Point-by-point response to the reviewers' comments

The comments from the reviewers are in bold followed by our responses in regular text. The text in quotation marks represents the content we revised in the new manuscript. And following the reviewer's suggestion, we renamed the model developed in this study from ORCHIDEE_NLAT to LSM_Nlateral_Off.

■ Reviewer 1

This study introduced a newly developed offline model of lateral N transfers, called ORCHIDEE_NLAT, within the framework of the land surface model ORCHIDEE. The ORCHIDEE_NLAT was used to simulate historical changes in riverine DON, PON, and DIN exports across the globe. Overall, it is an important work of global riverine N transport model development. The manuscript is well written, and the model structure is clearly illustrated. Currently, the accuracy of the model in simulating riverine N exports is actually low, especially at regional scale. I understand it is very challenging to accurately simulate N transfers at the global level, but I still have some suggestions for authors to improve the model in the future.

➢ Major comments

1. **The ORCHIDEE-CNP and ORCHIDEE-Clateral are both used to provide the land-to-river inputs. ORCHIDEE-Clateral provides runoff, drainage, DOC, and POC inputs, while ORCHIDEE-CNP provides inputs of DON and DIN leaching from manure. Can ORCHIDEE-CNP provide all these forcing data? Using the outputs of two models may bring uncertainties and make this study complicated. Since runoff and drainage are critical components that determine DIN, DON, and PON fluxes, different water inputs simulated by two versions of land models can bring inconsistencies in water flux information behind N fluxes.**

   Thanks for your thoughtful comment on the forcing data of our model. Indeed, it is better to have all input data from the same version of the ORCHIDEE model than from two different model versions. However, the leaching of dissolved organic matter (DOC and DON) and the erosion of particulate organic matter (POC and PON) are currently not represented in ORCHIDEE-CNP. We thus cannot obtain the DOC and DON, nor the POC and PON inputs to rivers from ORCHIDEE-CNP, this model version only providing the inorganic N fluxes (leaching of DIN (NO_3^-, NH_4^+) from soil to rivers). Conversely, ORCHIDEE-Clateral represents the land-to-river flux of DOC and POC, yet does not include a representation of the corresponding DON and PON fluxes, nor terrestrial N cycling in general. Therefore, we use typical C/N ratios of fluvial organic matter to estimate PON and DON fluxes from the POC and DOC fluxes simulated by ORCHIDEE-Clateral.

The difference in runoff and drainage simulated by ORCHIDEE-CNP and ORCHIDEE-Clateral are very limited (Fig. S1), as these two models use the same hydrological module (Sun et al., 2021; Zhang et al., 2022) and have been run with the same climate and land use forcing data (Table 1). This clarification has now been included in the revised manuscript.

"Runoff and drainage are critical components that determine DIN, DON, and PON fluxes. As ORCHIDEE-CNP and ORCHIDEE-Clateral used the same scheme to simulate soil hydrology (Sun et al., 2021; Zhang et al., 2022) and they have been run with the same climate and land use forcing data (Table 1).Therefore, the difference in runoff (0.9%) and drainage (1.7%) simulated by the two ORCHIDEE branches are very limited (Fig. S1)." (lines 208-214)

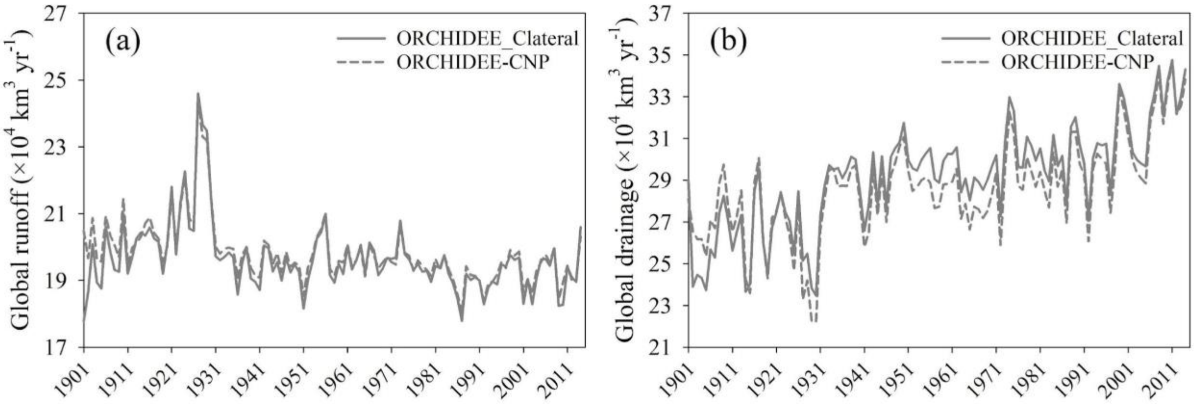


Figure S1. Comparison of global runoff (a) and drainage (b) simulated by ORCHIDEE-Clateral and ORCHIDEE-CNP.

2. **In the aquatic N module, why not consider the transformation process from PON to DON, and from inorganic N to organic N?**

We agree that transformation from PON to DON and from inorganic N to organic N are important processes for the ecology of streams and rivers. However, they play a minor role in the flux of total N to the ocean. In our study, we aimed to develop a lateral transfer scheme that can be coupled to global land surface models, representing the transfer of N from the land to ocean in a simple but efficient manner. For this, we have ignored some processes that would notably increase the model complexity, but have no strong effect on the simulated riverine exports of total N, and these include the transformations from PON to DON, and from inorganic N to organic N. A previous study shows that the transformation fraction of riverine POC to DOC during the lateral transport process is limited (about 0.3%) (Zhang et al., 2022). It can thus be inferred that the fraction of PON transformed to DON is also limited, suggesting that uncertainties due to the omission of PON to DON transformations are limited.

Previous research also found that at global scale river metabolism is strongly dominated by heterotrophic metabolic activities fuelling on terrestrial organic matter inputs, whereas in-situ aquatic production only plays a secondary role (Battin et al., 2023). Thus, we have assumed that for riverine N cycling, decomposition of organic matter and denitrification of DIN are much more important than algae uptake of DIN forming new PON, hence we have ignored the transformation between inorganic and organic N caused by the growth and mortality of algae. To our knowledge, there is still no reliable global model that can well simulate global fluvial autotrophic production of algae and the accompanying N assimilation. Nonetheless, we acknowledge that ignoring the transformation process from PON to DON, and from inorganic N to organic N may result in uncertainties in our simulation results. We have added some text to discuss these potential uncertainties in the revised manuscript.

“The role of autotrophic production is another process currently omitted. Autotrophs (aquatic macrophytes, algae, cyanobacteria, bryophytes, some protists, and bacteria) in freshwater systems take up DIN from the water column (King et al., 2014) and may play a significant role in N cycling within rivers (Wachholz et al., 2024). In future model developments, the role of autotrophic production on N retention should thus be considered, although the large dominance of the heterotrophic metabolism on a global scale suggests that in-situ aquatic production is a second-order control on N cycling (Battin et al., 2023). The transformation of PON to DON is also not included in the current version of LSM_Nlateral_Off. A previous study suggests that the instream transformation of POC to DOC is limited (about 0.3%) (Zhang et al., 2022). It can thus be assumed that the fraction of PON transformed to DON is also rather negligible.

Nevertheless, we plan to incorporate this transformation process into our model in the next phase of our research.” (lines 901-914)

3. **The residence time method is used to calculate N transport along the river networks. This method is commonly used but very simple and may not be able to accurately capture water transport processes. Authors may consider using hydrological kinetic equations in the future.**

Thanks for your excellent advice. Considering the complexity of the hydrodynamic formulas and the associated forcing data required for their implementation, we adopted the residence time method in the first version of LSM_Nlateral_Off. The residence time method is simple and easy to be applied at a large spatial scale. Nonetheless, as you have suggested, simulating N transport with hydrodynamic formulas in the next version of our model is a valuable suggestion for future research and has been included in the outlook section of our revised manuscript:

“The residence time method was used to estimate water and N transport within river networks. This method is simple and has been widely used in large scale simulations of fluvial water, carbon and N transports (Beusen et al., 2015; Jepsen et al., 2019; Zhang et al, 2022). However, it may not fully capture the seasonality of water and N flows accurately in some regions (Fig. 5 a2 & b2). To improve the accuracy of simulating fluvial water and N transport, the residence time method currently used in LSM_Nlateral_Off could be replaced with hydrological kinetic equations in future versions of the model.” (Lines 874-882)

4. **The validation of model results only focuses on TN and NO3. (1) How to validate DON and PON flexes? USGS provides organic N observation. (2) The assumption of a linear relationship between observed TN and NO3 may ignore the variations in organic N.**

