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Hydrology and Earth System Sciences
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Discussions

Interactive comment on "The Influence of Assimilating Leaf Area Index in a Land Surface Model on Global Water Fluxes and Storages" by Xinxuan Zhang et al.

Anonymous Referee #2

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The authors would like to thank the reviewer for their time, effort, and detailed comments. All suggestions have been incorporated into the manuscript and explained in this document. We also thoroughly proofread and revised the whole manuscript.

General comments

Synthetic observations are used to assess the impact of assimilating satellite-derived LAI estimates into the Noah land surface model. A major shortcoming of the assimilation system used in this study is that LAI assimilation has no direct impact on soil moisture. As a result, dry precipitation biases cannot be compensated for. This issue was at least partly solved in other assimilation systems. Unfortunately, the relevant literature is not completely cited.

This paper is not well written, not complete for understanding, and cannot be published in the present form. Methods description is incomplete. Interpretation of results is made in the Result section instead of the Discussion section.

Recommendation: major revision.

Particular comments:

- L. 39-40: Examples of joint assimilation of LAI and soil moisture in a land surface model can be found in the literature.

We have reviewed several studies that used LAI-SM joint assimilation (Pauwels et al. 2007; Sabater et al. 2007; Barbu et al. 2011; Fairbairn et al. 2017) and cited them in the discussion section:

"Overall the improvement of water variables through LAI assimilation is not remarkable enough to compensate the model degradation caused by the biased precipitation forcing data. Previous studies (Pauwels et al. 2007; Sabater et al. 2007; Barbu et al. 2011; Fairbairn et al. 2017) have tested the performance of the joint assimilation of LAI and soil moisture over regional domains and showed promising results. However, no experiment was performed at the global scale. Future work could investigate a multi-variate data assimilation system that concurrently merges both LAI and soil moisture (or TWS) observations globally."

All the cited LAI-SM joint DA studies were conducted over regional domains. We emphasized "at global scale" in the last sentence of the abstract to make the statement more accurate:

"*Future work could investigate a multi-variate data assimilation system that concurrently merges both LAI and soil moisture (or TWS) observations at global scale*."

- Barbu, A. L., Calvet, J. C., Mahfouf, J. F., Albergel, C., & Lafont, S. (2011). Assimilation of Soil Wetness Index and Leaf Area Index into the ISBA-A-gs land surface model: grassland case study. Biogeosciences, 8(7), 1971-1986.
- Fairbairn, D., Barbu, A., Napoly, A., Albergel, C., Mahfouf, J. F., & Calvet, J. C. (2017). The effect of satellite-derived surface soil moisture and leaf area index land data assimilation on streamflow simulations over France. Hydrology and Earth System Sciences, 21(4), 2015-2033.
- Pauwels, V. R., Verhoest, N. E., De Lannoy, G. J., Guissard, V., Lucau, C., & Defourny, P. (2007). Optimization of a coupled hydrology–crop growth model through the assimilation of observed soil moisture and leaf area index values using an ensemble Kalman filter. Water Resources Research, 43(4).
- Sabater, J. M., Rüdiger, C., Calvet, J. C., Fritz, N., Jarlan, L., & Kerr, Y. (2008). Joint assimilation of surface soil moisture and LAI observations into a land surface model. Agricultural and forest meteorology, 148(8-9), 1362-1373.

- L. 95-97: In the same context and at the continental scale, Albergel et al. showed that sequential LAI assimilation can be used to analyse soil moisture at various depth, in addition to vegetation biomass (https://doi.org/10.5194/gmd-10-3889-2017). This property is particularly useful in dry conditions, when surface soil moisture tends to be decoupled from deeper soil layers.

Thank you for providing this reference. We added it to the manuscript. "*Only a few studies discussed the influences of LAI assimilation on the estimation of water variables such as soil moisture or streamflow (Pauwels et al. 2007; Sabater et al. 2008) and most of them focus on limited regions. Most recently, Albergel et al. (2017) conducted a study on a much larger domain–Europe and the Mediterranean basin–and showed that LAI assimilation can be used to improve soil moisture at various depths.*"

- Albergel, C., Munier, S., Leroux, D.J., Dewaele, H., Fairbairn, D., Barbu, A.L., Gelati, E., Dorigo, W., Faroux, S., Meurey, C. and Le Moigne, P.: Sequential assimilation of satellite-derived vegetation and soil moisture products using SURFEX_v8. 0: LDAS-Monde assessment over the Euro-Mediterranean area, Geosci. Model Dev., 10, 3889-3912, https://doi.org/10.5194/gmd-10-3889-2017, 2017.

