S_{rz,max}(1+\beta)}\right)$	(10)	Sriwongsitanon et al. (2016)
Slow response reservoir	$\frac{dS_s}{dt} = R_s - Q_s$	(11)	$R_s = min(f_s R, R_{s,max})$	(12)	Döll and Fiedler (2008)
			$Q_s = S_s / K_s$	(13)	Döll et al. (2003)
Fast response reservoir	$\frac{dS_f}{dt} = R_f - Q_{ff} - Q_f$	(14)	$R_f = R - R_s$	(15)	-
			$Q_{ff} = max(0, S_f - S_{ftr})/K_{ff}$	(16)	-
			$Q_f = S_f / K_f$	(17)	-

Note: all the time scale-dependent parameters need to be divided by Δt to make the equations dimensionally correct and suitable for any other time scales.

- in the reference column indicates that the formula is taken from the FLEX model.

3 Model ~~Setups~~Setup

For the assessment of model performance, the WAYS model is applied at the global scale with ~~the~~ a spatial resolution of 0.5 ~~degree~~ degrees for the historical period from 1971 to 2010. Two simulations are conducted based on two products of the global root zone storage capacity from Wang-Erlandsson et al. (2016). The model is calibrated in the period 1986-1995 and validated in the period of 2001-2010 ~~depends~~ depending on the availability of the reference data.

3.1 Driving Data

3.1.1 Meteorological Data

The model is ~~driving~~ driven by the climate data set from the Global Soil Wetness Project 3 (Kim, 2017), GSWP3 (http://hydro.iis.u-tokyo.ac.jp/GSWP3/), for the historical period from 1971 to 2010. The GSWP3 data set is generated based on the Twentieth Century Reanalysis ~~project~~ Project (Compo et al., 2011). It has been ~~proved~~ proven to be able to represent realistic ~~sub-monthly~~ submonthly variability over the entire 20*th* century (1901-2010) and has been used as a forcing data set in several other hydrological ~~modelling~~ modeling studies (Veldkamp et al., 2017; Masaki et al., 2017; Liu et al., 2017; Tangdamrongsub et al., 2018). The climate variables used in this study ~~includes~~ include precipitation, minimum temperature, maximum temperature, relative humidity, surface downwelling longwave radiation, surface downwelling shortwave radiation and wind speed at 10 ~~meter~~meters. All the variables are ~~at~~ on a daily scale and have a 0.5 degree spatial resolution~~and~~ ; in addition, the wind speed at 10 ~~meter are~~ meters is converted to the wind speed at 2 ~~meter~~ meters based on the conversion function in Allen et al. (1998), as it is required by the Penman-Monteith FAO 56 PM method for potential evapotranspiration ~~calculation~~calculations.

3.1.2 Land Use Data

The land cover data ~~we used is~~ that we used are the Global Mosaics of the standard MODIS land cover type data product (MCD12Q1) with a spatial resolution of 0.5 ~~degree~~ degrees in the year of 2001, which ~~is~~ are derived from the IGBP Land Cover Type Classification (17 classes) and are reprojected into geographic coordinates of latitude and longitude on the WGS 1984 coordinate reference system (Friedl et al., 2010).

3.1.3 Root Zone Storage Capacity

The root zone storage capacity (RZSC) data ~~is~~ are a crucial parameter in WAYS. The global root zone storage capacity data used in this study ~~is from Wang-Erlandsson et al. (2016)that is~~ are from Wang-Erlandsson et al. (2016), derived by using the "Earth observation-based" method. This method determines the soil moisture deficit at the global scale by using the state-of-the-art observation-based precipitation data and satellite-based evaporation data, under the assumption ~~of vegetation optimises~~ that vegetation optimizes its root zone storage capacity to bridge critical dry periods and ~~do~~ does not invest more in ~~their~~ its roots than necessary. ~~It~~ This method has been well justified (de Boer-Euser et al., 2019) and overcomes the shortcomings of the traditional methods (look-up table approach; field ~~observation based~~ observation-based approach) at the global scale, such as data scarcity, location bias, ~~risks~~ and risks of unlikely vegetation and soil combinations due to data uncertainty (Feddes et al., 2001). The method has been shown to increase the model performance at both the basin and global scales (Gao et al., 2014b; Nijzink et al., 2016; Wang-Erlandsson et al., 2016). Moreover, it has been proven to be able to produce plausible root zone storage capacity in boreal regions by investigating the relationship between RZSC and numerous environmental factors, including climate variables, vegetation characteristics, and catchment characteristics (de Boer-Euser et al., 2019) .

Since there are two global root zone storage capacity products ($S_{R,CHIRPS-CSM}$ and $S_{R,CRU-SM}$) presented by Wang-Erlandsson et al. (2016) based on different precipitation and evaporation data sets and there is no preference ~~on each products. In~~ for either product, in this study, both RZSC products are used. $S_{R,CHIRPS-CSM}$ ~~covering~~ covers the latitudes from 50°N to 50°S and is derived based on the United States Geological Survey (USGS) Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) precipitation data (Funk et al., 2014) and the ensemble mean of three satellite-based global-scale evaporation data sets: the Commonwealth Scientific and Industrial Research ~~Organisation~~ Organization (CSIRO) Moderate Resolution Imaging Spectroradiometer (MODIS) Reflectance Scaling EvapoTranspiration (CMRSET) data (Guerschman et al., 2009), the Operational Simplified Surface Energy Balance (SSEBop) data (Senay et al., 2013), and the MODIS evapotranspiration (MOD16) data (Mu et al., 2011). $S_{R,CRU-SM}$ ~~covering~~ covers the latitudes from 80°N to 56°S and is derived by using the Climatic Research Unit Time Series version 3.22 precipitation data (Harris et al., 2014) together with the ensemble mean of only SSEBop and MOD16 ~~due to the reason that~~ because CMRSET overestimates evaporation at high latitudes (Wang-Erlandsson et al., 2016). ~~Two~~ Since Wang-Erlandsson et al. (2016) suggested that a Gumbel normalization of RZSC by land cover types with different return periods could further improve the model performance, we have accordingly adjusted the RZSC in this study. The two selected global root zone storage capacity products are shown in ~~Fig. ??~~ Figure S13, and their mean ~~Latitudinal~~ latitudinal values are shown in ~~Fig. ??. Similar pattern and magnitude~~ Figure S14. Similar patterns and magnitudes of RZSC can be found, and there is good agreement between the two products at different latitudes, especially at low latitudes around the ~~Equator which~~ equator, where the products reflect the fluctuation with high consistency. ~~The large difference are~~ A large difference is seen mainly in the northern ~~Mid-latitude~~ midlatitude area, where the absolute difference in percentage is still less than 20%.

~~Two global root zone storage capacity products at 0.5 degree: (a) $S_{R,CRU-SM}$; (b) $S_{R,CHIRPS-CSM}$. Figures are produced based on the data provided by Wang-Erlandsson et al. (2016). Grey color indicates no data.~~

~~Mean Latitudinal root zone storage capacity of $S_{R,CRU-SM}$ and $S_{R,CHIRPS-CSM}$~~

3.2 Calibration Data

The WAYS model has a few parameters, and while some of them are obtained independently from the literature, some have to be determined by model calibration (see Table 2). The WAYS model is calibrated against the ISLSCP II UNH/GRDC Composite Monthly Runoff data (Fekete et al., 2011) from 1986 to 1995 at a 0.5 degree resolution, which ~~is a~~ are composite runoff data ~~combines~~ that combine simulated water balance model runoff estimates and monitored river discharge. The ISLSCP

Table 2. Parameter ranges of the WAYS model

Parameter	Range	Literature	Parameter	Range
$S_{i,max}$	distributed	Wang-Erlandsson et al. (2014)	β	(0, 2)
$S_{rz,max}$	distributed	Wang-Erlandsson et al. (2016)	C_e	(0.1, 0.9)
$R_{s,max}$	7/4.5/2/5 (Sand/Loam/Clay)	Döll and Fiedler (2008)	K_f	(1, 40)
K_s	100	Döll et al. (2003)	K_{ff}	(1, 9)
f_s	distributed	Döll and Fiedler (2008)	S_{ftr}	(10, 200)
F_{DD}	distributed	Müller Schmied et al. (2014)	T_{lag}	(0, 5)
T_t	0	Müller Schmied et al. (2014)		

II UNH/GRDC Composite Monthly Runoff data ~~is also a standard dataset~~ also comprise a standard data set in the second phase of ISIMIP (Inter-Sectoral Impact Model Inter-comparison Project) ~~project~~ (ISIMIP2a) (Warszawski et al., 2014) for calibration and validation, as it assimilates discharge ~~measurement~~ measurements at gauge stations and ~~also~~ preserves the spatial specificity of the water balance while being constrained by the station observations. The data can be downloaded from The Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=994).