(1) Thanks for the data information. Indeed, USGS provides data on nitrogen concentrations and water discharge across the United States. Based on these data, a previous study (Scott et al., 2007) calculated the long-term (1975-2004) mean annual loads and fractions of total organic nitrogen (TON) at 854 stations nationwide. Given that the total nitrogen (TN) flow simulated by LSM_Nlateral_Off has been thoroughly evaluated, we specifically assessed the model's performance for organic nitrogen by

comparing the simulated TON fraction (i.e. TON yield / TN yield) with the observed TON fraction reported by Scott et al. (2007). Please see:

"As an additional evaluation, we compared our model results against observed N concentrations and water discharges across the United States provided by the U.S. Geological Survey (USGS). Based on these data, a previous study (Scott et al., 2007) calculated the long-term (1975-2004) mean annual loads of total organic N (TON) and TON fractions (TON yield / TN yield) at 854 stations nationwide. LSM_Nlateral_Off simulates a spatial pattern for the TON fraction which closely matches that reported by Scott et al. (2007), with high values in western regions and low values in the east (Fig. S7). This suggests that LSM_Nlateral_Off not only effectively simulates TN fluxes, but also captures the organic and inorganic fractions across the United States relatively well." (lines 545-555)

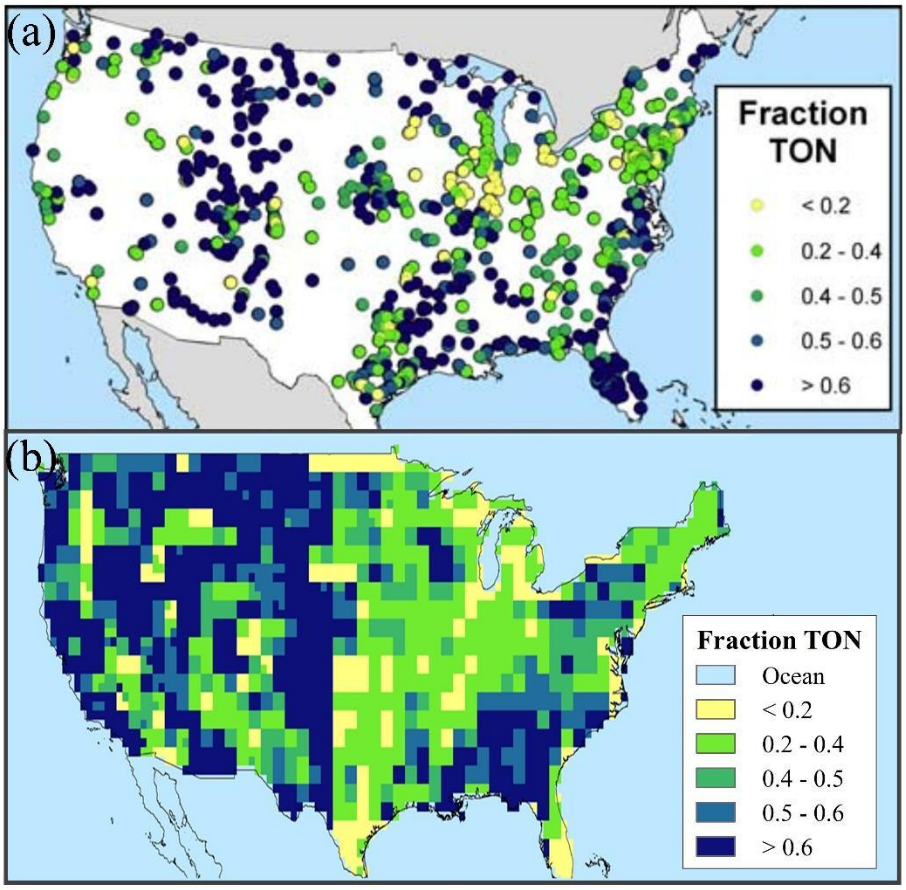


Figure S7. Spatial patterns of long-term (1975-2004) mean annual total organic nitrogen (TON) fractions: (a) observed TON fractions reported by Scott et al. (2007); (b) TON fractions simulated by LSM_Nlateral_Off.

(2) We agree that the assumption of a linear relationship between observed TN and NO_3^- may ignore the variations in organic nitrogen. However, previous studies (Romero et al., 2021) and observation data from GRQA indicate a significant correlation between TN concentration and NO_3^- concentration, with an R^2 value of 0.78 (Fig. S2). Therefore, calculating TN from NO_3^- data using an empirical formula appears to be a reasonable approach for evaluating our model at global scale, for which TN observation data remain scarce.

5. **The simulated total N fluxes in the 1920s is questionable as authors have already mentioned. What are climate data sources? How about the precipitation change? ORCHIDEE has already been used to simulate lateral C and sediment fluxes, and does the same issue occur in these simulated variables? Better to check it and make it right.**

The climate forcing data is taken from the Global Soil Wetness Project Phase 3 (GSWP3). The forcing data information has been added in Table 1. Between 1926 and 1931, the global total amount of heavy precipitation (>25 mm d^{-1}) was higher, which caused more runoff and TN flow into rivers (Fig. S9). Empirical research on long-period runoff fluctuations also evidenced elevated global runoff in the same period (Probst and Tardy 1989). ORCHIDEE has been used to simulate global lateral C transfer processes, revealing a similar phenomenon in the simulated variables of lateral carbon transfer (Zhang et al., under review). We have double checked the climate data and model code to ensure the accuracy of our simulations and data analysis. The relevant text has also been adjusted in the revised manuscript:

"The global TN input into rivers, TN export to oceans and denitrification in rivers all show a slight peak between 1926 and 1931 due to the relatively higher surface runoff during this period (Fig. S9). This higher runoff results mostly from meteorological forcings, as the global total amount of heavy rainfall (>25 mm d^{-1}) was higher during this period (Fig. S9). Note that Probst and Tardy (1989) provide empirical evidence for elevated global runoff during this period and we thus consider this peak as realistic." (lines 609-615)

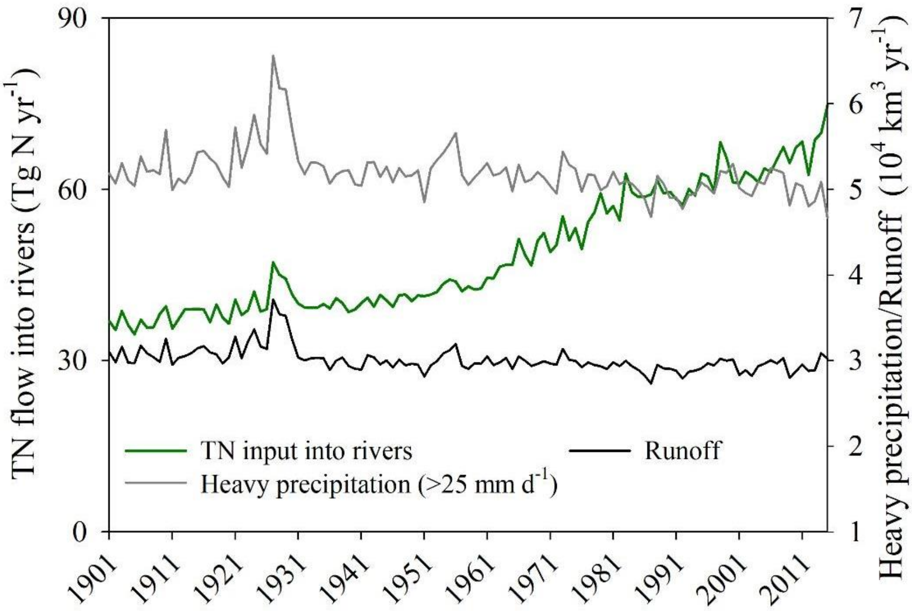


Figure S9. Global annual TN flow into rivers, runoff and heavy precipitation (> 25 mm d^{-1}) from 1901 to 2014.

➢ **Minor comments**

1. **L64. N leaching into the aquatic environment. LOAC includes land.**

    Thanks, "LOAC" has been changed to "aquatic environment" (lines 71)

2. **L91-93. This is also an issue for LSM.**

    Sorry for the inaccurate expression. We have modified it from

    "Therefore, their complexity and high data requirements for calibration and evaluation limit their applicability, in particular the long-term evolution of global N fluxes and transformation processes"

    to

    "Therefore, their complexity and high requirements for hard-to-get forcing datasets constrain their applicability, in particular for the long-term evolution of global N fluxes and transformation processes." (lines 99-102)

3. **L157-159. Does ORCHIDEE-CNP have soil organic C pools? It should also have POC outputs.**

    Yes, ORCHIDEE-CNP has three soil organic C pools, physically protected, chemically recalcitrant and active carbon pool. However, it does not simulate soil and carbon erosion processes. As a result, it cannot provide POC inputs from land to rivers.