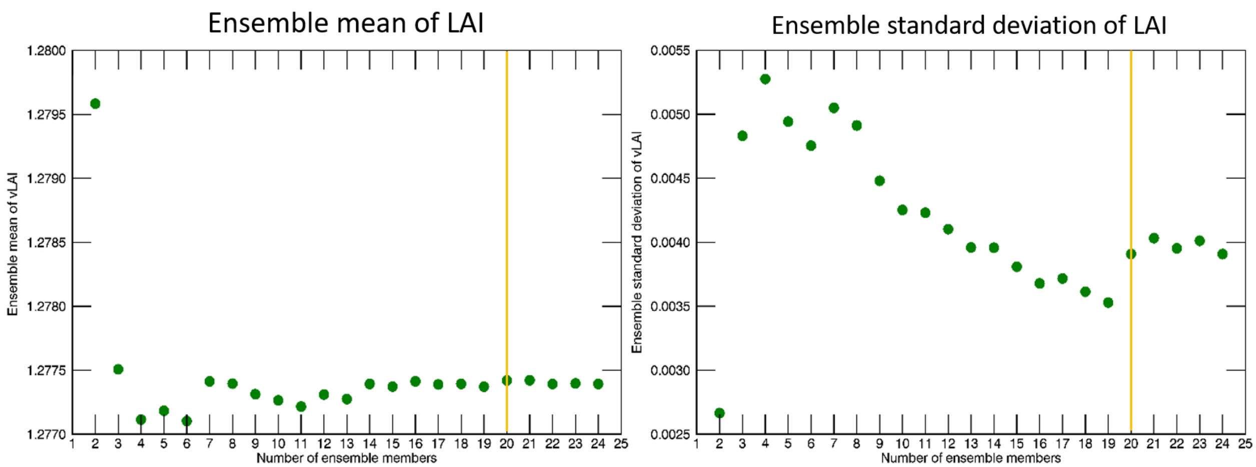
- L. 109 (Section 2): A section describing the DA method is needed. What are the analysed variables? Does LAI DA impacts soil moisture?

The DA method in this study is implemented in the NASA Land Information System (LIS). The method has been applied in many sequential data assimilation studies. We added references for the DA method in section 2.2:

"*The two DA runs are then conducted under the same conditions (DA-dry and DA-wet) using a one-dimensional EnKF assimilation algorithm which is a built-in DA method in LIS. The EnKF DA algorithm is suitable for non-linear and intermittent land surface processes (Reichle et al. 2002a, b). Details of the algorithm have been illustrated in previous studies (Reichle et al. 2010; De Lannoy et al. 2012; Liu et al. 2015; Kumar et al. 2019).*"

- L. 138: How are subsurface waters represented? Do you represent inundations plains? Lakes?
TWS is the sum of snow water equivalent, surface water, soil moisture, and groundwater. So, subsurface water (i.e., groundwater) is included. Lakes and inundation plains are considered as surface water, which is also included in TWS.

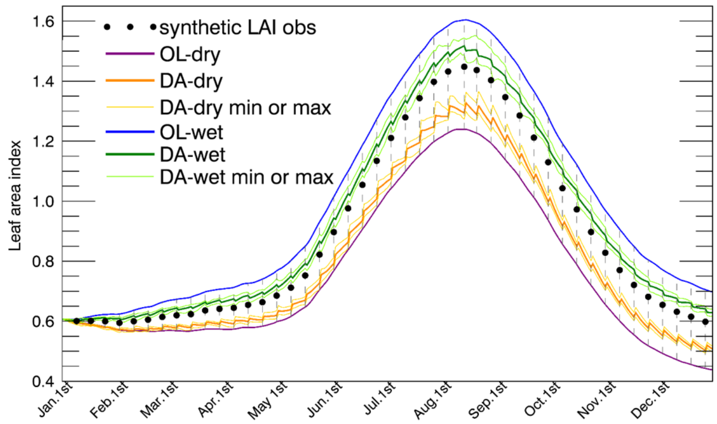
- L. 188 (ensemble members): How is this ensemble generated?
The model ensemble is generated by perturbing the meteorological forcing inputs (precipitation and shortwave/longwave radiations). The figure below shows the ensemble size sensitivity test. The model performance tends to become steady when more than 20 members are considered, which is why all the DA simulations run for 20 members.



