Response to Anonymous Referee #2

We would like to thank Referee #2 for the insightful and constructive comments. All your comments and suggestions are very helpful for improving our manuscript. We have carefully considered and addressed all of these comments, and significantly revised our manuscript. Please find our point-by-point response below. For clarity, the reviewer's comments are listed in black, while our response are shown in blue.

"This paper evaluates the spectral nudging scheme implemented in the WRF model in order to evaluate the impact of spectral nudging on precipitation simulation over the Tibetan Plateau (TP). The spectral nudging is scale-discriminated so that only large spatial scales are constrained. The authors found that model simulations show clear improvements in their representations of downscaled precipitation intensity and its diurnal variations, atmospheric temperature and water vapor when spectral nudging is applied towards the horizontal wind and geopotential rather than towards the potential temperature and water vapor mixing ratio. The topic of the paper is interesting and it's a good fit for the scope of GMD. The description of the method is clear. The experiment design that testing nudging strength and nudging variables is appealing and convincing. However, there are still some rooms for the improvement. For example, the evaluation of this study can be improved with some additional information. In the following, some comments are listed for author's revision."

Author Response: Thank you for your positive comments and encouragement for our study! We have fully addressed every comment and revised our manuscript accordingly.

"1. The authors used the regional averaged difference between control (not nudged) simulation and several nudged simulations to show the impact of nudging on constrained fields. Please also quantify how well the nudged variables (e.g. T, U, V and Q) matched the ERAI reanalysis."

Author Response: Done. Following your suggestion, vertical profile of zonal wind (U; m s^{-1}), meridional wind (V; m s^{-1}), atmospheric temperature (T; K) and specific humidity (Q; kg kg^{-1}) of the difference between ERAI and model's simulation is shown in the new Figure 9. Generally, applying spectral nudging method in WRF model leads to better consistence with ERAI compared to Control (without spectral nudging), especially for U and T (Figure 9a, 9b and 9c). But SNlowU and SNlowT have comparable results with Control, and the reason is referred to the reply to Comment 4. For specific humidity (Figure 9d), all simulations have smaller Q in the whole layer, indicating that WRF model can effectively reduce the wet bias of water vapor of ERAI over the TP.
In order to quantify how well the nudged variables matched the ERAI, statistical error metrics of column-averaged U, V, T and Q derived from seven WRF simulations versus ERAI over the TP for the study period are given in Table 2. Compared to Control, the use of spectral nudging technique obviously improved the consistence between regional model field and driving field, with lower RMSEs of the constrained variables.

Aforementioned new Figure 9, new Table 2 and relevant descriptions have been added in 'Section 4.3' (Line: 332-369) in the revised manuscript.

