Overall evaluation:

This is an interesting manuscript that proposes a new image assimilation system to improve the spatial structure accuracy of soil moisture in land surface models. The method is innovative by introducing image observations and curvelet transform to optimize the model spatial patterns. The experiments generally demonstrate the capability of the proposed approach. I think this manuscript merits publication after addressing several issues.

Response:

Thanks to your valuable comments and suggestions. Following your suggestions, we have revised the manuscript carefully from the beginning to the end. The point-by-point response is listed below according to your specific comments.

Major comments:

1. The introduction needs to be improved. Soil moisture is widely assimilated in land surface models, the authors should clearly point out the limitations of current land data assimilation systems in representing spatial patterns and explain why improving spatial accuracy is important. More discussions are needed on existing studies that tried to retain spatial information in land DA. This will help highlight the motivation and significance of the current study.

More details are needed. For example, why the western East Asia is selected as the experimental region. Even in state-of-the-art land surface models, the soil hydrothermal processes (particularly over the Tibetan Plateau) are not generally well represented, it is challenge for most of the models to obtain a reliable soil moisture simulation. Therefore, is this a good choice for selecting this region as the study area?

Response:

The following content is added in the introduction part to emphasize the significance of spatial structure adjustment.

(1) Some discussions on the significance of spatial structural characteristics of soil moisture has been added to Line 59-68 of the revised manuscript.

Spennemann et al. (2018) emphasized the significance of the identification of Land-Atmosphere interaction region, which is crucial to enhance the weather/seasonal forecast and the better understanding of the physical mechanisms involved. Because in these hotspot regions, soil moisture variability has the potential to modulate the atmospheric conditions by changing the latent- and sensible energy fluxes on time scales ranging from diurnal to seasonal (Seneviratne et al., 2010). Zhu et al. (2023) revealed that positive (negative) abnormal soil moisture in the eastern (western) Qinghai-Tibet Plateau during spring is associated with increased precipitation and runoff in the Yangtze River Basin during summer, while the opposite holds true. Xu et al. (2021) highlighted that the presence of extensive snow cover and soil moisture anomalies in Siberia during spring alters the thermal conditions of both the surface and atmosphere throughout summer, and then leads to anomalous atmospheric transient wave activities, which consequently stimulate and strengthen the atmospheric Rossby wave train, and ultimately result in abnormal summer precipitation patterns in South China.

The following references have been added to the reference part of the revised manuscript:

Spennemann, P.C., Salvia, M., Ruscica, R. C., Sörensson, A. A., Grings, F., Karszenbaum, H.: Land-atmosphere interaction patterns in southeastern South America using satellite products and climate models. Int J Appl Earth Obs Geoinformation, 64, 96-103, https://doi.org/10.1016/j.jag.2017.08.016, 2018.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., Teuling, A. J.: Investigating soil moisture–climate interactions in a changing climate: A review. Earth Sci. Rev., 99(3-4), 125-161, https://doi.org/10.1016/J.EARSCIREV.2010.02.004, 2010.

Zhu, C., Ullah, W., Wang, G., Lu, J., Li, S., Feng, A., Hagan, D., F., T., Jiang, T., Su, B.: Diagnosing potential impacts of Tibetan Plateau spring soil moisture anomalies on summer precipitation and floods in the Yangtze River Basin. J G R Atmospheres,128(8), 10.1029/2022jd037671, 2023.

Xu, B., Chen, H., Gao, C., Zeng, G., Huang, Q.: Abnormal change in spring snowmelt over Eurasia and its linkage to the East Asian summer monsoon: The hydrological effect of snow cover. Front Earth Sci, 8: 594656, 10.3389/feart.2020.594656, 2021a.

(2) Some discussions about inadequate ability of current single point assimilation method to adjust the spatial structures have been added to Line 79-89 of the revised manuscript.

Furthermore, there are regional differences in the accuracy of the estimation of the observation error and the background error resulting from the single column assimilation, which ultimately contribute to the discontinuity of the abnormal spatial structure in the analyzed soil moisture field. The estimation of single-point observation error and background error through statistical methods is characterized by significant uncertainty, while point-by-point assimilation methods have limitations in capturing spatial information from neighboring pixels. In addition, the bias correction is commonly employed to rectify the discrepancy between model simulations and observations prior to assimilation. The prevailing assimilation system primarily addresses the bias by incorporating scale adjustments into the model simulation based on observed data. The spatial distribution structure information, however, is compromised as a result of rescaling (Zhou et al., 2019).