Moreover, ORCHIDEE-CNP does not represent DOC cycling, and cannot simulate DOC leaching from soils to rivers, either.

4. **L166-167. How to separate sewage TN into different N species.**

Apologies for not explaining the separation scheme of sewage in our manuscript. We partitioned the sewage TN into different N species following Naden et al. (2016), who assume that 10% of sewage TN is DON and the remaining 90% is DIN. This information has been added in the revised manuscript. Please see:

"TN from sewage was then partitioned into different N species following the approach of Naden et al. (2016), which assumes that 10% of sewage TN is DON and the remaining 90% is DIN." (lines 248-251)

5. **L197. A constant ratio may make the simulated DON less informative and accurate.**

Based on previous observation, the C:N ratios of dissolved soil organic matter mostly vary within a small range around 12 (8-25). As there is still no global database on the C:N ratio of DOM for different vegetation types, we have adopted a constant DOC:DON ratio in this study. We acknowledge that the constant DOC:DON ratio may induce some uncertainties in our simulation results, thus some text has been added to discuss this issue. Please see:

"The current version of LSM_Nlateral_Off also has several limitations in terms of biogeochemistry. One limitation is the use of a constant C:N ratio to simulate DON fluxes from soils to rivers. Research has shown that the C:N ratio varies over time and across different land cover types (Li et al., 2019; Yates et al., 2019). The use of a constant C:N ratio may thus reduce the accuracy and informativeness of the estimated DON flux. Addressing this limitation is an urgent priority for future research" (lines 883-889)

6. **L257. What about N deposition into sediment?**

The PON deposition is mainly affected by the rates of sediment deposition. Sediment and PON deposition are not represented in the current offline model. Recent results from ORCHIDEE-Clateral suggest that about 22% of POC entering river networks is deposited with sediments along the global river-floodplain network (Zhang et al., under review). We have added some text to discuss the potential uncertainties and biases in our simulation results due to the omission of PON deposition. Please see:

“At present, few studies have accounted for the effects of PON deposition and resuspension on lateral N transfer in rivers because of the challenge of representing these processes at the global scale. Moreover, PON deposition is mainly controlled by the rate of sediment deposition, a process which is not represented in the current model version. Therefore, PON deposition has not been simulated either. Recent results from ORCHIDEE-Clateral suggest that about 22% of POC entering the global river network is deposited with sediments before reaching the coast (Zhang et al., under review). Assuming a similar fraction of deposited PON, global PON export to oceans simulated by LSM_Nlateral_Off could be approximately 20% lower (about 2 Tg N yr $^{-1}$) than estimated here.” (lines 890-900)

7. Equations 4-11. Not all variables are explained. Please check.

Thank you for your suggestion. We have added explanations for all variables in the revised manuscript. In addition, the revised Tables A1 and A2 summarize information for all variables, fluxes, and processes included in LSM_Nlateral_Off.

“R_{fast_PON} and R_{stream_PON} (g N d^{-1}) represent PON decomposition rates in the fast and stream reservoirs, respectively. R_{fast_DON}, R_{slow_DON} and R_{stream_DON} (g N d^{-1}) represent DON decomposition rates in the fast, slow and stream reservoirs, respectively. R_{fast_DIN}, R_{slow_DIN} and R_{stream_DIN} (g N d^{-1}) represent DIN denitrification rates in the fast, slow and stream reservoirs, respectively.” (lines 325-329)

8. Figure 4. Put the NSE value into the figure.

Thanks for your suggestion, we have added the NSE values into Figure 4.

“

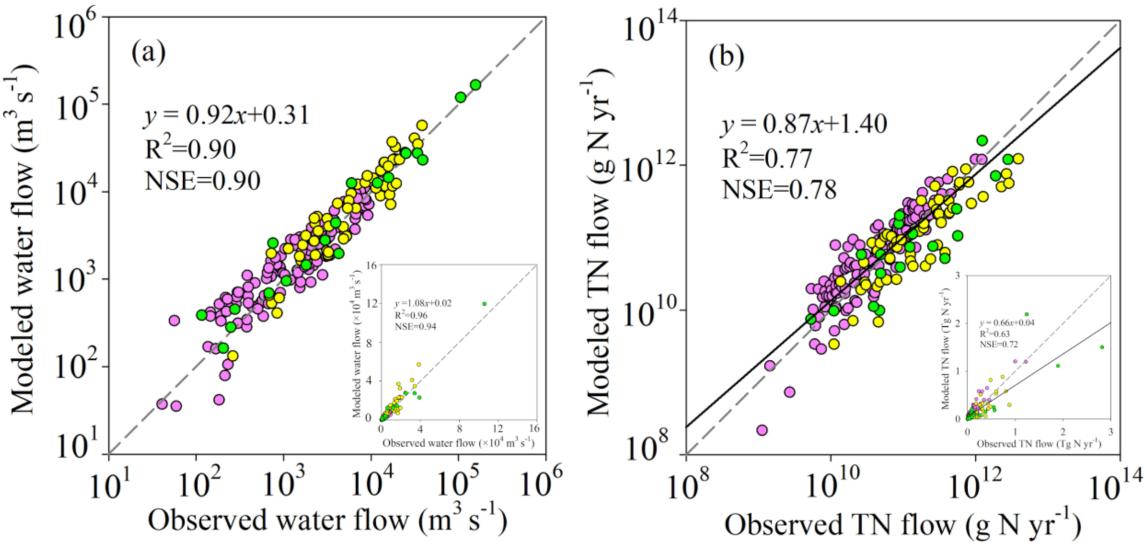


Figure 4. Evaluation of LSM_Nlateral_Off. Global-scale comparison between observed and modelled annual-mean water discharge (a) and TN flow (b). Pink symbols represent sites with observations of TN concentrations from GRQA, yellow symbols represent GRQA sites for which TN concentrations were estimated from observations of NO_3^- concentrations, and green symbols represent sites with observations of TN from published literature." (lines 572-578)

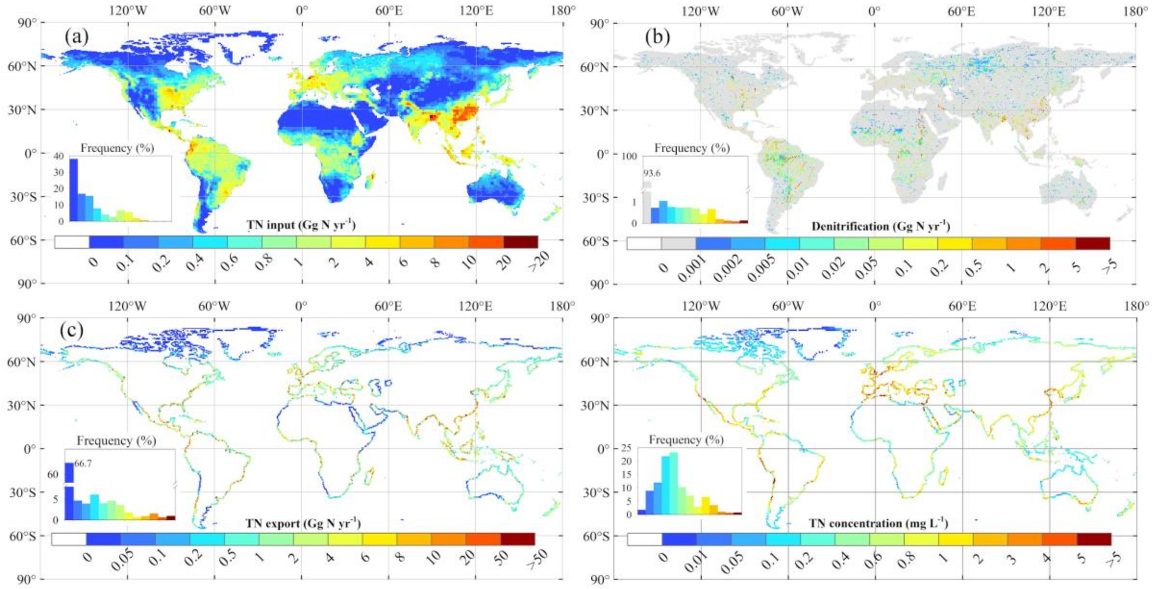
9. L507. Can you explain the decrease in PON export?

The reduction in PON mobilization from land to river decreased in response to global greening caused by increasing atmospheric CO_2 concentrations, and partly also climate warming. Global greening enhances vegetation cover (Cortés et al., 2021; Wang et al., 2022), thus, reduces soil erosion. Altogether, we find a general slight decrease in PON erosion across all plant functional types (PFTs) considered. This explanation has been included in the revised manuscript.