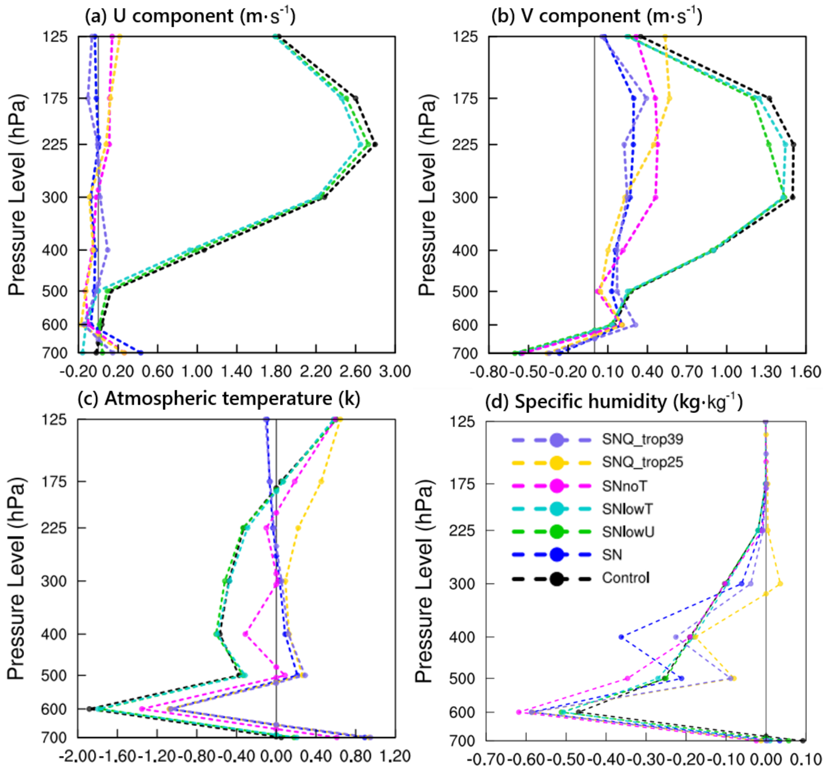

Figure 9: Vertical profile of difference fields between ERA-Interim and seven WRF simulations averaged over the study period for (a) zonal wind component (U; m s^{-1}), (b) meridional wind component (V; m s^{-1}), (c) atmospheric temperature (k), (d) specific humidity (kg kg^{-1}) over the TP. The vertical gray solid line represents the value of 0.0 at each pressure layer.

Table 2: Statistical error metrics of column-averaged zonal wind component (U; m s^{-1}), meridional wind component (V; m s^{-1}), atmospheric temperature (k) and specific humidity (kg kg^{-1}) derived from seven WRF simulations versus ERA-Interim (ERAI) over the TP for the study period.

		Control	SN	SNlowU	SNlowT	SNnoT	SNQ_trop25	SNQ_trop39
U (m s^{-1})	MB	1.61	0.29	1.57	1.49	0.31	0.30	0.26
	RMSE	2.06	0.80	2.03	1.97	0.79	0.82	0.81
V (m s^{-1})	MB	0.71	0.18	0.65	0.67	0.23	0.26	0.19
	RMSE	1.87	0.99	1.78	1.80	1.04	1.02	1.03
T (k)	MB	-0.35	0.01	-0.33	-0.31	-0.02	0.22	0.03
	RMSE	0.78	0.24	0.76	0.74	0.50	0.44	0.24
Q (kg kg^{-1})	MB	-0.05	-0.08	-0.06	-0.06	-0.09	-0.03	-0.05
	RMSE	0.29	0.35	0.30	0.29	0.27	0.22	0.25

"2. How the simulations of air temperature and water vapor mixing ratio are changed near the "lid" layer where the nudging is restricted toward both variables?"

Author Response: Thank you for this comment. We compared mean atmospheric temperature and specific humidity between model level of 25 and 39 derived from SNQtrop25 and SNQtrop39 to reveal the impact of limiting nudging of temperature and water vapor mixing ratio. Their differences (SNQ_trop25 minus SNQ_trop39) are displayed in Figure R1. In Figure R1a, restricting nudging of temperature generally leads to a higher atmospheric temperature, with an exception over the northern Tibetan Plateau. In terms of specific humidity, restricting nudging of water vapor mixing ratio has an overall larger specific humidity (Figure R1b). The evaluations indicate that simulation without nudging of temperature produces higher temperature, while simulation without nudging of water vapor mixing ratio produces wetter atmosphere.

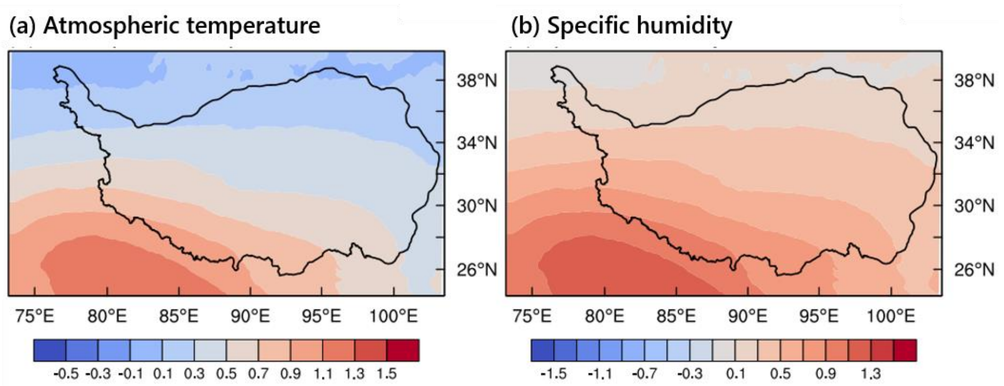

Figure R1. Difference of (a) atmospheric temperature (K) and (b) specific humidity ($kg\ kg^{-1}$) averaged over the study period derived from SNQ_trop25 minus SNQ_trop39.