The following reference has been added to the reference part of the revised manuscript:

Zhou, J., Wu, Z., He, H., Wang, F., Xu, Z., Wu, X.: Regional assimilation of in situ observed soil moisture into the VIC model considering spatial variability, Hydrol. Sci. J., 64:16, 1982-1996, 10.1080/02626667.2019.1662024, 2019.

(3) The introduction of research progresses on the adjustment of spatial information of soil variables is added to Line 94-108 of the revised manuscript.

The uneven spatial distribution of precipitation and the heterogeneousness of soil properties, land cover types and topography would result in significant spatial variations in the characteristics of soil moisture (Tian et al., 2021). The effectiveness of estimating soil moisture using observational data is limited due to significant spatial heterogeneity. Therefore, a lot of studies strive to acquire the precise spatial structural information of soil moisture to the greatest extent possible. Pauwels et al. (2001) employed the nudging technique to incorporate spatial structure information derived from remote sensing soil moisture observations, and obtained enhanced predictions of runoff. Han et al. (2012) examined the constraints of introducing the horizontal correlation features of satellite soil moisture observation data during land surface data assimilation. The findings demonstrated that incorporating surrounding observations and spatial horizontal correlation structure information may improve the analysis field of soil moisture in uncovered grids. The regional soil water assimilation scheme developed by Zhou et al. (2019) incorporates an empirical approach and accounts for spatial variability, resulting in significantly improved accuracy of soil moisture simulation in both temporal and spatial dimensions. The findings of these studies suggest that enhancing soil moisture levels is of utmost importance; however, it is equally crucial to acquire a more precise comprehension of the spatial distribution of soil moisture for effective management strategies, particularly in key regions like the Qinghai-Tibet Plateau where land-air interactions are significant and there are large spatial variations of soil moisture.

The following references have been added to the reference part of the revised manuscript:

Tian, S., Renzullo, L. J., Pipunic, R. C., Lerat, J., Sharples, W., Donnelly, C.: Satellite soil moisture data assimilation for improved operational continental water balance prediction, Hydrol. Earth Syst. Sci., 25(8): 4567-4584, https://doi.org/10.5194/hess-25-4567-2021, 2021.

Pauwels, V. R. N., Hoeben, R., Verhoest, N. E. C., Troch, F. P. D.: The importance of the spatial patterns of remotely sensed soil moisture in the improvement of discharge predictions for small-scale basins through data assimilation, J Hydrol, 251(1-2), 88-102, https://doi.org/10.1016/S0022-1694(01)00440-1, 2001.

Han, X., Li, X., Hendricks Franssen H. J., Vereecken, H., Montzka, C.: Spatial horizontal correlation characteristics in the land data assimilation of soil moisture. Hydrol. Earth Syst. Sci., 16(5), 1349-1363, https://doi.org/10.5194/hess-16-1349-2012, 2012.

Zhou, J., Wu, Z., He, H., Wang, F., Xu, Z., Wu, X.: Regional assimilation of in situ observed soil moisture into the VIC model considering spatial variability, Hydrol. Sci. J., 64:16, 1982-1996, 10.1080/02626667.2019.1662024, 2019.

The following contents are added to explain the purpose of research area selection in Line 129-132:

The study area selected in this research is mainly East Asia, encompassing the alpine regions of Siberia, the vegetative regions of eastern China, as well as the Qinghai-Tibet Plateau and desert regions of western China. The estimation of observation error and model error becomes more challenging in the Tibetan Plateau region, particularly for single point assimilation. Including the plateau region can effectively showcase the advantages of image assimilation method.