"This decrease is mainly attributed to global greening, which enhances vegetation cover (Cortés et al., 2021; Wang et al., 2022) and reduces soil erosion, resulting in lower PON inputs from the land and, thus, PON exports to oceans." (lines 603-606)

10. Figure 7. Better to use mg/L as a concentration unit.

Yes, we have changed the unit to mg/L.



"Figure 7. Spatial patterns of annual mean N fluxes and concentrations during 2001-2014: (a) TN inputs into rivers; (b) denitrification rates in rivers; (c) TN exports to oceans; (d)

TN concentrations at rivers mouths. To display the spatial patterns of denitrification in rivers better, we excluded data with denitrification rates less than 0.001 GN yr^{-1} per grid."

(lines 666-671)

11. L586. Figs.

Sorry for the mistake. We have corrected this typo. (line 687)

12. L625-627. ON inflow is simulated by ORCHIDEE CNP and Clateral, not NLAT. Right?

Indeed, the ON inflow from land to rivers is calculated based on the OC inflow simulated by ORCHIDEE-Clateral and observation-based C:N ratios of dissolved and particulate matter.

13. Figure 11c. Wrong name of NLAT.

Sorry for the mistake. In this study, DIN is derived from ORCHIDEE-CNP, while DON and PON are determined using DOC and POC outputs from ORCHIDEE-Clateral, along with C:N ratios specific to each soil organic matter pool. Consequently, in Figure 11, the offline model's name (ORCHIDEE-NLAT) has been replaced by ORCHIDEE-CNP and ORCHIDEE-Clateral. The offline model, originally named ORCHIDEE-NLAT, has now been renamed LSM_Nlateral_Off as recommended by the reviewers and editors.

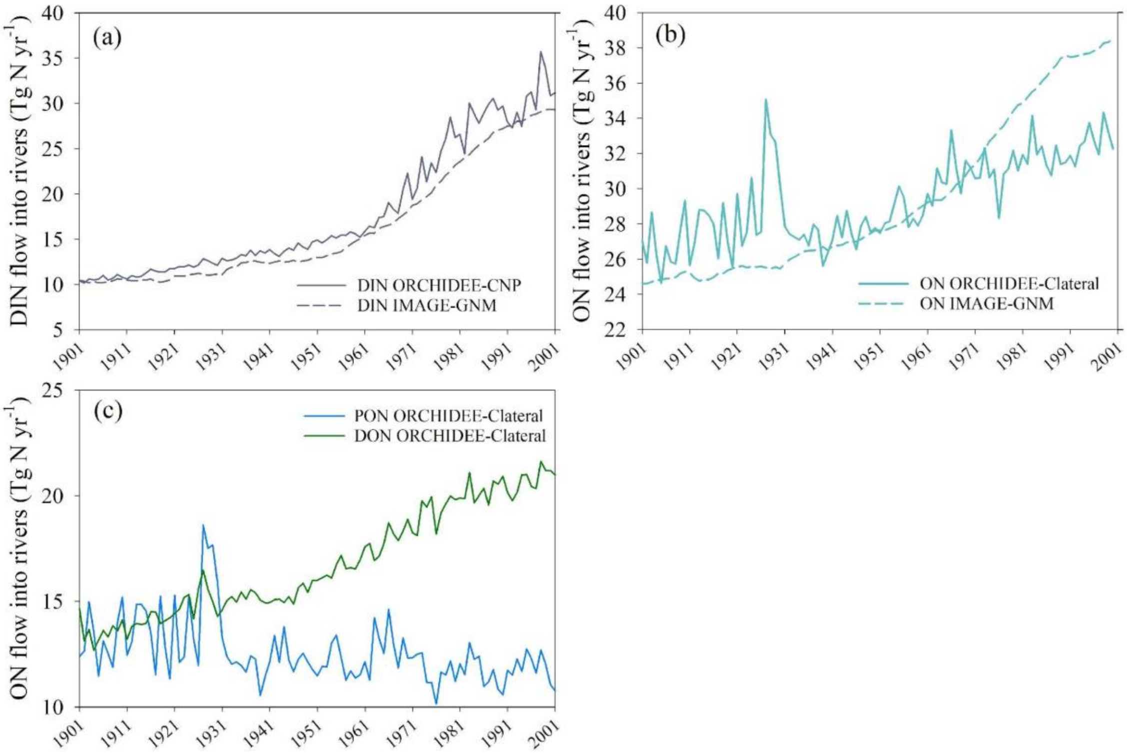


Figure 11. Global terrestrial N flows into rivers from 1901 to 2001 simulated by ORCHIDEE model versions and IMAGE-GNM (Vilmin et al., 2018): (a) DIN; (b) ON (DON+PON); (c) DON and PON derived from ORCHIDEE-Clateral. (lines 755-758)

14. L738-741. Another important thing is to improve model structure and data quality.

Indeed, we agree with you, and have added this in the revised manuscript. Please see:

"This highlights the necessity for improvements in model structure and quality of both forcing data and evaluation data, as well as the implementation of ensemble-mean assessments, akin to the recent approach applied to constrain carbon exports to the oceans (Liu et al., 2024)." (lines 846-850)

15. L863. Doi is invalid.

Sorry for the invalid DOI, we uploaded the data and code but forgot to publish it. Now it works, https://zenodo.org/records/13309551.

"The source code of the LSM_Nlateral_Off model is available online (https://zenodo.org/records/13309551). All forcing and validation data used in this study are publicly available online. The specific sources for these data can be found in Table 1." (1002-1006)

- **Reviewer #2**

The authors developed a new scheme for the lateral transfer of nitrogen over the land surface and via the river network at 0.5° resolution. They implemented their scheme into the land surface model ORCHIDEE and named it ORCHIDEE_NLAT. The scheme considers three nitrogen compounds: PON, DON, and DIN. The manuscript presents an important contribution to Earth System Modelling. It utilizes the ORCHIDEE capabilities by providing daily nitrogen loads, and not only annual loads as in existing previous studies. It also comprises a good discussion on uncertainties (Sect. 3.4)

- **Major comments**

1. **(1) What I do not understand is why they did not run the full ORCHIDEE model themselves. Instead, the ORCHIDEE_NLAT offline scheme was fed by output from ORCHIDEE-CNP and ORCHIDEE-Clateral. Hence, its results heavily rely on input data from other ORCHIDEE versions. (2) If the present offline scheme is an independent model, why it is also called ORCHIDEE? (3) Are there any processes duplicated in ORCHIDEE_NLAT, which had already been simulated by these other ORCHIDEE versions? (4) It should be clarified whether specific characteristics of the model output are due to the process representation in ORCHIDEE_NLAT or whether they originate from the used input from the other OCHIDEE versions.**

   (1) The overarching idea behind the development of an offline model was to provide a computationally efficient numerical tool in which the mathematical representation of aquatic biogeochemical processes could easily be implemented, calibrated and evaluated. This strategy holds for the processes currently implemented but also for future processes involved in the C-N and other elemental cycles. Furthermore, by construction, it can also be used to route the N leaching fluxes produced by other LSMs (land surface models) in the future, allowing for applications at various scales and across different regions. This overarching goal has been briefly elaborated in the revised manuscript.

   "The offline strategy provides a computationally efficient numerical model in which the mathematical representation of aquatic biogeochemical processes can easily be implemented, calibrated and evaluated. Furthermore, by construction, it can also be used to route the N leaching fluxes produced by any other LSMs in the future, allowing for applications at various scales and across different regions" (lines 170-175)

(2) Yes, the current offline scheme is an independent model, and has the potential to be forced with output datasets from other land surface models. Therefore, following the reviewers' and editor's suggestions, we propose renaming the model to LSM_Nlateral_Off (Land Surface Model, N lateral transfer module, Offline).

(3) The water flow processes in LSM_Nlateral_Off are consistent with that in ORCHIDEE-Clateral, while the lateral N transport processes are newly developed in this study and have not been simulated in any other versions of ORCHIDEE.

(4) Based on our analysis, the characteristics of water and N inflows from land to rivers are derived from the simulation results of ORCHIDEE-Clateral and ORCHIDEE-CNP. However, denitrification, as well as water and N exports to oceans result from the combined influence of the input data from other versions of ORCHIDEE and the process representation implemented in LSM_Nlateral_Off. We have added an explanation on this point in the revised manuscript.