“3. The large simulated precipitation bias and high precipitation RMSE over the Himalaya mountain region shown in Figure 2 and Figure 4 are possibly caused by the topographic differences between ERAI and WRF model. What are the impacts of nudging toward geopotential height on simulated results?”

Author Response: Thank you for this comment. Owing to the sharply lifted topography height and the complex terrain over the Tibetan Plateau (TP) and along the Himalayas, which lead to a large pressure gradient, the atmospheric circulation here is characterized as southerly and regulated by orographic drag (Zhou et al., 2021). In order to explain the impact of nudging toward geopotential height on precipitation simulation, spectral nudging experiment with eliminating nudging of geopotential height has been run.
The mean 500 hPa geopotential height derived from ERAI, Control, SN and SNnoG (spectral nudging without nudging of geopotential) is shown in Figure R2. Generally, there is an obvious meridional atmospheric pressure gradient. Control simulation resolved more orographic drag and thus weakened northward atmospheric flow over the TP (Figure R2a and Figure R2b). Compared with ERAI and Control simulation, SN (Figure R2c and Figure R2e) has an enhanced atmospheric pressure gradient along the Himalayas, and the difference between SN and SNnoG (Figure R23d and Figure R2f) is neglectable. The comparisons indicate that nudging of geopotential height can improve model’s ability in resolving the topographic effect that forcing more atmosphere convergence at the southern slope of the Himalayas and leading to a greater pressure gradient near the southern edge of the TP, while less water vapor can reach the interior region of the TP.

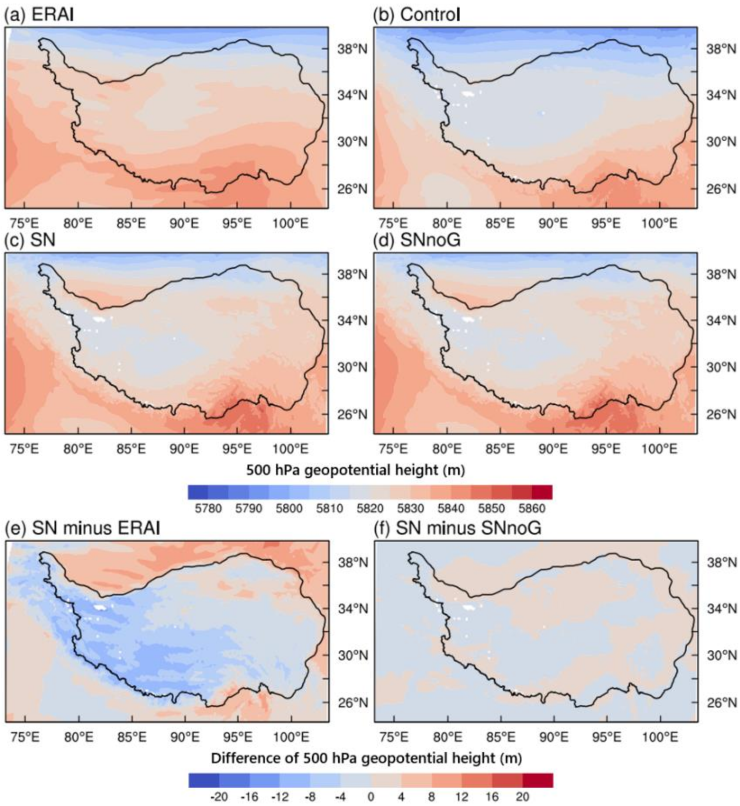

Figure R2. Monthly mean geopotential height (m) at 500 hPa derived from (a) ERAI, (b) Control, (c) SN, (d) SNnoG and the differences derived from (e) SN minus ERAI, (f) SN minus SNnoG for the study period.

"4. Please explain whether the nudging coefficient of horizontal winds and potential temperature shows similar results with control simulation."