3.3 Validation Data

In this study, the ERA-Interim/Land runoff data ~~is used for the validation of runoff simulation~~ are used for validation of the runoff simulation, and the Normalized Difference Infrared Index (NDII) is used for the validation of the WAYS model for root zone water storage simulation. ~~By considering~~ Considering the time period of coverage of both data sets (ERA-Interim/Land: 1979-2010, NDII: 2000-present) and ~~also~~ the study period (1971-2010) of this work, the period 2001-2010 ~~are select~~ is selected as the validation period. For runoff evaluation, ISIMIP2a simulations are also included, as they use the same climate forcing as our study in the same period. The purpose of inclusion of the ISIMIP2a simulations for comparison can be found in the model evaluation section (see Section 4).

3.3.1 ERA-Interim/Land Runoff Data

ERA-Interim/Land is a global land surface reanalysis data set ~~that is~~ produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Balsamo et al., 2015). The gridded data set ERA-Interim/Land is selected for model evaluation mainly because the current version of the WAYS model does not include a runoff routing model on the global scale. Therefore, the results are not comparable with observed gauge data. Since the ERA-Interim/Land data set is well assessed with ~~quality check by comparing~~ a quality check through comparison with ground-based and remote sensing observations, it has been used as reference data for many studies (Xia et al., 2014; Dorigo et al., 2017). ERA-Interim/Land runoff data ~~is~~ are one of the ~~variable in~~ variables in the ERA-Interim/Land reanalysis data set and ~~it is also~~ are widely used as benchmark data (Alfieri et al., 2013; Orth and Seneviratne, 2015; Reichle et al., 2017) ~~, due to its good agreements with~~ due to their good agreement with the Global Runoff Data Centre (GRDC) data set and the large improvement compared to the ERA-Interim runoff reanalysis datawhich was used to be , which were used as one of the reference data sets (Wang-Erlandsson et al., 2014; Balsamo et al., 2015). The ERA-Interim/Land runoff data used for this study is downloaded from in this study were downloaded from the ECMWF website (http://apps.ecmwf.int/datasets/) at a 0.5 degree resolution and a daily scale from 2001 to 2010.

It should be noted that there are other reanalysis runoff data available, such as ERA-Interim, GLDAS and NECP. However, they show low robustness based on the available research results. For instance, GLDAS v1.0-CLM was found to overestimate runoff globally, and GLDAS v1.0-Noah generated more surface runoff over the northern middle-high latitudes (Lv et al., 2018) . GLDAS v2.0-Noah showed a significant underestimation trend in exorheic basins (Wang et al., 2016). The snowmelt-runoff peak magnitude simulated by GLDAS v2.1-Noah was found to be excessively high in June and July (Lv et al., 2018). NECP runoff was found to be too high during the winter and too low during the summer in the Mississippi River Basin (Roads and Betts, 2000) . ERA-Interim was found to be less close to the observed stream flows compared with ERA-Interim/Land data (Balsamo et al., 2015) .

3.3.2 NDII Data

NDII has been was developed by Hardisky et al. (1983) for satellite imagery analysis based on calculations of the ratios of different values between infrared reflectance (NIR) and short wave shortwave infrared reflectance (SWIR)by calculating the ratios of different values between them. NDII has been found to have a strong correlation with the vegetation water content and canopy water thickness (Serrano et al., 2000; Jackson et al., 2004; Hunt and Yilmaz, 2007; Wilson and Norman, 2018). It can also be used to effectively determine the water stress of plants by taking the advantage of the property of shortwave infrared reflectance, which has the a negative relationship with leaf water content because of the large absorption by leaves (Steele-Dunne et al., 2012; Friesen et al., 2012; van Emmerik et al., 2015). Recently, Sriwongsitanon et al. (2016) found a promising linkage between NDII and the root zone water storage. Even though the NDII reflects the dynamics of RZWS better in moisture stress periods rather than in periods of moisture stress freethan in moisture stress-free periods, the general good correspondence between NDII and RZWS offering a potential value of the NDII indicates that NDII has potential as a proxy for RZWS. Therefore, in this study, NDII is used as the benchmark to assess the performance of the model for in RZWS depiction.

NDII is calculated by applying the following equation from Hardisky et al. (1983):

$$NDII = \frac{\rho_{0.85} - \rho_{1.65}}{\rho_{0.85} + \rho_{1.65}} \tag{18}$$

where $\rho_{0.85}$ is the reflectance at the $0.85\,\mu m$ wavelength and $\rho_{1.65}$ is the reflectance at the $1.65\,\mu m$ wavelength. NDII is a normalized index that ranges between -1 and 1. A low value of NDII indicates high canopy water stress, which also reflects the that there is less water content in the root zone (Sriwongsitanon et al., 2016).

In our work, the NDII is computed based on the satellite data MODIS level 3 surface reflectance product (MOD09A1) (Vermote, 2015), which provides an estimate of the surface spectral reflectance of Terra MODIS Bands 1 through 7 corrected for atmospheric conditions such as gassesgases, aerosols, and Rayleigh scattering in the Sinusoidal sinusoidal projection. The

MOD09A1 product is available ~~at~~ on an 8-day temporal scale ~~and~~ with a 500 m spatial resolution globally from 2000-02-24 ~~to~~ until the present. Each MOD09A1 pixel contains the value ~~that is~~ selected from all the acquisitions within the 8-day composite on the basis of high observation coverage, low ~~view~~ viewing angle, the absence of clouds or cloud shadow, and aerosol loading. The satellite image processing and NDII calculation are ~~done~~ performed by using the Google Earth Engine platform (http://earthengine.google.com). ~~Since some~~ Some of the MOD09A1 images are missing. In total, 452 NDII rasters are generated for the validation period (2001-2010).

3.4 Calibration Strategy

A global parameter optimization algorithm (Tolson and Shoemaker, 2007), dynamically dimensioned search (DDS), has been applied in this study for model ~~parameters~~ parameter calibration. DDS is designed for computationally expensive optimization problems and has been used in many studies related to ~~the~~ distributed hydrological model calibration at global and regional scales (Moore et al., 2010; Kumar et al., 2013; Rakovec et al., 2016; Nijzink et al., 2018; Smith et al., 2018).

Since the reference data, i.e., ISLSCP II UNH/GRDC data, ~~is at~~ are at a monthly temporal scale, the ~~simulated runoff~~ runoff simulated by WAYS in the calibration period (1986-1995) is also averaged to the monthly scale for ~~the sake of~~ consistency. The ~~criteria~~ criterion of fit for calibration is the Nash-Sutcliffe efficiency coefficient (NSE)~~and the optimization algorithm DDS~~ , and the DDS optimization algorithm is run with 2000 iterations for each grid ~~cells~~ cell for parameter estimation, as suggested by the author of DDS (Tolson and Shoemaker, 2007).

4 Model Evaluation

To evaluate model performance, simulated runoff and root zone water storage values are compared to the reference data (see Section 3.3) for the validation period (2001-2010) in ten major river basins of the world ~~by~~ considering the coverage of the root zone storage capacity products ($S_{R,CHIRPS-CSM}$ covers only the latitudes from 50°N to 50°S).

4.1 Runoff Evaluation

~~The~~ WAYS simulated runoff values are compared to the ERA-Interim/Land runoff as well as ~~the multi-model~~ to the multimodel global runoff simulations from ISIMIP2a~~project~~. ISIMIP is a community-driven global platform that supports ~~for model inter-comparison~~ model intercomparison studies at both global and regional scales, while ISIMIP2a focuses on the historical period, and all the models are driven by four state-of-the-art climate forcing ~~(Warszawski et al., 2014). Since the~~ factors (Warszawski et al., 2014). Since WAYS uses the same driving data as the ISIMIP2a ~~simulations are widely studied and~~ models and the ISIMIP2a simulations have been widely discussed in many studies (Schewe et al., 2014; Müller Schmied et al., 2016; Gernaat et al., 2017; Zaherpour et al., 2018), ~~the~~ we also perform a comparison between WAYS and the ISIMIP2a models ~~can provide added-value for evaluation in addition to examine only with reference data~~to further evaluate our model. To make the climate forcing consistent with the WAYS model, only the ~~GSWP3 driven~~ GSWP3-driven simulations are used for comparison. The evaluation is ~~done at monthly scale~~ performed at the monthly scale, even though the WAYS model simulates the runoff at ~~daily scale due to the reason that~~ the daily scale, because only monthly runoff data are available for some of the ISIMIP2a models (Warszawski et al., 2014).