2、The authors claim the capability of improving deep soil moisture through assimilating surface data. But no clear explanations are given on the underlying mechanism. Some discussions should be added regarding how the surface information propagates to deeper layers through model physics. Moreover, when comes to the complexity of the soil hydrothermal processes of the Tibetan Plateau (e.g., soil freezing and thawing) and the difficult of the model to parameterize these processes, how to

Response:

According to the comments of the reviewer, we attempted to explain how assimilating of surface soil moisture improves deeper soil moisture on the basis of the physical process of vertical soil water movement. The actual model results were utilized to validate the gradual impact of analysis increment on deeper soil moisture. The following additional figures and associated descriptions have been added to lines 155-158 of the revised manuscript:

Soil moisture and its vertical transport is governed by infiltration, runoff, gradient diffusion, gravity, and root extraction by canopy transpiration. Only the vertical transport of soil water is considered in the CoLM model. The water in the soil will percolate through the soil pores due to the combined effects of gravity and capillary forces. According to the principle of mass conservation, the vertical movement of soil water can be mathematically described by the Richards equation.

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} - E - R_{fm}$$

And the relevant description has been added to the revised manuscript in Line 524-531:

Vertical motion of soil water is integrated over the layer thickness, in which the time rate of variation in water mass must equal to the net flow across the bounding interface, and plus the rate of internal source or sink. The terms of water flow across the layer interfaces are linearly expanded by using first-order Taylor expansion. Therefore, when the surface data were assimilated, the net flow across the bounding interface to deeper layers become more reasonable corresponding to surface variation.

Of course, when it comes to the process of permafrost and snow processes, such as soil freezing and thawing in the Tibetan Plateau region, the variations of soil moisture are much more complex, and the mechanism of data assimilation on permafrost needs to be studied more thoroughly in the future.

In addition, the subsequent soil moisture time-depth profiles of real experiments are utilized to elucidate the process by which surface soil moisture assimilation impacts deep soil moisture. The following figure and related discussions are added to Line 532-573 of the revised manuscript:

In order to further elucidate the vertical impact of data assimilation, the vertical propagation characteristics of surface assimilation influence are also examined based on actual experiment results. The vertical-temporal profiles of soil moisture on different underlying surface types selected in the Tibetan Plateau and plain areas are given in Fig. 12, so as to elucidate the physical processes how the surface soil moisture assimilation influences soil moisture at a depth of 7–28 cm. The spatial locations of selected single points are depicted in Fig. 12a. In order to emphasize the soil moisture variation difference between plateau areas and plain areas, bare soil points are situated in the eastern and western regions of the plateau (represented by blue and black five-pointed stars), while corn and needleleaf evergreen boreal tree (represented by red and orange five-pointed stars) are positioned within the plain area. Figs. 12b–12c illustrate the difference of soil-moisture analysis field between DA experiment and CTL experiment, as well as the temporal characteristics of soil moisture analysis field at different depths of selected points in plateau areas. The vertical ordinate denotes the position of node depth for each soil layer in the CoLM model. The most notable difference in the vertical variation of soil moisture among the two points on the plateau is primarily attributed to the differences in both magnitude and depth of this vertical change. In the western plateau region, soil moisture at bare soil points is generally low, usually below 0.2 m3/m3 (Fig. 12b). Additionally, the surface undergoes significant temporal variations that may be related to the prevalence of small-scale convective weather systems in this plateau area. The vertical variation of bare soil moisture in the plateau region primarily occurs above 50 cm, while the soil moisture exhibits a consistent pattern below 50 cm. The vertical variation of soil moisture is correlated with the intensity of soil moisture anomaly. As depicted in Figs. 12b and 12c, the vertical impact of minor perturbations in bare soil moisture within the plateau region is negligible, primarily occurring above a depth of 3 cm. The similarity between the two bare soil points lies in the fact that significant changes in soil moisture can rapidly impact the top 10 cm of soil, resulting in similar characteristics observed in the soil moisture above this depth. However, abnormal soil moisture exhibits a noticeable time lag effect below 10 cm. The characteristics of assimilation influence exhibit similarities to the features observed in vertical changes of soil moisture. Assimilation significantly enhances surface soil moisture around July 10th, and the increasement in soil moisture analysis within the plateau region can also rapidly impact the 10 cm depth of soil, with a maximum positive analysis increment reaching 0.16 m3/m3. The impact of assimilation can affect soil moisture at a depth of approximately 10 cm within one day, while it takes approximately 15 days for this analysis to affect the 50 cm depth. However, the impact of the analysis increment can be sustained for over a month at the depths ranging from 20 cm to 50 cm.