Author Response: Thank you for this comment. There are similar results of SNlowU and SNlowT with control simulation for vertical profile of mean atmospheric temperature and horizontal wind speed. One important factor that influences the model's result is the nudging coefficient when spectral nudging is applied. The nudging coefficient relates to how often nudged variable is relaxed towards the driving fields. The nudging coefficient for SN simulation is set to 0.0003 s^{-1} (default value), indicating that nudging variable was relaxed to the driving field at every 50 min. Similarly, the nudging coefficient of 0.000045 s^{-1} for horizontal wind and temperature (in SNlowU and SNlowT simulations) indicates that the relaxation time scale is 6 h, which equals to the input temporal interval of ERAI (driving fields). It may weaken the impact of applying spectral nudging on simulating the variability and small-scale characteristics of horizontal wind and temperature. Therefore, spectral nudging with lower nudging coefficient for temperature and horizontal wind produced similar patterns with control simulation.
Relevant explanation has been added in the revised manuscript in 'Section 4.3' (Line: 352-358).

"5. Figure 7 and Figure 8 show the cross section of vertical wind and thus imply the convective processes over the TP and south slope of the Himalaya. I suggest that the authors should also consider the advection and atmospheric circulation in midtroposphere, which will make moisture lifted by convection to the interior of the TP."

Author Response: Thank you for this comment. According to your suggestion, the impact of spectral nudging technique on horizontal moisture transport in mid-troposphere has been evaluated in the revised manuscript. Column-mean northward water vapor transport (meridional wind multiples specific humidity), as well as eastward water vapor transport (zonal wind component multiples by specific humidity), derived from ERAI, ERA5 and spectral nudging experiments is shown in the new Figure 6 (added in the revised manuscript). Relevant descriptions are available in 'Section 4.1' (Line: 278-301) of the revised manuscript.