"Input data for LSM_Nlateral_Off are provided by ORCHIDEE-CNP and ORCHIDEE-Clateral. Therefore, the magnitude and spatio-temporal patterns of N inflows from land to rivers are exclusively derived from these two model branches. In contrast, quantification of denitrification and N exports to oceans result from the combined influence of the input data from ORCHIDEE and from the process representation implemented in LSM_Nlateral_Off. In what follows, we investigate spatial, seasonal and decadal trends resulting from the offline coupling of these three models." (lines 584-591)

2. **Lateral nitrogen flows are simulated for the period 1901-2014. Unfortunately, no information on the atmospheric forcing for the land surface model is provided (i.e. for the input provided by ORCHIDEE_CNP).**

Sorry for omitting the information on the climatic data used to drive ORCHIDEE-CNP and ORCHIDEE-Clateral. The climate data for both models are derived from the Global Soil Wetness Project phase 3 (GSWP3) , and we have added this information in Table 1:

"Table 1. List of (1) forcing data used to run ORCHIDEE-Clateral, ORCHIDEE-CNP and LSM_Nlateral_Off, and (2) observational data used to evaluate the simulation results. S_{res} and T_{res} are the original spatial and temporal resolution of the forcing data, respectively.

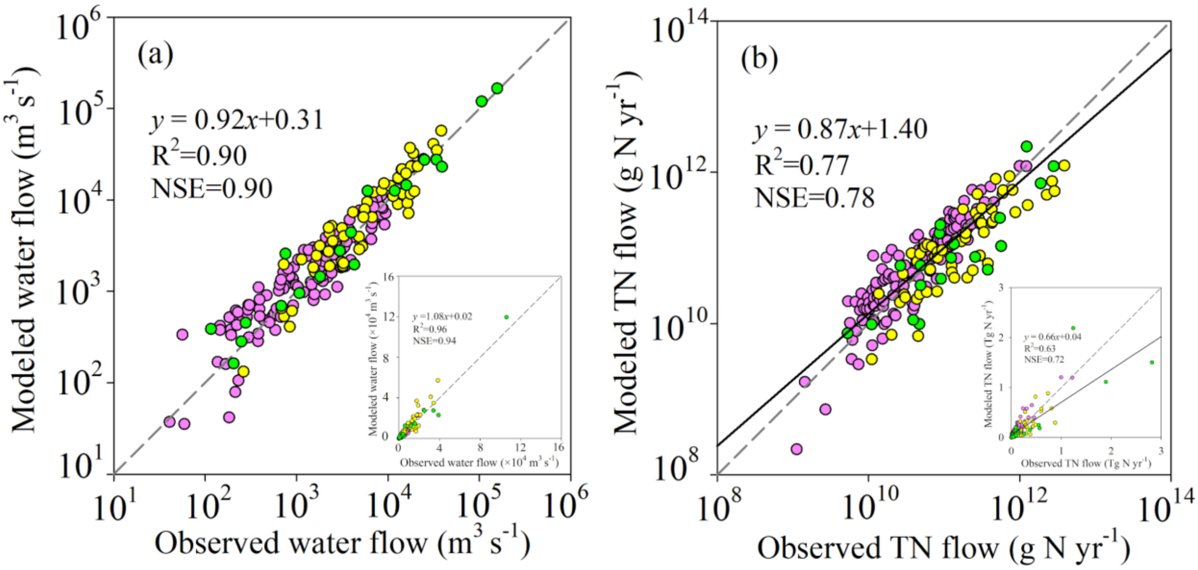
	Data	S_{res}	T_{res}	Data source
Forcing data forORCHIDEE-Clateral and ORCHIDEE-CNP	Climatic forcing data (precipitation, temperature, incoming shortwave/ longwave radiation, air pressure, wind speed, relative humidity)	1°	3 hours	Global Soil Wetness Project Phase 3 (GSWP 3) (Kim et al., 2017)
	Land cover	0.5°	1 year	ESA-CCI LUH2v2 database (Hurtt et al., 2011; Lurton et al., 2020)
	Soil texture class	0.5°	/	Reynolds et al. (1999)
	Soil bulk density and pH	30"	/	HWSD v1.2 (FAO/IIASA/ISRIC/ISSCAS/JRC,2012)
	Fertilizer application	0.5°	1 year	(Lu et al., 2017)
	Manure application	5′	1 year	(Zhang et al., 2017)
	Nitrogen deposition	0.5	1 year	IGAC/SPARC CCMI
Forcing data of LSM_Nlateral_Off	Runoff Drainage DOC and POC with runoff DOC and POC with drainage Soil temperature (TS)	1°	1 day	ORCHIDEE-Clateral (Zhang et al., 2022. Zhang et al., under review)
	DIN with runoff and drainage DON leaching from manure application	1°	1 day	ORCHIDEE-CNP (Sun et al., 2021)
	DIN and DON with sewage	0.5°	5 years	(Beusen et al., 2016)
	Flow direction Topographic index (f_{topo})	0.5°	/	(Vörösmarty et al., 2000)

	Riverine water discharge	/	1 day	GRDC[a]
Evaluation data	Riverine TN and NO_3^- concentration	/	point measurement	GRQA[b]
	Riverine TN concentration	/	point measurement	Table S1

[a] Global Runoff Data Centre (GRDC) (Federal Institute of Hydrology, 2018); [b] Global River water Quality Archive (GRQA) (Virro et al., 2021)." (lines 252-257)

3. **I do not find the evaluation of the model results in Sect. 3.1 to be very convincing. In this respect, Figure 4 shows a rather trivial logarithmic plot where large (low) simulated discharge/N values correspond to large (low) observed values. It shows that the model values are generally of the right order of magnitude but hide the true magnitude of `the biases. It may be better to show NSE or RRMSE in such a figure. (2) In this respect, Figure 5 shows large biases with RRSME greater than 30% and medium to low NSE for the three rivers considered. While I do not expect a high performance for nitrogen loads, I am rather surprised by the low performance of the simulated river discharge. If this performance is already low, it will most likely prevent a good performance of the simulated nitrogen loads. (3) In addition, it is implied that Fig. S8 shows a good agreement with the assessment of Marzadri et al. (2021), which I strongly disagree with (see comment below). (4) Also, the reasoning for existing model biases is insufficient (see comments below). In my opinion, the evaluation section requires a strong improvement before it is suitable for publication.**

   (1) Thank you for your suggestion. We have included both the logarithmic and normal plots and added NSE in the revised Fig. 4. The NSE values indicate that our model accurately captures the observed water and TN flow.



"Figure 4. Evaluation of LSM_Nlateral_Off. Global-scale comparison between observed and modelled annual-mean water discharge (a) and TN flow (b). Pink symbols represent sites with observations of TN concentrations from GRQA, yellow symbols represent GRQA sites for which TN concentrations were estimated from observations of NO_3^- concentrations, and green symbols represent sites with observations of TN from published literature." (lines 572-578)

(2) We agree that the statistics (RRMSE and NSE) for these three sites with long timeseries of N observations in Fig. 5 are not particularly good. However, please note that the model evaluation was performed on a daily time step. It is a big challenge for global-scale river models to accurately simulate water discharge and TN flows at a daily time step. The water discharge simulated by ORCHIDEE-Clateral has been evaluated in several previous studies (Lauerwald et al., 2017; Zhang et al., 2022), demonstrating that ORCHIDEE-Clateral effectively captures both the quantity and seasonality of water discharge. In addition, we have added an evaluation of water discharge at 346 GRDC sites in the revised manuscript. Please see the details below:

"The seasonality in water discharge is an important control factor for the seasonality in TN fluxes. Therefore, the observational data derived from GRDC was used to further assess the performance of LSM_Nlateral_Off in reproducing the monthly seasonality of water discharge. At the 346 GRDC sites with continuous measurements (Fig. S4), we computed the monthly average value, taken as the observed water discharge of that month. For the world's 20 largest rivers (Dai & Trenberth, 2002), which accounts for approximately 31% of the total global river discharge (Table S2, Fig. S4), LSM_Nlateral_Off effectively simulates both the magnitude and seasonality of water discharge (Fig. S5). The Nash-Sutcliffe Efficiency (NSE) values range from 0.07 to 0.92, with 17 out of the 20 rivers achieving an NSE greater than 0.5 (Fig. S5). However, the model demonstrates a significantly weaker accuracy in capturing the seasonality of water discharge in some low-flow rivers, with NSE values below zero at 84 (24% of the sites number contributing to 17% of the global river discharge) of the 346 GRDC sites (Fig. S6). The model's limitations in capturing seasonality are attributed to three main reasons, as discussed above.” (lines 529-544)

Table S2. Information of world’s largest 20 rivers (Dai & Trenberth, 2002).