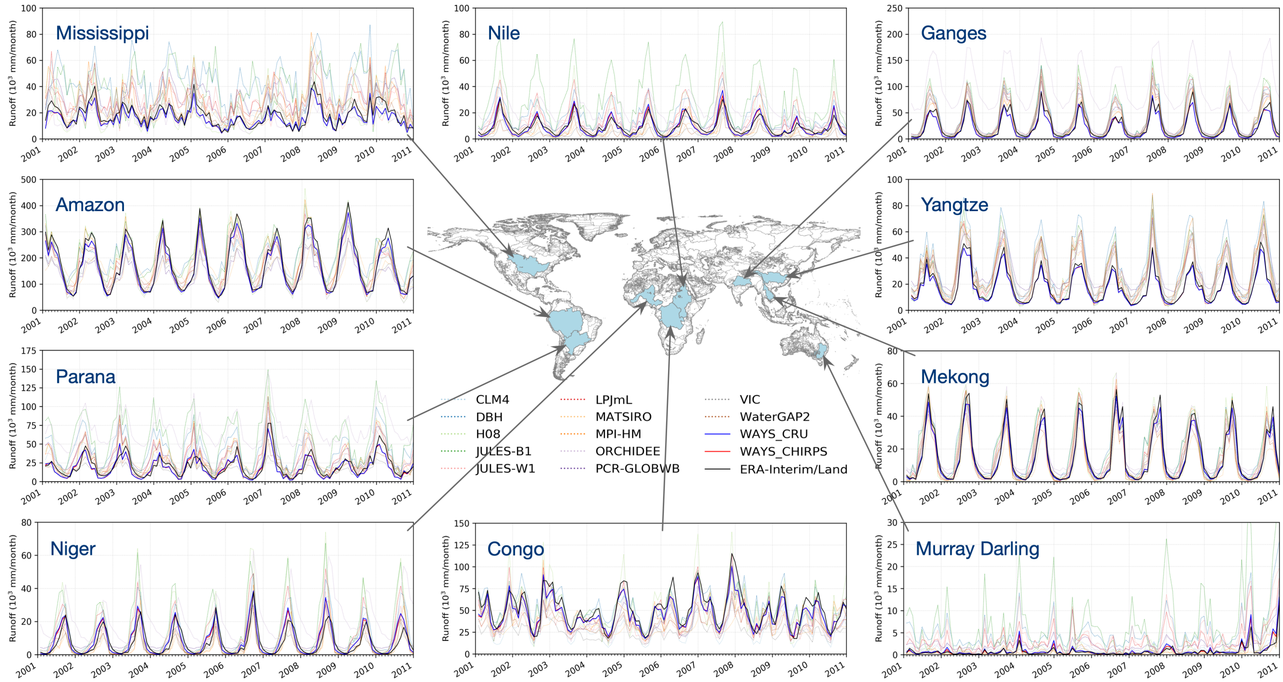

Figure 2. Time series of monthly runoff simulated by WAYS and ~~also~~ the ISIMIP2a models, as well as the reference data. The ~~highlighted~~ basins highlighted in the world map ~~indicates~~ indicate the selected catchments for model evaluation. The solid lines in blue and red indicate the WAYS ~~simulation~~ simulations with two different RZSC products. The solid line in black indicates the ~~reference~~ ERA-Interim/Land data, and ~~dash~~ dashed lines ~~represents~~ represent the ~~simulation of~~ ISIMIP2a model simulations. In some plots, the red line is not visible and is covered by the blue line due to the small differences between the two WAYS runs. WAYS is calibrated using Composite Monthly Runoff data, while the ISIMIP2a models are not calibrated for the simulation.

Figure 2 shows the time series of runoff from reference data and different models. WAYS_CRU in the legend indicates the runoff simulated by the WAYS model with root zone storage capacity product $S_{R,CRU-SM}$, and WAYS_CHIRPS ~~implies~~ denotes the simulation with RZSC product $S_{R,CHIRPS-CSM}$. First, it can be seen that the two WAYS simulations with different RZSC products show extremely good correspondence in all selected basins. This result is consistent with the investigation of RZSC data sets in Section 3.1.3, where there is a high consistency in the two used products~~even~~ , which even show that RZSC itself naturally ~~shows~~ exhibits high variability along the latitudes (see Figure ~~?? and ??~~S13 and S14). This result confirms the robustness of ~~RZSC products~~ the RZSC products that we used in our WAYS model for runoff simulation. ~~Results~~ The results show good agreements between WAYS simulations and the reference data, i.e., ERA-Interim/Land in the selected basins, ~~whilst~~ while the ISIMIP2a models present stark differences in ~~simulating runoff. E.g.~~ the simulated runoff. For example, the ISIMIP2a models show a clear trend of overestimation in some of the basins (Mississippi, Ganges, Yangtze, Parana and

Murray Darling), where the spread of the runoff ensembles ~~are~~ is also large. This ~~is partly due to the reason that~~ result occurs partly because some of the ISIMIP2a models are not calibrated at all (Zaherpour et al., 2018), ~~whilst the~~ whereas WAYS is calibrated to a Composite Monthly Runoff data set ~~which~~ that assimilates the monitored river discharge (Fekete et al., 2011).

In ~~Mekong rive~~ the Mekong River basin, all the models show a high consistency in monthly runoff generation, with a narrow spread of the ensemble. This ~~can be contributed by~~ result may be due to the natural characteristics of ~~Mekong river~~the Mekong River, i.e., highly predictable timing and size of the wet-season peak. ~~Because~~ In addition, precipitation in this region is concentrated in an extremely regular wet-season peak under the impact of tropical ~~monsoon~~ monsoons (Adamson et al., 2009). The ~~outperforming of WAYS~~ manner in which WAYS outperforms the other models is also observed in the northernmost (Mississippi) and southernmost (Murray Darling) catchments ~~in~~ of our selected basins, ~~whilst~~ while the ISIMIP2a models show extremely large differences in ~~runoff simulation~~ the runoff simulations with large uncertainties. The good performance is particularly highlighted in the Murray Darling basin, ~~the monthly runoff~~ where the monthly runoffs are extremely low, due mainly to the anthropogenic climate impacts (Cai and Cowan, 2008; Potter and Chiew, 2011), which is extremely difficult for other models to capture ~~it without overestimations~~ without overestimation (see Figure 2). A slight overestimation is found in the WAYS model in two African basins, i.e., the Nile and Niger. This result can be explained by the general overestimation of the precipitation value in climate forcing data GWSP3 in these regions (Muller Schmied et al., 2016). In these two regions, the ISIMIP2a simulations also show dramatic overestimations. ~~Oppositely,~~ In contrast, the models show a trend of underestimation in ~~anther African basin~~another African basin, the Congo. This result might be caused by both the quality of precipitation and the complexity of natural processes here (Tshimanga and Hughes, 2014). Wang-Erlandsson et al. (2014) reported in ~~his~~ their work that Congo precipitation and runoff estimates are particularly uncertain in general. It is worth ~~to highlight~~ highlighting that the WAYS model can still capture ~~well~~ the monthly variability of runoff in this basin well.

To evaluate the ability of the WAYS model ~~for distributionreplication~~to replicate the distribution, a comparison study on ~~he~~ the probability of exceedance is ~~done~~ conducted, and the result is shown in Figure 3. The probability of ~~exceedence reveals of~~ exceedance reveals the model performance at different magnitudes. With a visual inspection, we can see that WAYS is able to reproduce the runoff distribution well with a good match to the ERA-Interim/Land data, especially in the ~~basins of~~ Congo, Parana and Mississippi basins, while the ISIMIP2a model simulated runoff ~~skewed differently to~~ is skewed differently than that of the ERA-Interim/Land runoff distribution. In a few basins (Nile, Ganges, Parana and Mississippi), some of the ISIMIP2a ~~model~~ models even show a bear-sized shift of distribution relative to the reference data~~highlight~~ , highlighting that these models struggle to ~~simulation~~ simulate the monthly runoff at all different magnitudes. In the Nile and Niger basins, WAYS also shows a slight offset for both simulations, but ~~still lie~~ it still lies within the uncertainty range. ~~Results~~ The results also show a large uncertainty ~~of~~ in the runoff simulations in ~~upper tails~~ the upper tails, which reflects the larger deviation in ~~high value producing than in middle and low value simulation~~ the high values produced than in the middle- and low-value simulations for the models. Such biases in reproducing the runoff distribution in the ISIMIP2a models, in turn~~delivers~~ , deliver large ensemble spreads in the time series.