Figures 12d and 12e are similar to Figs. 12b and 12c, but they are selected from the plain areas. It is evident that the vertical variation characteristics of soil moisture differ significantly among different vegetation types. The analysis increment for corn is relatively minimal. Image assimilation leads to a substantial increase in surface soil moisture around July 10th. The maximum positive analysis increment can reach up to 0.12 m3/m3, with a vertical change level reaching approximately 30 cm. The effect is gradually transmitted to a depth of approximately 2 meters over time, with a duration of about one month. In the case of needleleaf evergreen boreal tree, the analysis increment is relatively small, and surface soil moisture gradually increases from around July, with its influence extending to a depth of approximately 100 cm. Seen from the above analysis, it is evident that the assimilation of surface soil moisture gradually impacts the deeper layers of the model as integration progresses, with a lasting effect of approximately 1 month. This phenomenon also serves as the primary factor contributing to the simulation improvement of soil moisture at a depth of 7–28 cm.

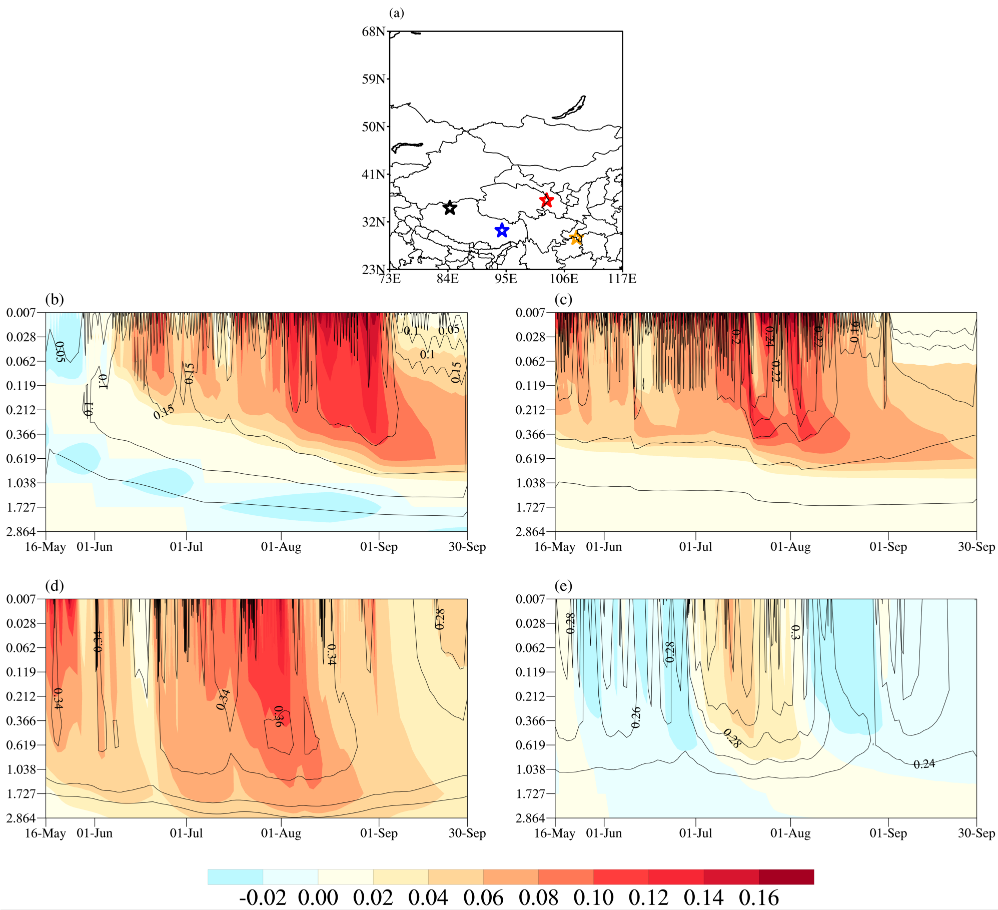

Figure 12: (a) The location of designated grid. The soil-moisture temporal variation of the difference between the DA experiment and CTL experiment (represented by shadow) and the soil moisture profiles (indicated by contours) under different land types: (b) bare soil (black five-pointed star), (c) bare soil (blue five-pointed star), (d) corn (red five-pointed star), and (e) needleleaf evergreen boreal tree (orange dots).

3、The soil moisture product of EAR5_Land was assimilated and used to assessment, please explain in detail the rational for this approach. Why not choose an independent soil moisture product to evaluate the assimilation results?