A detailed description can be found in section 2.2 of the manuscript.
"The model ensemble is generated by perturbing a set of meteorological forcing. To select the optimal ensemble size, a sensitivity test is performed for ensemble sizes spanning from 2 to 24 members (not shown here). The number of ensemble members has a strong impact on the model results at small sizes, while the model performance tends to become steady when more than 20 ensemble members are considered. Thus, all the DA simulations are run for 20 members."

- L. 196-197: Why are these instabilities generated by DA?
The initial condition of OL and DA runs is generated by a 10-year spin-up run which uses the original MERRA-2 precipitation as metrological forcing. The OL and DA runs are forced by either doubled or halved precipitation that is not consistent with the spin-up run. So, the model needs to run for a certain time before stabilizing. The figure below shows the global averaged LAI time series from the beginning of the simulation (Jan. 1st, 2011) to Dec. 31st, 2011. The LAI simulated by OL and DA runs does not get stable until around May. Therefore, we decided to eliminate the first 5-month model outputs in the analyses.

We added this explanation in the manuscript in section 2.3. "*The initial condition of OL and DA runs is generated by a spin-up run that uses the original MERRA-2 precipitation as input. However, the OL and DA runs are forced by either doubled or halved precipitation, which is not consistent with the spin-up run and the model needs some time to stabilize. The first 5-month model outputs are therefore eliminated from the evaluation to avoid the model systematic* *instability at the beginning of the OL and DA simulations and the evaluation, thus, focused only on model outputs from 2011-06-01 to 2013-05-31.*"



- L. 203 (Eq. 1): Why do you use NCRMSE and not standard score metrics such as RMSE or ubRMSE (i.e. standard deviation of differences)?

In the manuscript, we compared the result of LAI and five water related variables (ET, CIE, CWS, SSM, and TWS). Units of these variables are very different, which is why we decided to adopt unitless statistical metrics. UbRMSE is certainly another valid option.

- L. 217 (Figure 3):

(1) Please change evaporation units. Since these time series are daily, should be per day instead of per second.

(2) It seems that CWS anomalies are 3 order of magnitude larger than ET anomalies. Why?

(3) Define here what you mean by "anomaly" (not defined in the text).

(4) NR anomalies: with respect to what?

(5) Is NR the benchmark or not?

(6) Real values have to be showed at some stage. Not only anomalies.

1) The ET value showed in Figure 3 is the model output, which is an average over the day. So, the unit is "kg m^{-2} s^{-1}"
2) CWS is the canopy water storage which include the water stored in the leaves and the intercepted water. So, it is much larger than the ET.
3) Anomalies are defined in section 2.3. "*Each of the anomaly time series is computed relative to the mean of its respective model run.*"
4) NR anomalies are calculated with the respect to the mean of NR run.
5) NR is not the benchmark of OL or DA anomalies. OL anomaly is calculated with the respect to the mean of OL. DA anomalies follow the same rule.
6) We analyzed the anomalies because they are unitless and this is good practice when comparing the impact DA has on different variables. Nevertheless, we understand the value of showing actual values and, in the revised manuscript, we added these time series as Figure 3:

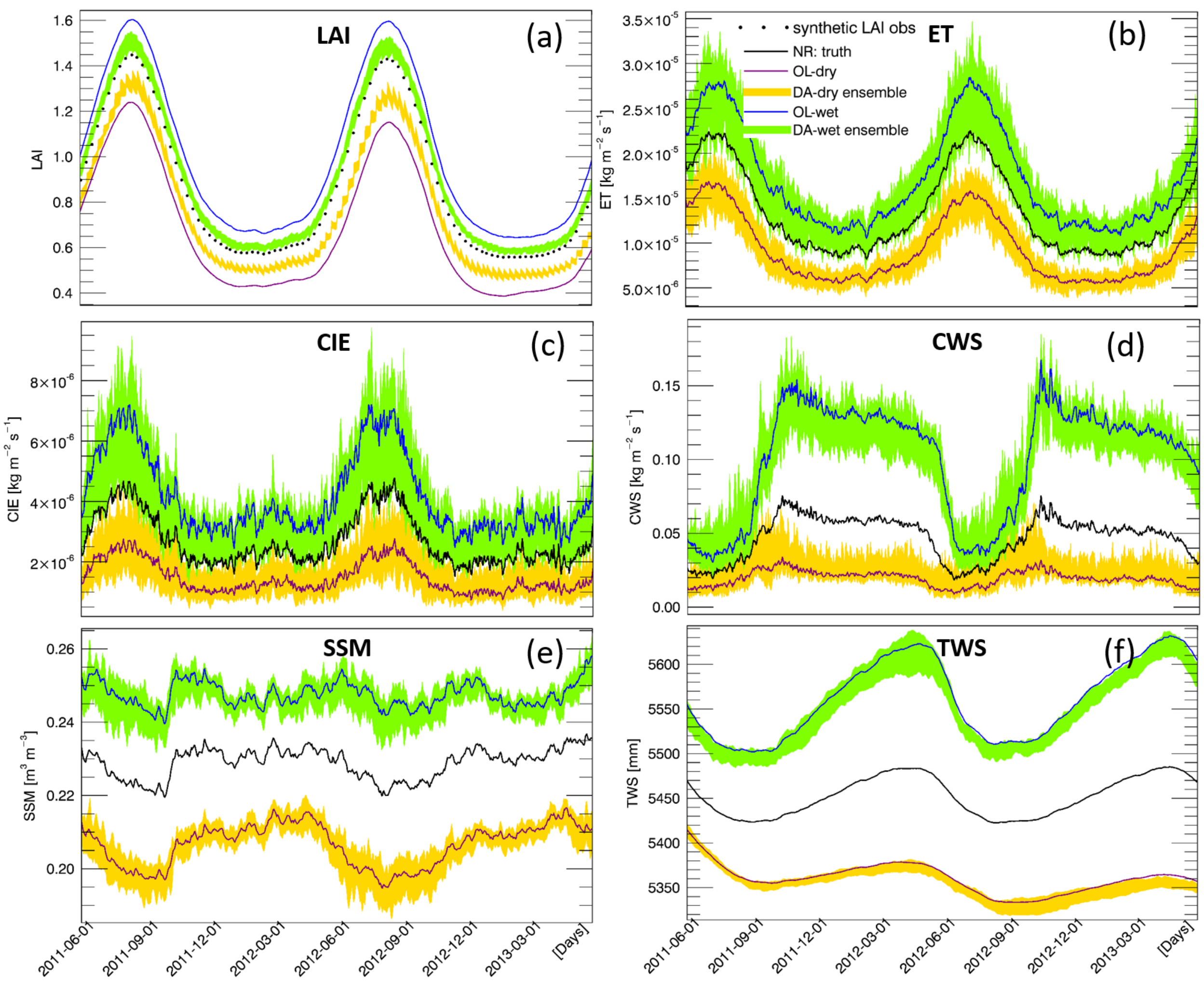


Figure 3. Global averaged daily values of LAI and five water variables (2011-06-01 to 2013-05-30).

Section 3.1 LAI

"Figure 3a and Figure 4a show the time series of global averaged LAI values and corresponding anomalies, respectively. As expected, LAI values are largely impacted by the extreme precipitation conditions. The wet condition introduces more vegetation, while the dry condition limits the vegetation growth throughout the two-year period. The DA procedure effectively corrects the LAI errors caused by the biased precipitation input."

Section 3.2 Water fluxes and storages

"Daily time series of global averaged values and corresponding anomalies of the five water variables are shown in Figure 3(b-f) and Figure 4(b-f), respectively. The model well simulates the seasonality of all water fluxes/storages considered here. The OL runs reveal that global average values of all five variables are impacted by the highly biased precipitation conditions."

- L. 243 ("thus the NCRMSE . . . becomes smaller"): Why?

In JJA, the stomatal closure can help to preserve water. So, the system does not lose too much water under the dry condition which result in smaller difference between DA-dry and the NR truth, and consequently shows smaller NCRMSE.

- L. 276-277 (LAI assimilation unable to correct for dry precipitation bias): Why?