To further assess the performance of the WAYS model, three general metrics for runoff comparison are selected for the evaluation, i.e., the Nash-Sutcliffe Efficiency (NSE), root mean squared error (RMSE) and percent bias (PBIAS). The estimated

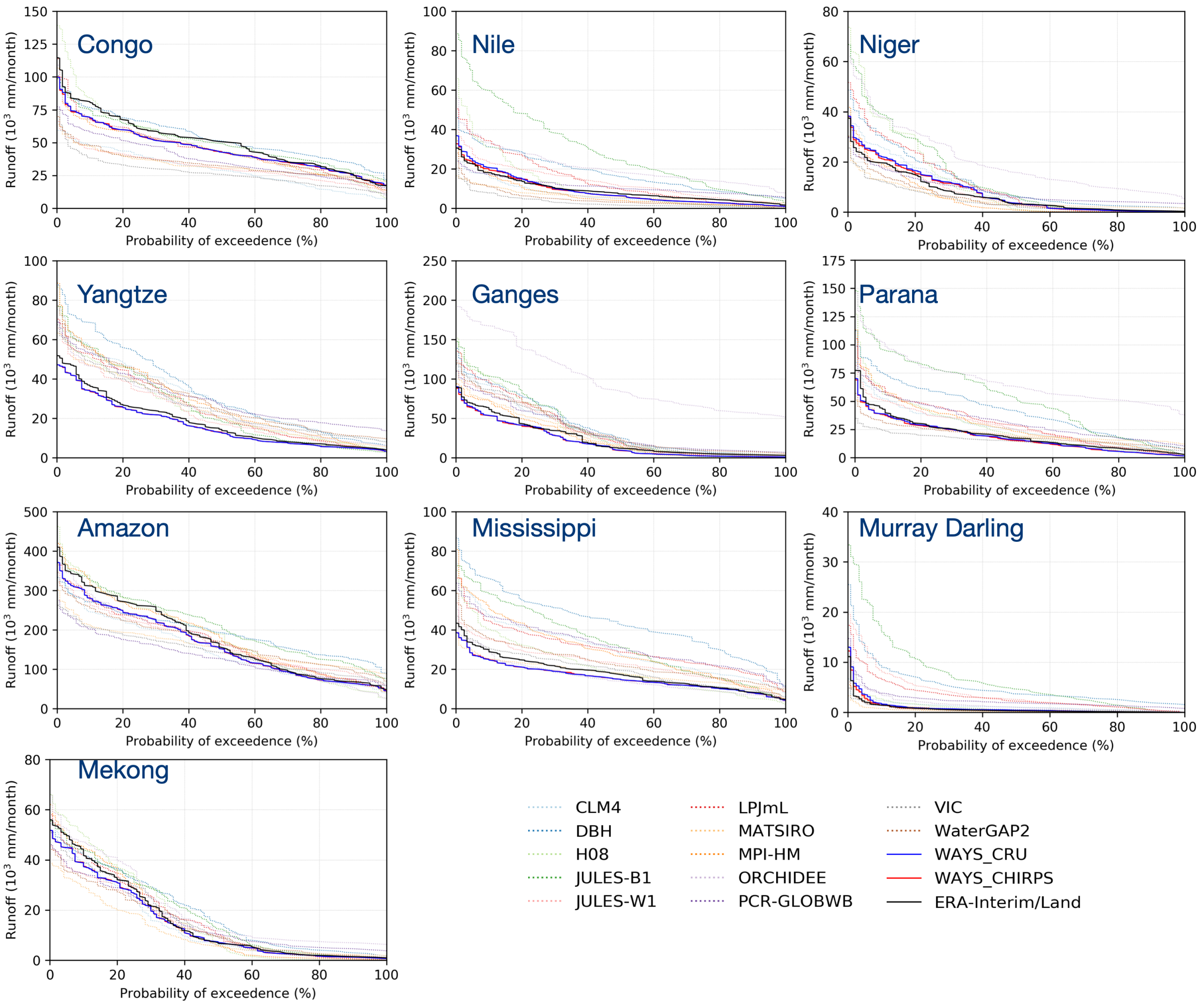

Figure 3. The probability of ~~exceedence~~ exceedance for monthly runoff simulated by different models as well as the reference data in ten selected basins. The solid lines in blue and red indicate ~~the~~ WAYS ~~simulation~~ simulations with two different RZSC products. The solid line in black indicates the ~~reference~~ ERA-Interim/Land data, and ~~dash~~ dashed lines ~~represents~~ represent the ~~simulation of~~ ISIMIP2a model simulations. In some plots, the red line is not visible and is covered by the blue line due to the small differences between the two WAYS runs. WAYS is calibrated using Composite Monthly Runoff data, while the ISIMIP2a models are not calibrated for the simulation.

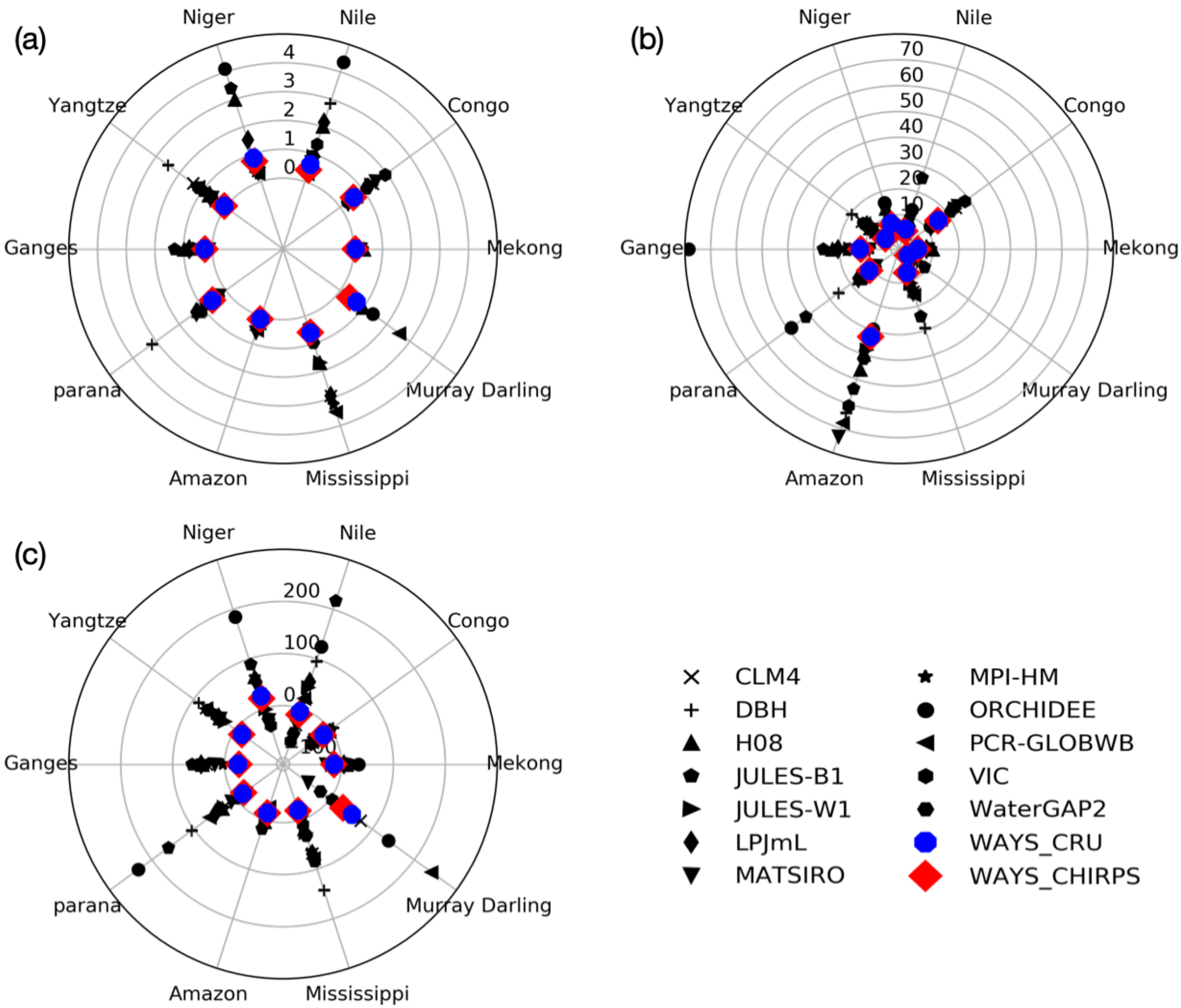

Figure 4. The ~~catchments~~ catchment clockwise pole plot according to different metrics, (a) 1-NSE, (b) RMSE, and (c) PBIAS. Colored ~~makers~~ markers indicate the score for the WAYS model with two different simulations, and black ~~makers~~ markers represent the score for ISIMIP2a models. For all the metrics, the value of 0 is the benchmark.