Response:

Thanks for your valuable suggestion. The CLDAS reanalysis data is chosen as the independent dataset, and an additional verification analysis of the assimilation results based on the CLDAS data is conducted. The CLDAS product is produced by using the near-real-time CLDAS atmospheric drive product, which incorporates a larger amount of ground station observation data and higher quality background field, the dataset exhibits excellent quality and offers high spatio-temporal resolution data in the China region (Shi et al., 2011; Liu et al., 2019).

The following description of CLDAS reanalysis data is added to Line 289-297 Of the revised manuscript:

The soil volume water content reanalysis product V2.0, generated by the land surface data assimilation system CLDAS of the National Meteorological Information Center of China Meteorological Administration, covers the Asian region (0–65°N, 60–160°E). The temporal resolution is 1 hour, and the spatial resolution is 0.0625°. The vertical direction is divided into five layers: 0–5 cm, 5–10 cm, 10–40 cm, 40–100 cm, and 100–200 cm. The CLDAS product is produced by using the near-real-time CLDAS atmospheric drive product, which incorporates a larger amount of ground station observation data and higher quality background field to drive various land surface models (such as CLM 3.5, CoLM and Noah-MP). As a result, the dataset exhibits excellent quality and offers high spatio-temporal resolution data in the China region (Shi et al., 2011; Liu et al., 2019). The CLDAS reanalysis data is therefore chosen as the independent dataset, and an additional verification analysis of the assimilation results based on the CLDAS data is conducted.

The following evaluation results are added to Line 402-??? of the revised manuscript:

The overlapping region (22–50°N，73–117°E) between the CLDAS data and the model region is selected for analysis. The spatial correlation coefficients of soil moisture before and after assimilation to CLDAS data are also computed, aiming to quantitatively assess the accuracy of the adjustment in soil moisture spatial distribution structure by the image assimilation system. The image assimilation results in a notable increase in the spatial correlation coefficient between CoLM soil moisture and the first layer (0–5cm) soil moisture of CLDAS, as depicted in Fig. 14a. Throughout the assimilation and prediction stages, this correlation coefficient consistently surpasses that of the CTL experiment, with a maximum value of 0.79. Moreover, after assimilation, there is an average increase in spatial correlation coefficient from 0.67 to 0.71. The image assimilation brings a more significant increase in the spatial correlation coefficient of soil moisture in the second layer (5–10 cm), as depicted in Fig. 14b. The highest spatial correlation coefficient reaches 0.79, while the average value increases from 0.67 to 0.73. The verification results of independent data further confirm that the image assimilation system has a strong capability in adjusting the spatial structure of soil moisture, particularly in relation to subsurface soil moisture.