A dry precipitation bias means that the system has (erroneously) has less water than in reality (NR in the synthetic experiment). Since no water is otherwise added to the system, LAI DA cannot fully correct water-related model states (such as soil moisture). The manuscript has been modified as below:

"*However, LAI assimilation is not able to correct the model when the input precipitation is negatively biased (dry condition). A dry precipitation bias means that the system has (erroneously) less water than in reality (NR in the synthetic experiment). Since no water is otherwise added to the system, LAI DA cannot fully correct water-related model states (such as soil moisture). The NCRMSEs of DA runs are either the same as in the OL runs (ET/CIE/CWS) or worse (SSM/TWS).*"

- L. 320-322: I don't see the logics. I would expect that large water-holding capacity would enhance the impact of LAI DA.

Our thought is that the LAI can affect soil moisture by changing the model's surface water condition. Over forest and woodland, the surface water condition is not changing much due to the large soil reservoir.

- L. 323 (forests and woodlands): Is this because of large rooting depth?

Large rooting depth is an important fact. Some discussion has been added to the manuscript: "*In other words, forest and woodland tend to have lower sensitivity in response to the change of precipitation conditions because of their large rooting depth.*"

- L. 331: Water-holding? Do you mean interception reservoir or soil reservoir?

It is soil reservoir. We changed it in the manuscript. "*This is due to large soil reservoir of forests and woodlands ……*"

- L. 374-375: This could be because the used DA system is not able to analysed RZSM from LAI observations. Please explain.

In the Noah-MP model, the relationship between LAI and soil moisture is very complex and indirect. So, the current LAI DA system is not able to have much of an effect on surface moisture at all depth.

Editorial comments:

- L. 251 (Figure 4): Color scale is difficult to interpret. Please use several colors (e.g. blue in addition to red).

We changed the color scale of Figure 4.

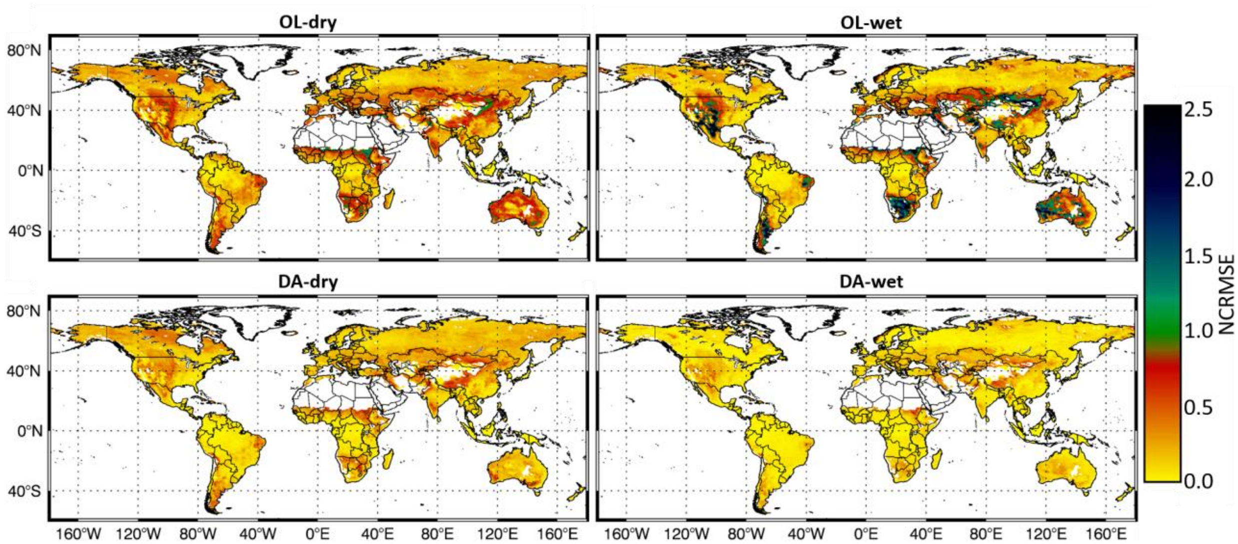


Figure 4. Maps of LAI NCRMSE for the OL and DA runs.

- L. 289 (Figure 5): Time axis labels are not readable. Please improve!