scores from the monthly runoff time series for WAYS and the ISIMIP2a models are present presented in Figure 4. For better comparison, the NSE values are converted to the values of 1-NSE , thusthe values; thus, numbers closer to 0 indicates indicate better performance. The model performance of WAYS is generally better compared to than that of the ISIMIP2a models, and the estimated scores based on different criteria are also close to the benchmarks. The 1-NSE comparison (Figure 4 (a)) indicates that the model performance of WAYS in the selected basinsexcept for , except for the Niger and Nile, is particularly favorable when compared to the other ISIMIP2a models. In these basins, both of two the WAYS simulations (WAYS_CRU and WAYS_CHIRPS) are ranked in the top five (14 model simulations in total in the comparison). In six basins, both of the WAYS simulations have the 1-NSE metric scores less than 0.3resulting , resulting in a value of NSE larger of greater than 0.7. In the Yangtze, Amazon and Mekong, the WAYS mode model is even ranked as the best one, with both of two simulations outperformed the simulations outperforming the others. The relatively low performance of WAYS in the Niger and Nile is the result of the model slightly overestimating the middle and high runoff values (Figure 3). The RMSE comparison (Figure 4 (b)) delivers similar information as information similar to the 1-NSE comparisonthat , in which WAYS shows generally better performance. In the Amazon, all the model simulations show large RMSE due to the large value of monthly runoff in this catchment. By examining the percent bias (Figure 4 (c)), it is evident that the WAYS model performs well in most of the basins, as the scores of the two WAYS simulations are close to the benchmark. The A relatively poor performance of WAYS model on the WAYS model in the percent bias assessment is found in the Murray Darling basinwith the PBIAS values are round , with PBIAS values of approximately 100%, but they are still lie within the uncertainty range by checking based on a check with other models. This large value may be caused by the extremely low runoff induced runoff-induced low value of the benchmark, while a little difference in in which a slight difference in the absolute value will cause a large difference in the percentage.

Combining the time series analysis, most commonly used metrics metric examination in hydrology as well as the probability of exceedence and probability of exceedance assessment, our results show a comprehensive assessment of the model performance on in runoff simulation. Strong The strong performance of WAYS with the subtle difference between the runoff simulation and reference data in all the tests indicating particularly favourable indicates the particularly favorable applicability of WAYS in runoff simulation across major basins. Even though , relatively poor performance relatively poor performances are found in two African basins, but the biases are still lie within the uncertainty range by investigating based on investigations of other models. Such a trend of overestimation could also be explained by the overestimation of the precipitation value in the forcing data in this these regions (Muller Schmied et al., 2016). In addition, it is worth acknowledging that global hydrological models show large different in runoff simulation differences in runoff simulations across basins. Previous studies emphasized that large ensemble spreads from GHMs could be caused by model structural uncertainties (Haddeland et al., 2011; Gudmundsson et al., 2012). Lacking The lack of physical process representations, e.g., transmission loss, in the hydrological models can also explain some of the biases between the simulated runoff and the reference data (Gosling and Arnell, 2011).

The performance of WAYS is further evaluated against the gauge observations. Since WAYS does not have a native runoff routing module at the moment, a third-part runoff routing tool, CaMa-flood, is applied to route the WAYS simulated runoff (Yamazaki et al., 2011). The evaluation results can be found in the Supplementary Information (SI).

4.2 ~~The~~ Validation of Root Zone Water Storage

Similar to the runoff evaluation, the performance of the simulation of root zone water storage by the WAYS model is also evaluated at ten major river basins in the period from 2001 to 2010. The spatial pattern as well as the RZWS dynamics at different latitudes and in different months can be found in the SI of the paper. Since the NDII is a normalized index and ~~in a~~ on an 8-day temporal scale, the WAYS simulated root zone water storage is ~~firstly averaged to~~ first averaged over an 8-day temporal scale and then normalized to the range between 0 and 1 before the comparison. A few time steps are missing in the NDII data set. To keep the compared data sets consistent, only pair-wised RZWS data are selected for the model evaluation.

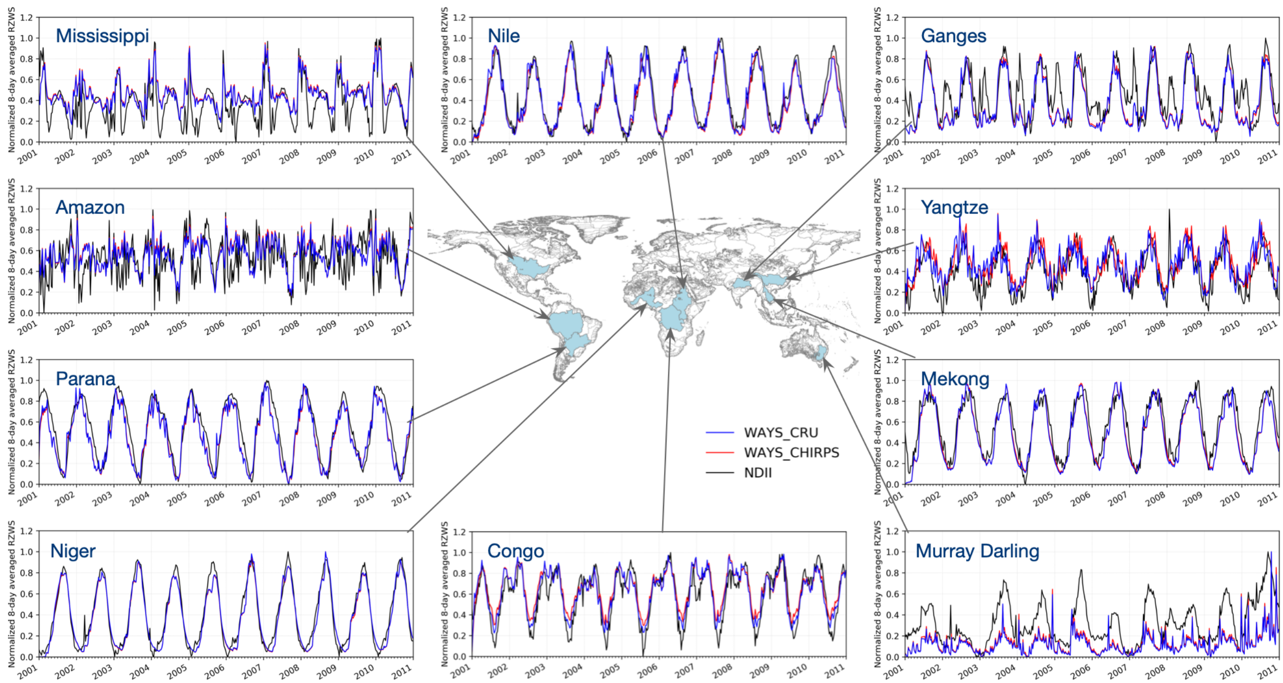

Figure 5. Time series of 8-day normalized RZWS simulated by the WAYS model and NDII value.

The 8-day NDII values are compared to the 8-day averaged root zone water storage values of ~~WAYS model~~ the WAYS model, and the results are shown in Figure 5 and Table 3. Figure 5 shows ~~the comparison of~~ a comparison of the time series of NDII and simulated RZWS in the selected basins, and Table 3 presents the corresponding rank correlation (Spearman's rho) between NDII and RZWS. The ~~simulated RZWS~~ RZWS simulated by GEPCI-hydro is not compared to the other model, as the RZWS variable is not available in other GHMs. For ISIMIP2a, some models produced the root zone soil moisture ~~with~~ within a fixed depth of the soil profile in the model structure. However, ~~it~~ this is still a different variable compared with the root zone water storage.