No.	**Name**	**GRDC_ID**	**Lat**	**Long**	**Station, Country**
1	Amazon	3629000	-1.95	-55.51	Obidos, Brazil
2	Congo	1147010	-4.30	15.30	Kinshasa, Congo
3	Orinoco	3206720	8.25	-64.25	Pte Angostu, Venezuela
4	Changjiang	2181900	30.77	117.62	Datong, China
5	Brahmaputra	2651100	25.18	89.67	Bahadurabad, Bangladesh
6	Mississippi	4127800	33.25	-91.25	Vicksburg, MS, United States
7	Yenisey	2909150	68.25	86.75	Igarka, Rusia
8	Parana	3265601	-32.67	-60.71	Timbues, Argentina
9	Lena	2903420	71.75	127.25	Kusur, Russia
10	Mekong	2469260	15.12	105.80	Pakse, Laos
11	Tocantins	3649950	-3.76	-49.65	Tucurui, Brazil
12	Tapajos	3629152	-5.15	-56.85	Jatoba, Brazil
13	Ob	2912600	66.57	66.53	Salekhard, Russia
14	Ganges	2646200	24.08	89.03	Farakka, India
15	Irrawaddy	2260500	22.25	95.75	Sagaing, Myanmar (Burma)
16	St. Lawrence	4143550	45.25	-75.25	Cornwall, ON, Canada
17	Amur	2906900	50.75	137.25	Komsomolsk, Russia
18	Xingu	3630050	-3.21	-52.21	Altamira, Brazil
19	Mackenzie	4208025	68.25	-133.75	Arctic Red, Canada

20	Xijiang	2186800	24.25	110.75	Wuzhou, China

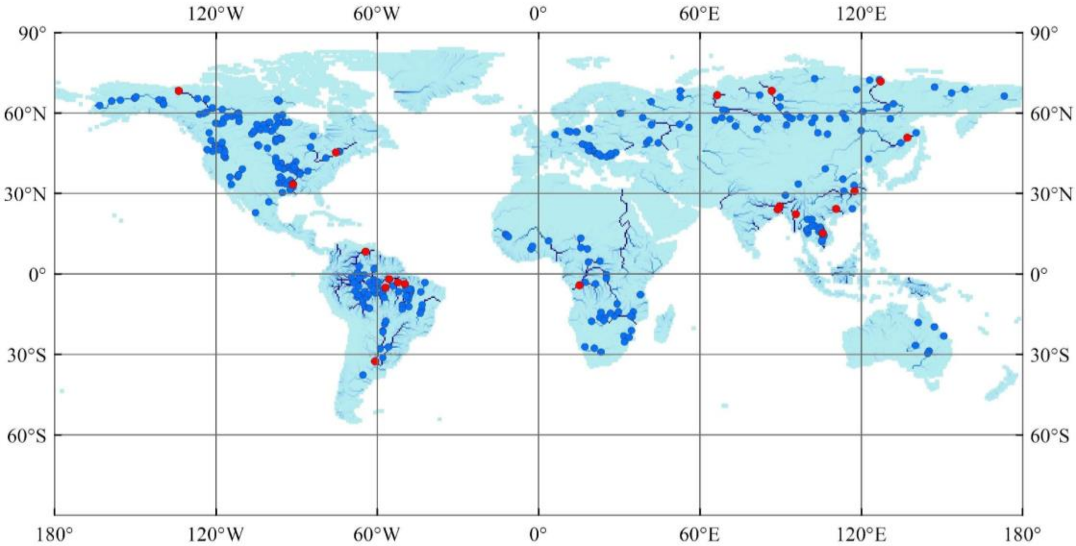


Figure S4. Location of observation sites for water discharge. Blue dots represent GRDC gauging stations with a catchment area greater than 50 000 km^2. Red dots represent gauging stations for the world's 20 largest rivers (Dai & Trenberth, 2002).

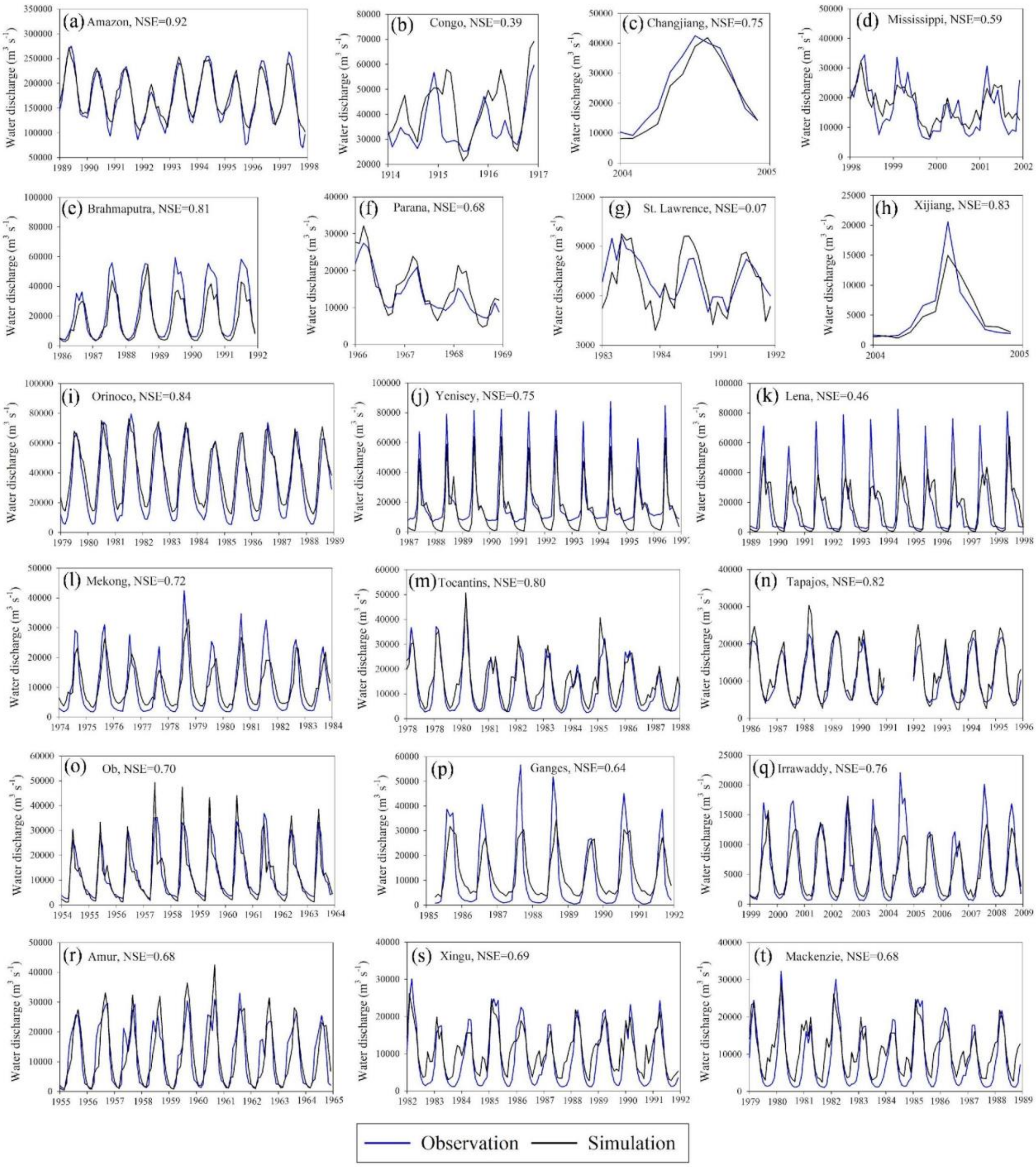


Figure S5. Comparison between simulated and observed time series of water discharge for the world's 20 largest rivers (Dai & Trenberth, 2002).

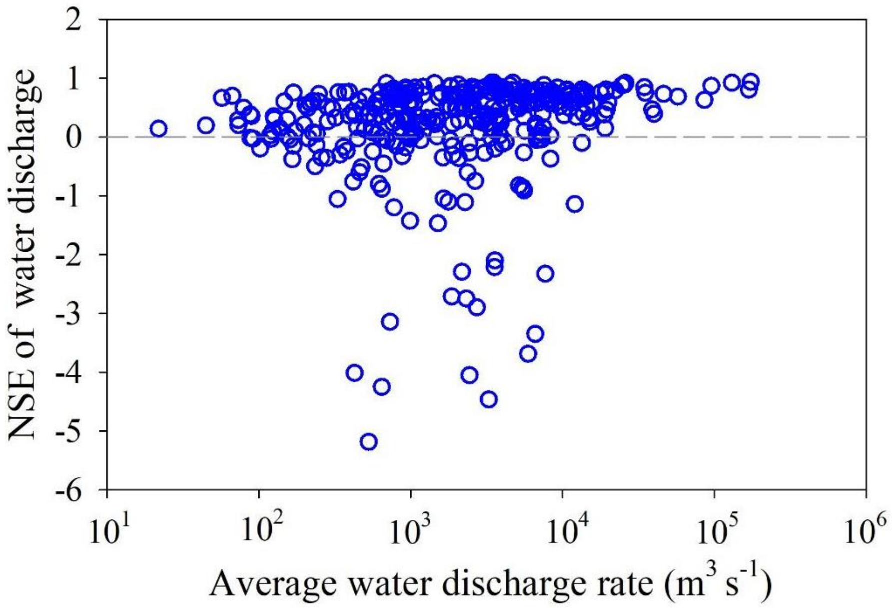


Figure S6. The Nash-Sutcliffe efficiency coefficient (NSE) of water discharge simulated by LSM_Nlateral_Off at 346 GRDC sites.