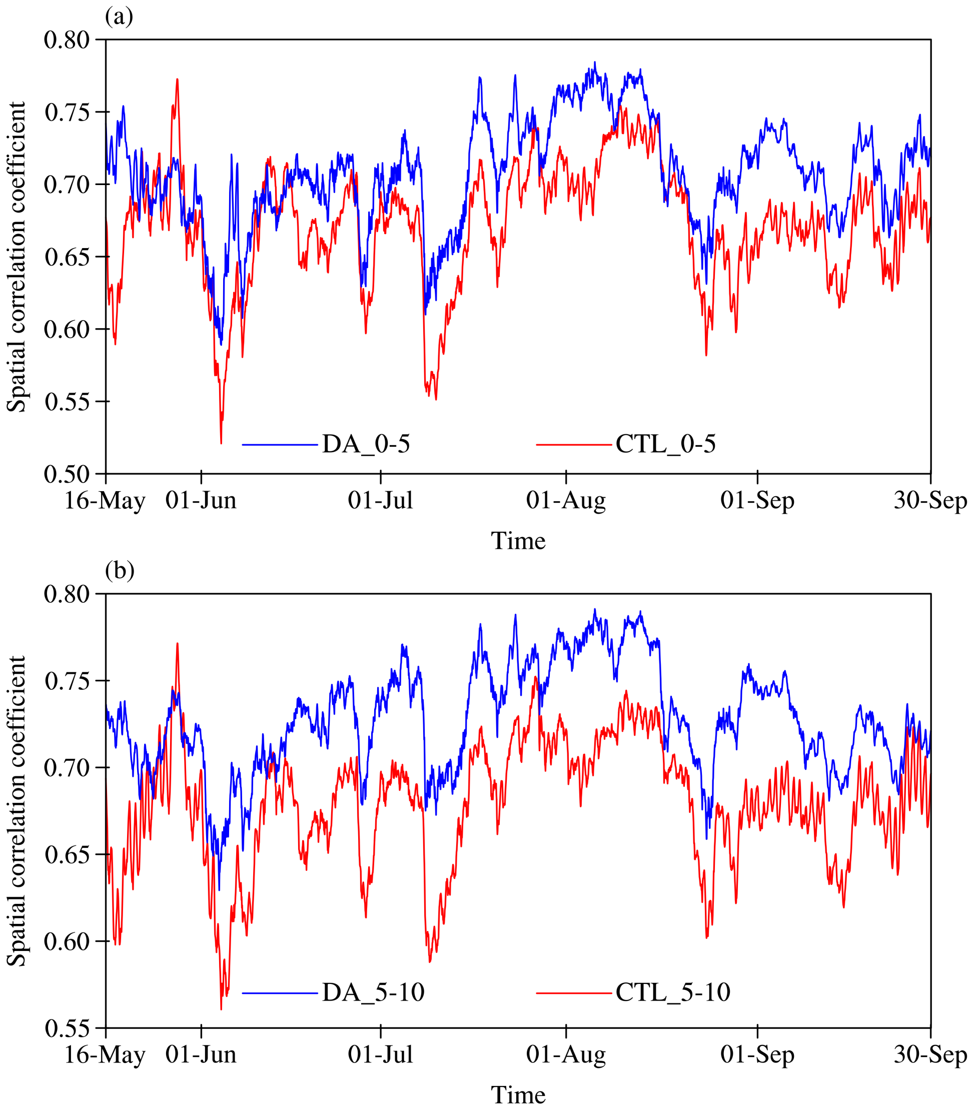

Figure 14: The spatial correlation coefficients of the CLDAS products to the CTL experiment (red solid line) and image assimilation experiment (blue solid line) for the first layer (0–5cm) and second layer (5–10 cm) from May 16 to September 30, 2016.

The following references have been added to the reference part of the revised manuscript:

Shi, C., Xie, Z., Qian, H., Liang, M., and Yang, X.: China land soil moisture EnKF data assimilation based on satellite remote sensing data, Sci China Earth Sci, 41, 375-385, https://doi.org/10.1007/s11430-010-4160-3, 2011.

Liu, J. G., Shi, C. X., Sun, S., Liang, J. J., Yang, Z.-L.: Improving land surface hydrological simulations in China using CLDAS meteorological forcing data. J Meteorol Res-prc, 33(6), 1194-1206, https://doi.org/10.1007/s13351-019-9067-0, 2011.

4. The evaluation of the image assimilation system relies heavily on the EAR5_Land soil moisture reanalysis data, in-situ soil moisture observations from dense observation network are recommended to be used in this study.

Response:

Thanks to your valuable suggestion.

In order to enhance the reliability of the results, we incorporate the CLDAS reanalysis data as an independent verification dataset. The CLDAS reanalysis data assimilates a substantial amount of high-density ground observation data in China. We have reasonable grounds to believe that the verification outcomes based on the CLDAS reanalysis data exhibit similarity with those derived from in situ observations. Numerous studies have also demonstrated that the CLDAS reanalysis data bear a strong resemblance to actual site observation data, as evidenced by a national regional average correlation coefficient of 0.89, a root-mean-square error of 0.02 m3/m3, and a deviation of 0.01 m3/m3. So the CLDAS and ERA5-Land datasets are chosen for separate assessment of their assimilation effects (Shi et al., 2011; Liu et al., 2019).

5. The conclusion needs to be strengthened by summarizing key findings, pointing out limitations and discussing future outlooks. Comparisons with existing studies are needed to highlight the specific improvements.

Response:

Thanks for your valuable suggestion. The conclusion and discussion part has been further refined, encompassing a recapitulation of significant findings for the study, and an emphasis on the limitations and future prospects of image assimilation methods, as well as the inclusion of comparative analysis with existing studies. The revised version of the conclusion in Line 662-705 is presented below.