First, it is clear ~~to see~~ that NDII shows totally different patterns in different basins. Clear seasonal cycles are shown in the Nile, Mekong, and Niger river basins and so on. Camel-like structures are observed in the Ganges and Congo basins, and

Table 3. The rank correlation of NDII and ~~WAYS simulated~~ WAYS-simulated RZWS in ten selected basins

Selected River Basins	Models	
	WAYS_CRU	WAYS_CHIRPS
Congo	~~0.875~~ 0.872	~~0.862~~ 0.871
Nile	~~0.962~~ 0.951	~~0.966~~ 0.967
Niger	~~0.955~~ 0.975	~~0.960~~ 0.975
Yangtze	~~0.709~~ 0.713	~~0.754~~ 0.764
Ganges	~~0.802~~ 0.803	~~0.807~~ 0.817
Parana	~~0.932~~ 0.931	~~0.938~~ 0.934
Amazon	~~0.533~~ 0.593	~~0.506~~ 0.552
Mississippi	~~0.675~~ 0.689	~~0.661~~ 0.677
Murray Darling	~~0.667~~ 0.614	~~0.678~~ 0.636
Mekong	~~0.945~~ 0.936	~~0.943~~ 0.938

relatively complex patterns are represented in the Mississippi, Murray Darling and Amazon basins. The simulated RZWS shows ~~a~~ good agreement in the time series with NDII in most of the selected basins. High values of rank correlation are also detected in these regions. Seven catchments ~~out~~ of ten have ~~the~~ a rank correlation value higher than 0.7, especially in the Nile, Niger, Parana and Mekong, where the correlation coefficients are even higher than 0.9, indicating the strong model performance of WAYS in these basins for root zone water storage simulation, as the NDII reflects the soil water content in the root zone (Sriwongsitanon et al., 2016). ~~Two~~ The two simulated RZWS time series with different root zone storage capacity products ~~show also identical behaviour~~ also show identical behavior with subtle differences~~between each other~~, except in the Yangtze ~~river~~ River basin due to the relatively larger differences in the averaged RZSC of the two products ($S_{R,CRU-SM}$: 135 mm, $S_{R,CHIRPS-CSM}$: 163 mm) in this basin. In the Ganges and Congo, the NDII time series show a two-humped structure~~while~~ , which the WAYS model can still capture~~it~~, even though underestimations are detected in some years. The rank correlation coefficients in these two catchments are higher than 0.8. In the Yangtze, a suddenly high value of NDII is found on the ~~day of~~ 25th of August in 2008. By investigating the NDII values a few days before and after ~~and also~~ this date and the precipitation amount in this period, the unrealistic high value might be caused by the quality of satellite data MOD09A1 on that day, ~~since~~ as it can be affected by many issues, including clouds, shadow, ~~view~~ viewing angle, aerosol loading and so on (Vermote, 2015).

~~The relatively larger~~ Relatively large differences between NDII and simulated RZWS are also found in some catchments. In the Mississippi, WAYS shows a good performance ~~on large values simulation while~~ in large-value simulations, while it struggles to simulate low values~~with considerable overestimations on it. Therefore~~, with considerable overestimation of them. Therefore, the rank correlation is also relatively low in this catchment~~with values around~~ , with values of approximately 0.67. The Mississippi river basin is the northernmost catchment ~~in~~ of our selected basins. The NDII ~~show~~ here shows a totally different pattern ~~compare~~ compared to the others, while ~~WAYS simulated RZWS show relatively~~ the WAYS-simulated RZWS can barely show a clear seasonal variation. ~~The possible explanation on it could be either NDII has difficulty to reflect the~~

~~RZWS or the WAYS has shortcoming to simulate the RZWS in this region. Because some studies reported that~~ There could be multiple reasons for this overestimation: our model has a relatively simple snowmelt module (degree-day method), which could consequently introduce biases into the simulation, especially in relatively cold regions. Additionally, the relatively uncertain forcing data could contribute to the mismatches between NDII and RZWS, as the largest uncertainties in precipitation occur mainly at the higher latitudes (Vinukollu et al., 2011). Some studies also reported that precipitation-induced spurious seasonal and ~~inter-annual~~ interannual variations also exist in the soil moisture in this basin (Yang et al., 2015). ~~Oppositely~~In contrast, WAYS shows a trend of underestimation in the Murray Darling. ~~The possible reason behind~~ A possible reason could be that deep rooted plants are widespread across the Murray Darling basin and can tap into groundwater (Runyan and D'Odorico, 2010; Lamontagn ; thus, the NDII may not be the correct proxy for moisture stress in this region. A vast amount of groundwater drawing from the saturated zone to the root zone could explain such underestimation of RZWS (Leblanc et al., 2011). Other reasons behind these findings could be the underestimated RZSC in this region as well as the intensive human activities, including dam construction, a water diversion system and river management, which will impact both the RZSC estimation and RZWS simulation (Reid et al., 2002; Kingsford, 2000). In the Amazon, the model can only ~~captures~~ capture a few downward ~~trough and shows difficulty to represent~~ troughs but shows difficulty in representing the complete complex dynamics of NDII, resulting in the lowest value of the rank correlation (~~0.533 and 0.506~~0.593 and 0.552) among all the selected basins. The primary reason ~~of~~ for this low performance could be the inability of NDII to represent RZWS in relatively wet regions where water stress for ~~plant is low . (Sriwongsitanon et al., 2016). In~~ plants is low (Sriwongsitanon et al., 2016). Among our selected basins, the Amazon has the highest averaged annual precipitation amount~~with a number~~, with a value of 2201 mm/year in the validation period. In this case, the performance of WAYS ~~on RZWS simulation in~~ in the RZWS simulation of such regions cannot be justified.

Overall, these model validation results over the ten selected river basins deliver generally good evaluated values that ~~suggesting~~ suggest the capability of the WAYS model for RZWS simulation, especially for ~~inter-annual~~ interannual variability simulation. However, attention should also be paid ~~in~~ to some regions, e.g.~~the basins in~~, the basins at high latitudes in the Northern Hemisphere as well as the regions with plenty of precipitation where moisture stress might be low and NDII may not ~~reflect correctly~~ correctly reflect the RZWS dynamics (Sriwongsitanon et al., 2016).

4.3 Evaporation Evaluation

RZWS has a close link to the total evaporation, as RZWS represents the available water that plants can use. In this section, the performance of WAYS in evaporation simulation is evaluated against the FLUXNET2015 data. FLUXNET2015 is a global network of micrometeorological flux measurement sites that measure the exchange of CO_2, water vapor and energy between the biosphere and the atmosphere (Pastorello et al., 2017). The tower-measured latent heat flux (LF, W/m^2) is converted to ET (mm/day) using the proportionality parameter between energy and depth units of ET (Velpuri et al., 2013) as follows:

$$ET = \frac{LE}{\lambda} \tag{19}$$

where λ is the latent heat of vaporization (2.45 MJ/kg). In total, 108 stations are selected based on the data availability in the period 1971-2010. The flux tower latent heat is converted to evaporation before the comparison. The correlation coefficients between simulated evaporation and the FLUXNET2015-derived evaporation are then calculated on the monthly scale.

The results are shown in Figure S15. The background is the annual averaged evaporation from WAYS for the period 1971-2010. The points indicate the comparison results between the flux tower and WAYS simulation. The locations of the points indicate the locations of the flux towers, and the colors indicate the correlation coefficient. WAYS is found to have relatively better performance in America, Europe and China than in Africa and Australia. However, a few stations near the boundary of America and Europe also show weak correlations between the simulations and flux tower data.

Figure S16 shows the percentage of data points within different intervals of the correlation coefficient. The calculated correlation coefficient is crowded in the interval of 0.6-0.8, while more than half of the stations (56%) show a correlation coefficient of more than 0.6. The relatively poor performance of the model in some regions could be partially explained by the following reason. FLUXNET2015 corresponds to point-based observation data, while WAYS simulates the evaporation on grid cells with a 0.5 degree spatial resolution. For the comparison, the model simulation in a certain pixel is selected based on the distance between the flux tower and the center of the pixel. The model simulation actually represents an averaged value for a 0.5 x 0.5-degree pixel. This averaging will inherently introduce errors when comparing the simulation to station-based data. Similar results are also found in other studies comparing FLUXNET2015 data to either model simulations or remote sensing-derived evaporations (Lorenz et al., 2014; Velpuri et al., 2013).

Furthermore, the average monthly evaporation is compared to the FLUXNET2015 data at each flux tower, and the results are shown in Figure 6. Good correspondence between the model simulation and flux tower data can be found by visual inspection. The points with a higher correlation coefficient show a better relationship between the model simulation and flux tower observation and are distributed closer to the diagonal. The evaluation results confirm the generally good performance of WAYS in monthly evaporation simulation. The detailed results on evaporation evaluation against FLUXNET2015 are provided in the SI as Excel files. In addition, an evaluation of the evaporation simulation is further conducted against LandFluxEVAL, a merged benchmark synthesis product of evaporation at the global scale (Mueller et al., 2013). The results can be found in the SI.