(3) We agree with the reviewer that our paragraph lacked nuance, and we have reformulated the statements, please refer to the response for minor comment #15.

(4) Please refer to the response for minor comment #14.

4. **Another point of concern is that the paper uses rather short reference periods for comparison (1900-1910, 1991-2000 and 2001-2014). This is too short for climatological studies and the identification of trends, especially given the large interannual and decadal variability in hydrological variables, i.e. precipitation and river runoff, which largely influence the lateral nitrogen flows into the ocean.**

Thank you for your valuable advice. In this manuscript, we did not attempt to identify the trends of N variables for the periods of 1901-1910 or 2001-2014. Over the past several decades, the cumulative effects of climate change, increased population, industrialization and agricultural fertiliser use have accelerated the global N cycle, and increased N leaching into river networks (Fowler et al. 2013), which is mainly caused by anthropogenic activities (Beusen et al., 2016). We attempt to quantify the differences in fluxes related to N lateral transfer and transformations between a stage with limited human influence (1901-1910) and a strong human influence (2001-2014). To mitigate the influence of interannual variability in climatological data on N lateral transfer, we employed ten-year average values to compare the differences between the two periods.

For example, the global mean annual TN input to rivers during 1901-1910 was

36.81 Tg N yr^{-1}, with a standard deviation (SD) of 1.56 Tg N yr^{-1}. In contrast, during 2001-2014, the global mean annual TN input is 64.89 Tg N yr^{-1}, with an SD of 2.93 Tg N yr^{-1}. The interannual variations of global TN inputs to the rivers over 1901-1910 and 2001-2014 are only about 4-5% of the mean annual TN input.

In addition, for the comparison of N inflows simulated by different ORCHIDEE versions (e.g., ORCHIDEE-CNP and ORCHIDEE-Clateral) and IMAGE-GNM, we present results for the period from 1901-2000, rather than 1991-2000 in the original manuscript. Please see section 3.3 and Fig. 11 in the manuscript.

5. **As the manuscript includes a lot of typos and some overly long sentences, I recommend a thorough English proof reading.**

Thank you. We have double checked the whole manuscript and corrected typos and mistakes.

In summary, the paper describes a relevant model development and provides valuable results, but currently suffers from several flaws, especially in the evaluation section and in the robust identification of trends. Hence, it may be accepted for publication after major revisions are conducted.

➢ **Minor comments**

In the following suggestions for editorial corrections are marked in *Italic*.

1. **Line 26. I found the naming of the new scheme (ORCHIDE-NLAT) inconsistent with the previously established lateral transfer scheme for carbon (ORCHIDEE_ Clateral). In addition, NLAT is a typical abbreviation for No. of latitudes. I suggest a consistent renaming of the new scheme to ORCHIDEE_NLAT.**

Thanks for your suggestion. We have changed ORCHIDEE-NLAT to LSM_Nlateral_Off.

2. **Line 182. "… of *the model* driving …"**

Thanks, we have corrected the sentence from:

"Figure 1. Sources of themodel driving data and the main aquatic N transformation processes in ORCHIDEE-NLAT."

to

"Figure 1. Sources of driving data extracted from other models (left) and main aquatic N transformation processes represented in LSM_Nlateral_Off (right)." (lines 201-202)

3. **Line 201, 214 and 218. In Sect. 2.1.2, you are referring to Table 1 several times. I could hardly find the table until I realized that it is located in Sect. 2.3.1 nine pages later.**

Thanks for your thoughtful suggestion, we have moved Table 1 from Sect. 2.3.1 to Sect. 2.1.2. (lines 252-257)

4. **Line 213. "… and *the data* were downscaled …"**

Thanks, we have corrected the text following your suggestion. (lines 243)

5. **Line 219. Sect. 2.1.3 comprises several sets of very similar equations, e.g. eqs.1-3, 4-8, 12-16, 17-19, 20- 24, 25-27. This makes this section lengthy and repetitive. Please shorten!**

Thank you for your detailed advice, we have shortened the text by integrating several similar formulas into one formula. For example, Eqs. 1-3 were changed from

"$$F_{fastout\_H2O} = \frac{S_{fast\_H2O}}{\tau_{fast} \times f_{topo}} \quad (1)$$

$$F_{slowout\_H2O} = \frac{S_{slow\_H2O}}{\tau_{slow} \times f_{topo}} \quad (2)$$

$$F_{downstream\_H2O} = \frac{S_{stream\_H2O}}{\tau_{stream} \times f_{topo}} \quad (3)$$"

to

"$$F_{out\_H2O} = \frac{S_{H2O}}{\tau \times f_{topo}} \quad (1)$$

where F_{out_H2O} (m^3 d^{-1}) represents water outflow rates from the fast ($F_{fastout\_H2O}$) /slow ($F_{slowout\_H2O}$) /stream ($F_{streamout\_H2O}$) reservoir; S_{H2O} (m^3) represents water stock in the fast (S_{fast_H2O}) /slow (S_{slow_H2O}) /stream reservoir (S_{stream_H2O}); τ represents water residence time for each reservoir, equal to 3.0 days, 25.0 days and 0.24 days for the fast, slow, and stream reservoirs, respectively (Ngo-Duc et al., 2006); f_{topo} represents the grid-cell-specific topographic index (unitless, Vörösmarty et al., 2000)." (lines 273-280)

6. **Line 354. "… flow rates *are* equal to …"**

Thanks, we have corrected the text following your suggestion. (line 403)

7. **Line 402 and 407. The RPE is commonly defined as mean bias or mean bias error (MBE). Please use one of the two common terms.**

Thanks, we have changed all RPEs to mean bias error (MBE).

8. **Line 403. Please provide the definition of the coefficient of determination that you have used.**

Thanks for your suggestion. As the coefficient of determination is a widely used statistical indicator, we provide a reference that defines it. Please see:

"R^2 represents how much variation in the observations can be explained by the model. For the definition of R^2, please refer to Renaud et al. (2010)." (lines 449-451)

9. **Line 426-428. Gramma of sentence seems wrong. Please improve.**

Thanks, we have changed the original text from

"The FV represents the relevant flux, rate or concentration, we have that for each grid cell, the monthly anomaly of FV can be calculated as the difference between the FV value for a given month and its annual mean:"

To

"If FV denotes the rate of water flow ($km^3\ yr^{-1}$), denitrification (Gg N yr^{-1}), TN flow (Gg N yr^{-1}) or TN concentration (mg L^{-1}) in rivers, then for each grid cell, the monthly anomaly of FV can be calculated as the difference between the FV value in a given month and the corresponding annual mean value:" (lines 474-478)

10. **Line 439. "Evaluation of the *simulated water discharge using* …"**

Thanks, we have corrected this sentence following your suggestion. (line 488)

11. **Line 447. The unit m^3/yr is strange. Please use the common units for river discharge: m^3/s or km^3/yr.**

Following your suggestion, we have changed the unit from $m^3\ yr^{-1}$ to $km^3\ yr^{-1}$.

"The absolute values of MBE for the simulated average water discharges are mostly smaller than 50% (Fig. S3a). At 25 sites (13% of all sites), the absolute values of MBE are larger than 100%, but the annual mean water discharge at each of these sites is less than 100 $km^3\ yr^{-1}$ (about 3200 $m^3\ s^{-1}$), indicating that large errors tend to occur at sites where water discharge is low (Fig. S3a)." (lines 492-497)

12. **Line 447-448. It is written**
"…indicating that large errors only occur at some sites draining relatively small basins"

This is not necessarily the case. Such an error may also occur in large basins in dry areas. Please clarify!

Thanks for your thoughtful suggestion. The result we intend to show is that the larger errors tend to occur in areas where the water flow is low. We have changed this statement to

"The absolute values of MBE for the simulated average water discharges are mostly smaller than 50% (Fig. S3a). At 25 sites (13% of all sites), the absolute values of MBE are larger than 100%, but the annual mean water discharge at each of these sites is less than 100 km^3 yr^{-1} (about 3200 m^3 s^{-1}), indicating that large errors tend to occur at sites where water discharge is low (Fig. S3a)." (lines 492-497)

We also have double checked the entire manuscript to make sure all similar errors in the manuscript have been revised.