The exchange of heat and water vapor between the land surface and the atmosphere plays a crucial role in influencing weather and climate change. The impact of soil moisture on atmospheric changes is frequently manifested through the persistent influence of large-scale soil moisture anomalies. The construction of an assimilation system with image assimilation capability is aimed at enhancing the spatial structure accuracy of soil moisture anomalies in the initial field of land surface models. The system is primarily based on the three-dimensional variational data assimilation framework, employing the curvelet transformation method with multi-scale transformation capability and anisotropic basis function as the observation operator. By incorporating image structural similarity as a weak constraint in the cost function, the spatial structure of soil moisture in the initial condition is effectively adjusted to align with the structural characteristics of observed soil moisture image, thereby enhancing the accuracy of soil moisture simulation.

The performance of the image assimilation system is systematically validated by conducting ideal experiments, with the ERA5-Land reanalysis data as ideal observations, and the CLDAS reanalysis product is incorporated for independent verification. The findings demonstrate that the assimilation of surface soil moisture observation images effectively and reasonably enhances the spatial structure of soil moisture analysis field. The spatial correlation coefficient between the analysis and ERA-Land reanalysis data increases significantly from 0.39 to 0.67, while the root-mean-square error decreases notably from 0.16 m^3/m^3 to 0.12 m^3/m^3. With the improvement of surface soil moisture, the spatial pattern of subsurface soil moisture is further optimized under the reasonable constraints of model dynamics and thermal processes. There is an increase (from 0.35 to 0.57) in the spatial correlation coefficient between the soil moisture at a depth of 7–28 cm and the ERA-Land data. The root mean square error decreases from 0.15 m^3/m^3 to 0.13 m^3/m^3.

The verification results based on independent data CLDAS consistently demonstrate a higher spatial correlation coefficient between CoLM surface (0–5 cm) soil moisture in the assimilation experiment and the CTL experiment, with a maximum correlation coefficient of 0.79 throughout both assimilation and prediction stages. The average spatial correlation coefficient for surface soil moisture increases from 0.67 to 0.71 after image assimilation. While for subsurface (5–10 cm) soil moisture, it steadily rises from 0.67 to 0.73 on average. These quantitative evaluation outcomes fully validate the practical applicability of the new image assimilation method.

The image assimilation system developed by this study could effectively optimize the spatial structure of soil variables in the background by incorporating constraint conditions of the observed spatial structures. The method demonstrates excellent applicability to various soil variables, effectively mitigating the negative impact of strong spatial heterogeneity of soil on data assimilation. The key challenge in image assimilation lies in obtaining accurate spatial structure observation of soil variables. The data of ground automatic stations with high spatial-temporal resolution established in China, along with satellite observation data that can overcome natural constraints and achieve large-scale uniform observation in various terrains, are capable of providing observational images depicting the spatial structure of land surface variables for image assimilation. The effective assimilation of the spatial structural characteristics of those high-density meteorological observation data, is the primary focus of our subsequent research. However, how to establish the direct spatial structure relationship between satellite-observed brightness temperature data and soil variables, and how to repair these non-uniform data into uniformly distributed data, these are the key technical problems that need to be solved in the future.

Additionally, it should be noted that the image assimilation method and the prevailing single-point land assimilation method in current practice are not mutually exclusive. The single-point land assimilation method is more suitable for assimilating sparse observation data in key areas. However, if the image assimilation method is used to optimize the fine structure of soil moisture in specific areas, the threshold σ mentioned above needs to be further increased, but this approach is susceptible to introducing additional observational errors. Therefore, by integrating the capacity of the image assimilation method in adjusting the large-scale spatial structure of soil variables and the capability of single-point land assimilation method in finely optimizing soil variables in crucial regions, and by leveraging the advantages offered by diverse types of meteorological observation data, we can attain more refined initial conditions for land models, which constitutes the primary objective of our subsequent research.

Minor issues:

1、Line 234, the word "ECM-WF/IFS" should be "ECMWF/IFS"

Response：

Thanks for your valuable suggestion. We have revised the word "ECM-WF/IFS" to "ECMWF/IFS" in Line 234.

2、Line 271, "seprately" should be "separately".

Response：

Thanks for your valuable suggestion. We have revised the word "seprately" to "separately" in Line 271.