4.4 The Effect of Root Zone Storage Capacity on Hydrological Simulation

RZSC is a key parameter of the WAYS model. Therefore, it is important to investigate how RZSC could affect the model simulation. In addition to the model simulated with satellite data-derived RZSC products ($S_{R,CHIRPS-CSM}$ and $S_{R,CRU-SM}$), we have additionally conducted WAYS simulations with RZSC derived from uncertain root depth and soil data. The uncertain RZSC ($S_{R,LOOKUP-TABLE}$) is derived based on literature values of root depth and soil texture data (Müller Schmied et al., 2014; Wang-E . Due to the global coverage of the RZSC data ($S_{R,CRU-SM}$), only the simulation with $S_{R,CRU-SM}$ is used for comparison. The spatial distribution of the uncertain RZSC is shown in Figure S17, and the differences between $S_{R,CRU-SM}$ and $S_{R,LOOKUP-TABLE}$ are shown in Figure S18. It can be seen that there are large differences between the two RZSC products. The simulation with uncertain RZSC $S_{R,LOOKUP-TABLE}$ shows overestimation globally except for some regions around low-middle latitudes.

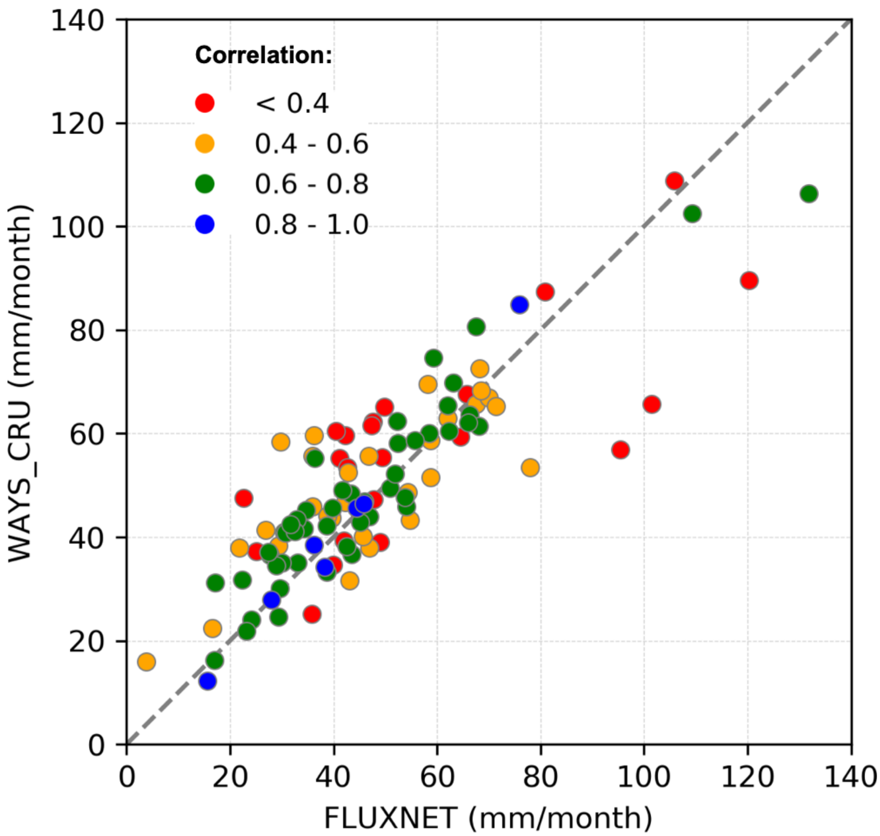

Figure 6. Averaged monthly evaporation of WAYS simulation (WAYS_CRU) against the FLUXNET data.

The latitudinal averaged RZSC further confirms the overestimation of $S_{R,LOOKUP-TABLE}$ at middle-high latitudes (Figure S19).

The large differences between these two RZSC data sets also introduce differences in simulated hydrological elements. Figure S20 shows the impacts of RZSC on the model simulation, including runoff, evaporation and RZWS. A blue color (decrease of RMSE and increase of the ranked correlation) indicates an improvement of the simulated results by replacing the uncertain RZSC ($S_{R,LOOKUP-TABLE}$) with satellite data-derived RZSC ($S_{R,CRU-SM}$), while a red color implies the opposite. For comparison, reference data are used for different variables. For runoff, evaporation and RZWS, the reference data are ERA-Interim/Land (2001-2010, monthly), LandFluxEVAL (1989-2005, monthly) and NDII (2001-2010, 8-days), respectively. Generally, the model simulations are improved by using the RZSC $S_{R,CRU-SM}$. This result emphasizes the importance of an appropriate representation of RZSC in WAYS. A decline of the model performance is also found in some regions at high latitudes and low latitudes. This result can be partially explained by the inherent uncertainty in the $S_{R,CRU-SM}$ data, as they are derived from other data sets. The RZSC derivation method itself as well as the input data can also introduce biases (Wang-Erlandsson et al., 2016).

Figure 7 shows the RMSE improvements of simulated monthly evaporation for different land covers obtained by implementing the satellite data-derived RZSC ($S_{R,CRU-SM}$) instead of the uncertain RZSC ($S_{R,LOOKUP-TABLE}$). The analysis reveals that the satellite data-derived RZSC ($S_{R,CRU-SM}$) has great potential to improve the evaporation simulation for all kinds of land covers. The largest improvements are found in broadleaf forests. The improvements in the needleleaf forest, mixed forest and savanna are relatively low. The findings also resonate with another work that used a simple terrestrial evaporation to atmosphere model (STEAM) for evaporation simulation (Wang-Erlandsson et al., 2016).

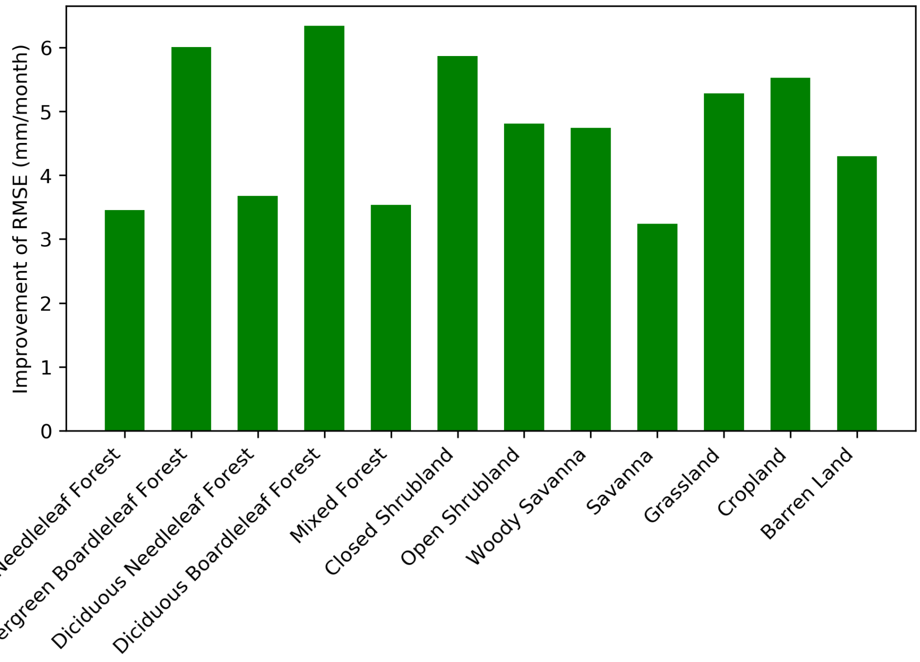

Figure 7. The improvement of RMSE in evaporation simulations for different land covers by using the satellite data-derived RZSC ($S_{R,CRU-SM}$) instead of the uncertain RZSC ($S_{R,LOOKUP-TABLE}$).

5 Discussion and conclusion

In this study, a global hydrological model has been developed that aims to simulate the soil water volume ~~storied~~ stored in the entire root zone, a critical variable for ~~eco-hydrology related researches~~ecohydrology-related studies, by considering the ~~globally~~ global spatial heterogeneity of the plant rooting system. The primary motivation behind the development of WAYS is to improve the integrality of soil water simulation in hydrological models by acknowledging the key role played by RZWS in many applications~~by RZWS~~ , as it connects the climate, hydrology and earth surface systems (Savenije and Hrachowitz, 2017). Existing models represent the soil profile with different schemes (Devia et al., 2015). However~~they still suffering~~ , they still suffer from the structure limitations of the models ~~to reflect~~ in reflecting the soil water dynamics for the entire rooting system

(Bierkens, 2015; Sood and Smakhtin, 2015). A persistent weakness in the RZWS simulation in the hydrological models is the lack of direct ~~observation for the~~ observations for model evaluation (Sriwongsitanon et al., 2016).