13. **Line 449-454.**
No, there are more factors. A very important factor is actually that biases in the land surface water balance of ORCHIDEE will introduce biases in runoff and, hence, in the discharge. And as you are using runoff inputs from an ORCHIDEE simulation, this factor is very likely the largest factor contributing to biases in streamflow/discharge.

Thanks for your thoughtful suggestion. Uncertainty in runoff and drainage is another important reason causing biases of N lateral transfer. We have added this reason in the revised manuscript as follows:

"(3) biases in runoff and drainage simulated by ORCHIDEE-Clateral, which may stem from deviations in meteorological data and the parameterization of soil hydraulic properties." (lines 502-505)

14. **Line 464-465, see comment to line 447-448.**

Please refer to the detailed response for your minor comment #12.

15. **Line 482-484 It is written:**

“Nevertheless, the agreement between both assessments (Fig. S8) lends further confidence in the capacity of our model to realistically simulate the N cycle along the global river network.”

I strongly disagree with this statement as Fig. S8 indicates considerable differences between both assessments.

We agree with the reviewer that our paragraph lacked nuance, and we have reformulated the statements as follows:

“Moreover, the simulated DIN concentrations display similar spatial patterns as those obtained from a recent observation-based machine learning (ML) assessment (Marzadri et al., 2021) in regions such as North America, Western Europe, Eastern China, and India (Fig. S8). However, in regions such as the Amazon, Africa, and Australia, LSM_Nlateral_Off simulates lower DIN concentrations compared to the ML assessment (Fig. S8). These lower DIN concentrations are attributed to different factors. In Australia, low N inflow into rivers results in low DIN concentrations, whereas in the Amazon and tropical rainforests of Africa, high denitrification rates are primarily responsible for the low DIN concentrations in the model (Fig. 7). The ML involves a significant degree of empirical modelling, and therefore does not fully reflect real-world conditions. Therefore, this comparison cannot be regarded as a direct evaluation of the model based on observational data. However, the consistency between the two models across most regions globally (e.g., North America, Western Europe, Eastern China, and India) suggests that LSM_Nlateral_Off overall performs reasonably well in simulating DIN lateral transfer processes.” (lines 555-571)

16. **Line 513-515 It is written:**

“The reality of this transient peak is however questionable as it results mostly from meteorological forcing, which is uncertain for the beginning of the 20th century.”

Unfortunately, no information on the atmospheric forcing is provided (see major remarks).

The climate forcing data is taken from the Global Soil Wetness Project Phase 3 (GSWP3). The forcing data information has been added in Table 1. During 1926-1931, the global total amount of heavy precipitation (>25 mm d^{-1}) was higher, which caused more runoff and more TN flow into rivers (Fig. S9). Empirical research on long-term runoff fluctuations also evidenced elevated global runoff during the same period (Probst and Tardy 1989). Relevant statements have been clarified in the revised manuscript:

"The global TN input into rivers, TN export to oceans and denitrification in rivers all show a slight peak between 1926 and 1931 due to the relatively higher surface runoff during this period (Fig. S9). This higher runoff results mostly from meteorological forcings, as the global total amount of heavy rainfall (>25 mm d^{-1}) was higher during this period (Fig. S9). Note that Probst and Tardy (1989) provide empirical evidence for elevated global runoff during this period and we thus consider this peak as realistic." (lines 609-615)

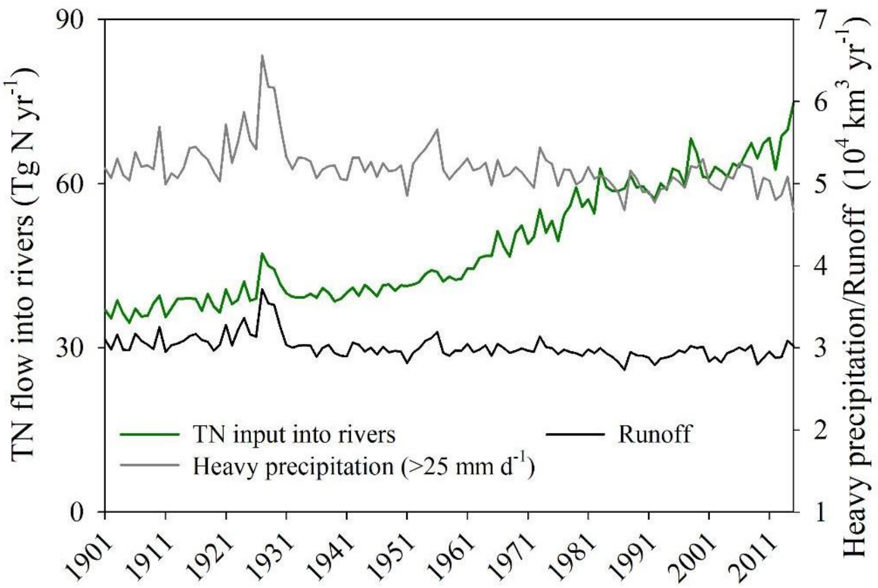


Figure S9. Global annual TN flow into rivers, runoff and heavy precipitation (> 25 mm d^{-1}) from 1901 to 2014.

17. Line 531. "… the grid boxes with …"

Thanks, we have corrected it to

"Over the entire simulation period, <u>the grid cells with</u> the highest relative denitrification increases are mostly located in the subtropics (Fig. 8b)". (line 631-633).

18. Line 541-545. Sentence is too long and difficult to read. Please rephrase.

Thanks, we have rephrased the original sentence from:

"Unsurprisingly, the TN export to oceans increased in most regions since the beginning of the 20th century (Fig. 8c) and in regions such as the south-eastern coastal areas of China, not only the recent TN exports to oceans are relatively high, but also the percentage increase over the 20th century exceeded 100% (Fig. 7c and Fig. 8c)."

to

"Unsurprisingly, TN exports to oceans have increased in most regions since the early 20th century (Fig. 8c). In several regions, such as the southeastern coastal areas of China, TN exports to oceans have even increased by more than 100% from 1901-1910 to 2001-2014 (Fig. 8c)." (lines 643-646)

19. Line 596. "…simulations, *and* downscale …"

Thanks, we have corrected it. (line 698)

20. Line 595-596. It is written:
"Ocean biogeochemical modelling community typically uses annual mean TN fluxes derived from Global News to force their simulations"

Please provide solid reference(s) for this statement, i.e. that is more than a utilization in a single study.

Following your suggestion, we have provided references for this statement. Please see:

"This result is important because the ocean biogeochemical modelling community typically uses annual mean TN fluxes derived from Global News to force their simulations (e.g., Lee et al., 2016; Stock et al., 2020; Tjiputra et al., 2020; Lacroix et al., 2021)," (lines 695-698)

21. Line 602. "… into *rivers*, denitrification …"

Thanks, we have corrected it. (line 704)

22. Line 624-628. The Sentences are too long and difficult to read. Please rephrase.

Sorry for the lengthy sentence. we have rephased it from:

"The results however markedly differ regarding organic N (ON=PON+DON) with IMAGE-GNM simulating a significant increase from 24.9 Tg N yr^{-1} during 1901-1910 to 37.9 Tg N yr^{-1} in during 1990-2000, while the ON inflow simulated by ORCHIDEE_NLAT shows a weaker increasing trend over the same period (26.5 Tg N yr^{-1} during 1901-1910 to 32.4 Tg N yr^{-1} during 1990-2000)."

to

"In contrast, the organic nitrogen (ON = PON + DON) fluxes simulated by ORCHIDEE-Clateral and derived from IMAGE-GNM differ significantly. The ON inflow simulated by IMAGE-GNM shows a substantial increase from 24.9 Tg N yr^{-1} during 1901-1910 to 37.9 Tg N yr^{-1} during 1991-2000, while ON simulated by ORCHIDEE-Clateral exhibits a weaker increasing trend over the same period, from 26.5 Tg N yr^{-1} to 32.4 Tg N yr^{-1}." (lines 725-731)

23. Line 726. "… model *used* in …"

Thanks, we have corrected it. (line 833)

24. Line 825. "… *reproduces* …"

Thanks, we have corrected it. (line 964)

25. Line 827. "… global *simulation* of …"

Thanks, we have corrected it. (line 965)

26. References.

The reference section has to be carefully checked as many references include the full names of the authors instead of initials for the given names.

Sorry for the mistakes. we have double checked the reference section to make all references be listed following the guide in the author guide of the ESD.

References in the response letter

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