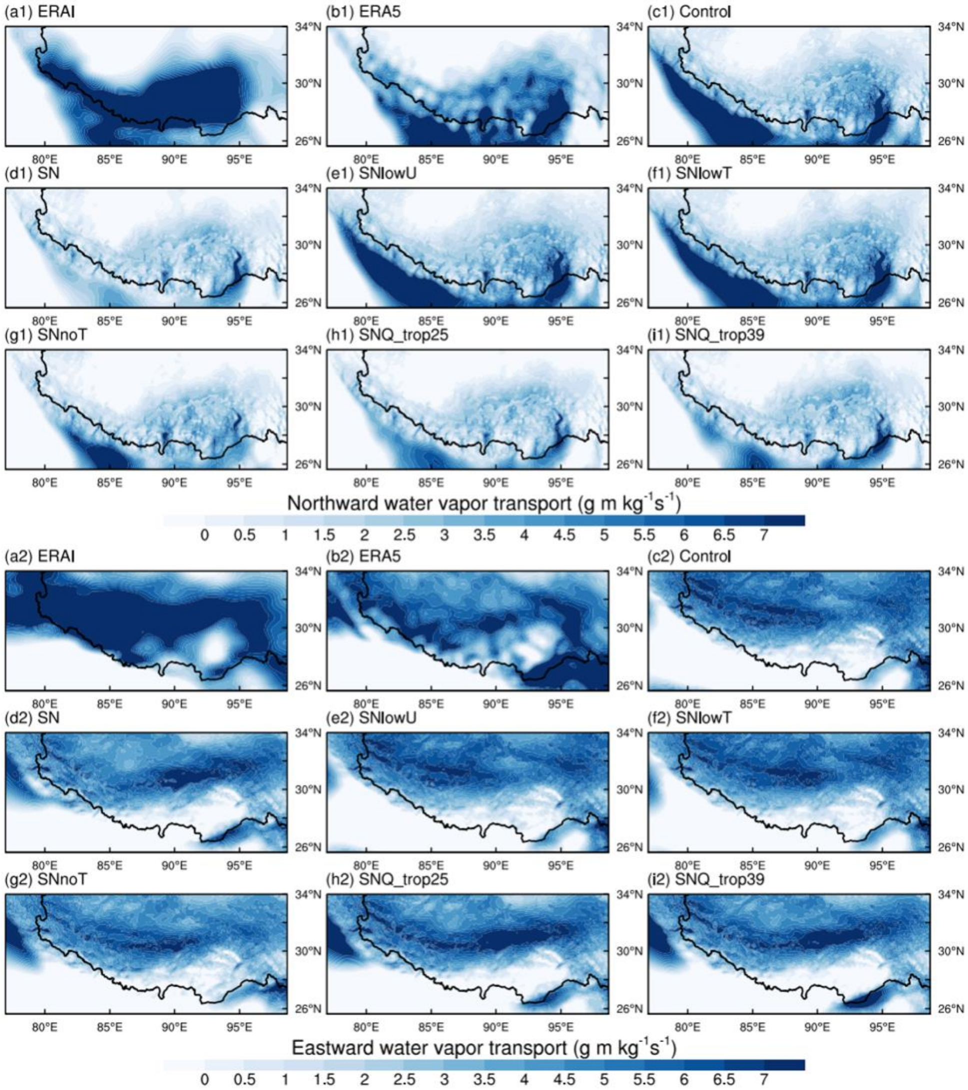

Figure 6: Column-integrated northward water vapor transport (meridional wind component multiples by specific humidity, units: g m kg^{-1} s^{-1}) averaged over the study period over the central Himalayas derived from (a1) ERAI (ERA-Interim), (b1) ERA5, (c1) Control, (d1) SN, (e1) SNlowU, (f1) SNlowT, (g1) SNnoT, (h1) SNQ_trop25 and (i1) SNQ_trop39, respectively. (a2)-(i2) are the same as (a1)-(i1) but for the eastward water vapor transport

(zonal wind component multiples by specific humidity).

"6. Please add more details about the spectral nudging method."

Author Response: Thank you for this suggestion. In the revised manuscript, introduction of spectral nudging technique has been added in 'Section 2.2 Spectral nudging' (Line: 125-144). In order to explain the experiment design and model configuration more clearly, relevant paragraphs in Section 2 have been reordered.

"7. Please use a more effective method to display the impacts of spectral nudging on specific humidity or atmospheric water content."

Author Response: Thank you for this suggestion. In the revised manuscript, vertical distribution of specific humidity was deleted in Figure 7 and Figure 8. Distribution of column-integrated northward water vapor transport (meridional wind component multiples specific humidity) derived from ERAI, ERA5 and model's simulations are plotted in Figure 6 in the revised manuscript to explain the impacts of spectral nudging on atmospheric water content. Relevant contents have been added in 'Section 4.1' (Line: 278-301).

"8. What is the accuracy of horizontal wind and atmospheric water transport fields in ERA5 over the TP?"

Author Response: Thank you for this comment. The accuracy of horizontal wind and atmospheric water transport fields over the Tibetan Plateau has been revealed by some researchers. Based on the study of He et al. (2019), the accuracy of ERA5 reanalysis for atmospheric specific humidity (Q), zonal wind (U) and meridional wind (V) components has been evaluated against the sounding sites over the Tibetan Plateau and its surroundings. In general, U with 30 km spatial resolution shows a mean bias (MB) of -0.2 m s^{-1} and root-mean-square errors (RMSEs) of 2.5 ~ 3.0 m s^{-1}. The V has a MB of 0.1 m s^{-1} and RMSEs of 2.9 ~ 3.3 m s^{-1}. In terms of Q, it shows an overall wet bias (MB: -0.5 ~ 0 g kg^{-1}, RMSE: 0 ~ 1.2 g kg^{-1}). According to another study of Zhou et al. (2021), the column-integrated northward water vapor transport ($Q \times V$; units: kg m^{-1} s^{-1}) of ERA5 over the central Himalayas shows a wet bias.

References:

He, J., Zhang, F., Chen, X., Bao, X., Chen, D., Kim, H. M., Lai, H. W., Leung, L. R., Ma, X., Meng, Z., Ou, T., Xiao, Z., Yang, E. G., and Yang, K.: Development and Evaluation of an Ensemble-Based Data Assimilation System for Regional Reanalysis Over the Tibetan Plateau and Surrounding Regions, J Adv Model Earth Syst, 11, 2503-2522, 10.1029/2019MS001665, 2019.

Zhou, X., Yang, K., Ouyang, L., Wang, Y., Jiang, Y. Z., Li, X., Chen, D. L., Andreas, P.: Added value of kilometer-scale modeling over the third pole region: a CORDEX-CPTP pilot study, Clim Dyn, 10.1007/s00382-021-05653-8, 2021.