Benefiting from recent ~~progresses~~ progress made in the field of hydrology and remote sensing, the WAYS model is developed based on an advanced lumped model~~FLEX (Fenicia et al., 2011; Gao et al., 2014a)~~ , FLEX (Fenicia et al., 2011; Gao et al., 2014a) , and evaluated with a proxy of RZWS, ~~a remote sensing based~~ the remote sensing-based index NDII (Hardisky et al., 1983). NDII is not new, but strong linkage between NDII and RZWS found by Sriwongsitanon et al. (2016) enlightened ~~the workof us. The~~ our work. This potential candidate as a proxy of RZWS bridges the gaps in the field, where RZWS cannot be directly observed at large ~~seale~~scales. The model FLEX is widely used and has been validated for root zone water dynamics simulation~~but at~~ , but at the basin scale (Gao et al., 2014b; Nijzink et al., 2016; de Boer-Euser et al., 2016; Sriwongsitanon et al., 2016). A variety of modifications and extensions are made based on FLEX ~~allows~~ that allow WAYS to simulate the hydrological cycles at the global scale with an advanced schema in the root zone system. Another key parameter that allows appropriate RZWS simulation in WAYS is the global RZSC ~~produced recently~~ recently produced by Wang-Erlandsson et al. (2016). Before that, it ~~is usually obtained from~~ was usually obtained by look-up approaches with inherently large uncertainty~~in it~~. RZSC reveals the spatial heterogeneity of the plant rooting system and has ~~direct relation with RZWS. Since the~~ a direct relation to RZWS. Moreover, RZSC is produced under the assumption that plants do not invest more in their roots than necessary to bridge a dry period. Thus, this assumption is also ~~hold~~ held by our work, and the root zone reservoir (Section 2.3) actually defines the part of the unsaturated zone that determines the dynamics of the runoff regime (Sriwongsitanon et al., 2016; Savenije and Hrachowitz, 2017).

The major goal of this study is to test the feasibility of WAYS for reliable RZWS simulation. The newly developed model is ~~validated on both the runoff simulation and also RZWS simulation . Strong performance are found in runoff~~ first validated for runoff and RZWS simulation ~~, especially its vantage performance compared to the ISIMIP2a models~~in ten major basins across the world and is then further evaluated against station observations, including flux tower and gauge data. Despite regional differences, general good performances are found for runoff and evaporation simulation. In addition~~to the runoff depiction~~, the WAYS model ~~show also~~ also shows a good representation of RZWS, with high values of rank correlation in most of the validated regions. The evaluation results confirm the capacity of WAYS as a useful tool to simulate ~~the~~ hydrological elements, particularly RZWS, at the global scale. However, we have to highlight that the model ~~also shows less preference~~ shows lower performance in some regions, e.g., the Amazon, in the RZWS simulation, where the reference data NDII may have ~~shortcoming to reflect RZWS.~~ shortcomings in reflecting RZWS. In these regions where NDII might not be a correct proxy for RZWS, an additional data set could be helpful for evaluation, e.g., the solar-induced fluorescence (SIF), which reflects photosynthesis and thus has a close relationship to the available water in the root zone. A combination of vegetation index data, such as EVI and NDVI, could also be alternatives, as they represent different characteristics of plants. However, further investigations need to be performed before this combination can be applied. It is also important to note that the high latitude regions are not covered by one of the key ~~parameter~~parameters, i.e., root water storage capacity, used by the WAYS model, and only major river basins ~~in~~ at middle and low latitudes are investigated. Thus, the performance of the model in the other regions is not justified. This is one of the limitations of this work, and further investigations ~~is~~ are needed.

It ~~also needs to be aware~~ should also be noted that during the evaluation of RZWS, the reference data NDII ~~is~~ represent a normalized index based on surface reflectance ~~can reflects~~ and can reflect only the dynamics of ~~the~~ RZWS rather than the absolute value (Sriwongsitanon et al., 2016). ~~So, the real value based~~ Therefore, a real value-based evaluation could be much more helpful for the model application. This could be another limitation of the work. ~~But it~~ However, this fact also emphasizes the importance and necessity of this work from the following two aspects: 1) ~~remote sensing based~~ The remote sensing-based approach, e.g., NDII, is ~~so~~ thus far one of the best available ~~method~~ methods for root zone information ~~retrieving~~ retrieval (Tobin et al., 2017). However, it ~~still limited by~~ is still limited in its ability to reflect the real value~~reflection. This urges the model developmentas it~~, which urges model development, as the model has the ability for absolute value simulation. 2) ~~remote sensing based~~ The remote sensing-based approach works only ~~on historical analysis~~for historical analysis, which limits its ability ~~for~~ to be used in future impact studies. This ~~also motive the model developmentas it work both for~~ issue also motivates model development, as the model can work for both past and future studies after appropriate evaluation.

Moreover, the current study does not consider the groundwater access and irrigation mainly due to the lack of global information. The groundwater table information is crucial for capillary rise simulation (Vergnes et al., 2014). Capillary rise simulation without proper water table information could significantly overestimate the evaporation. Thus, the capillary rise flux is ignored in this study. A similar strategy has also been applied by other works due to the absence of the information on the global water table (Döll et al., 2003; De Graaf et al., 2015; Hanasaki et al., 2018). Observations of irrigation on the global scale are also not available (Leng et al., 2015). Although there are simulated irrigation data available on the global scale, the inherent uncertainties could be propagated in our model simulation. Therefore, irrigation is also not considered at this time. However, this neglect could potentially introduce biases into the model simulation in irrigated areas and deep rooted plant-distributed regions, as both irrigation and capillary rise are an additional supply of soil water recharge. The biases may cause an underestimation of evaporation, especially in the dry summertime (Vergnes et al., 2014). This underestimation could consequently affect the simulation of RZWS and runoff because of the interlinkage of these three elements (Rockström et al., 1999). It is found that ignoring the capillary rise could reduce soil water content in the root zone (RZWS), while the runoff will also be reduced (Vergnes et al., 2014). However, these shortcomings can be simply overcome once the global data are available.

In summary, the newly developed global hydrological model WAYS improves the integrality of soil water simulation in hydrological models, as it simulates the water stored in the entire root zone. This added-value feature could benefit ~~for~~ many applications related to the root zone processes. For instance, the correct representation of RZWS could help researchers in the investigation of land-vegetation-climate-water integration, where RZWS plays a key role. The capability for RZWS simulation could also benefit the field of agriculture, as RZWS represents the plant available water, which is closely linked to the crop yields. Moreover, this can also ~~advances~~ advance the hydrological model itself, as the water ~~storied in~~ stored in the root zone controls the partitioning of the precipitation into evaporation, infiltration and runoff in the model (Liang et al., 1994). The precise simulation of variables in the root zone could ~~benefits~~ benefit the simulation of other elements in the model, thus ~~advances~~ advancing the model simulation ~~towards~~ toward an advanced philosophy, i.e.~~get~~, obtaining the right answers for the right reasons rather than simply ~~to get~~ obtaining the right answers (Kirchner, 2006). In addition, the WAYS model can be further improved by integrating a more sophisticated evaporation module, e.g., the STEAM model developed by Wang-Erlandsson et al. (2014), which separates the evaporation fluxes in a more detailed way. Finally, a runoff generation module recently developed by Gao et al. (2019), HSC-MCT, could provide another possibility to improve the WAYS model, as it offers another venue for determining one of the key parameters in WAYS (β) independently without calibration. This calibration-free module could actually benefit any conceptual hydrological model.

Code and data availability. The source code will be available after the paper is accepted. The meteorological data used in this work are available at the data center of the "Global Soil Wetness Project 3" (http://hydro.iis.u-tokyo.ac.jp/GSWP3/). The land use data are available at the Global Land Cover Facility (http://www.landcover.org). The root zone storage capacity is collected from the work of Wang-Erlandsson et al. (2016). The runoff data for model calibration are available at the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=994). The runoff data for model evaluation are available at the European Centre for Medium-Range Weather Forecasts (ECMWF) website (http://apps.ecmwf.int/datasets/). The NDII data and simulated hydrological data are available upon request from the corresponding author.

Author contributions. GM and JL contributed equally to the paper. GM and JL designed the study, analyzed the data and wrote the paper. JL designed the model structure, and GM wrote the model code.

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

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