We enlarged the font size of the axis label and showed the time less frequently (every 3-month). Please check below. We also enlarged the axis font size of all figures in the manuscript.

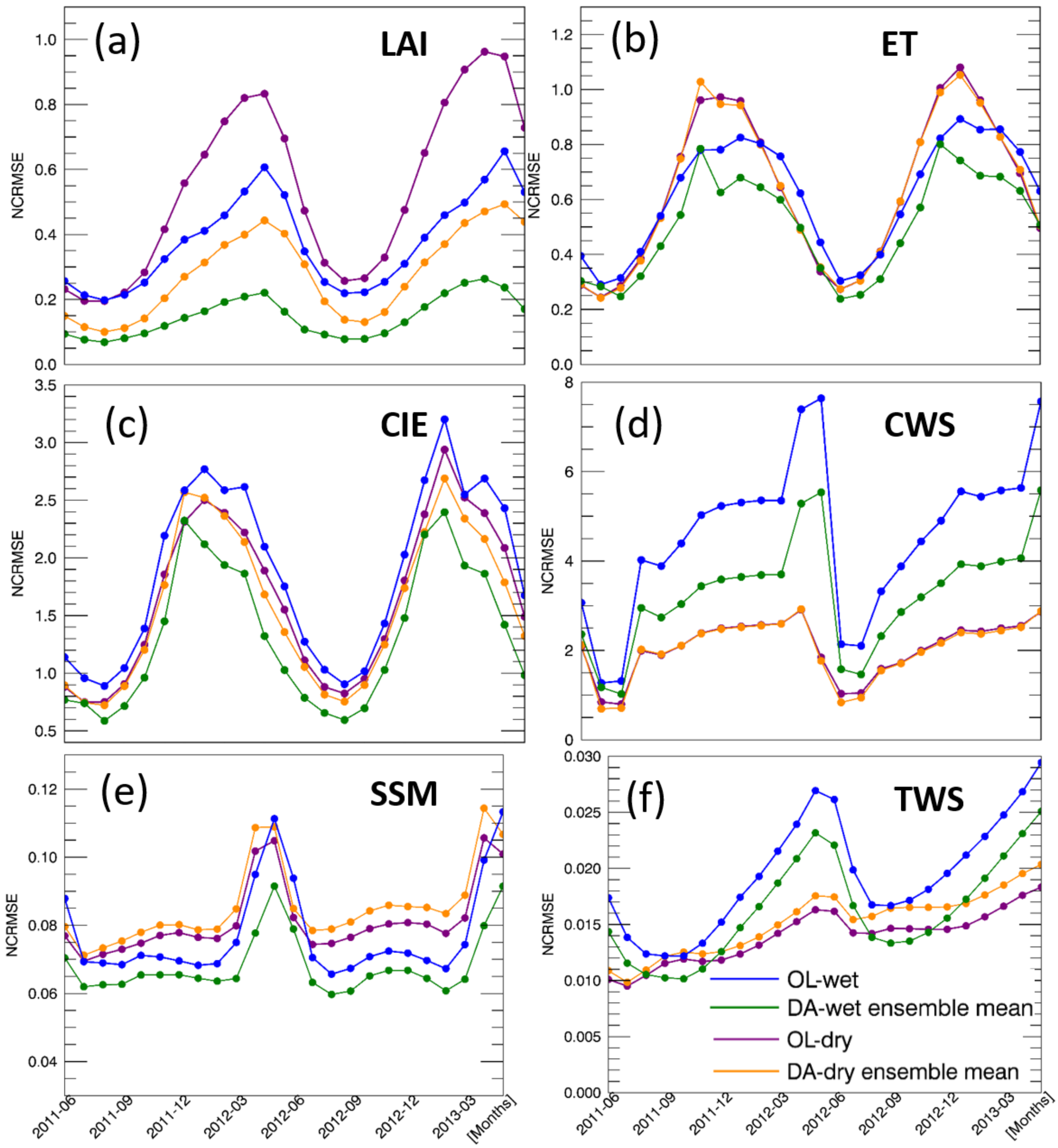


Figure 5. Monthly averaged NCRMSE for LAI and five water variables over the Northern hemisphere.

- L. 291 (Figure 6): Time axis labels are not readable. Please improve!

We enlarged the font size of the axis label and showed the time less frequently (every 3-month). Please check below.

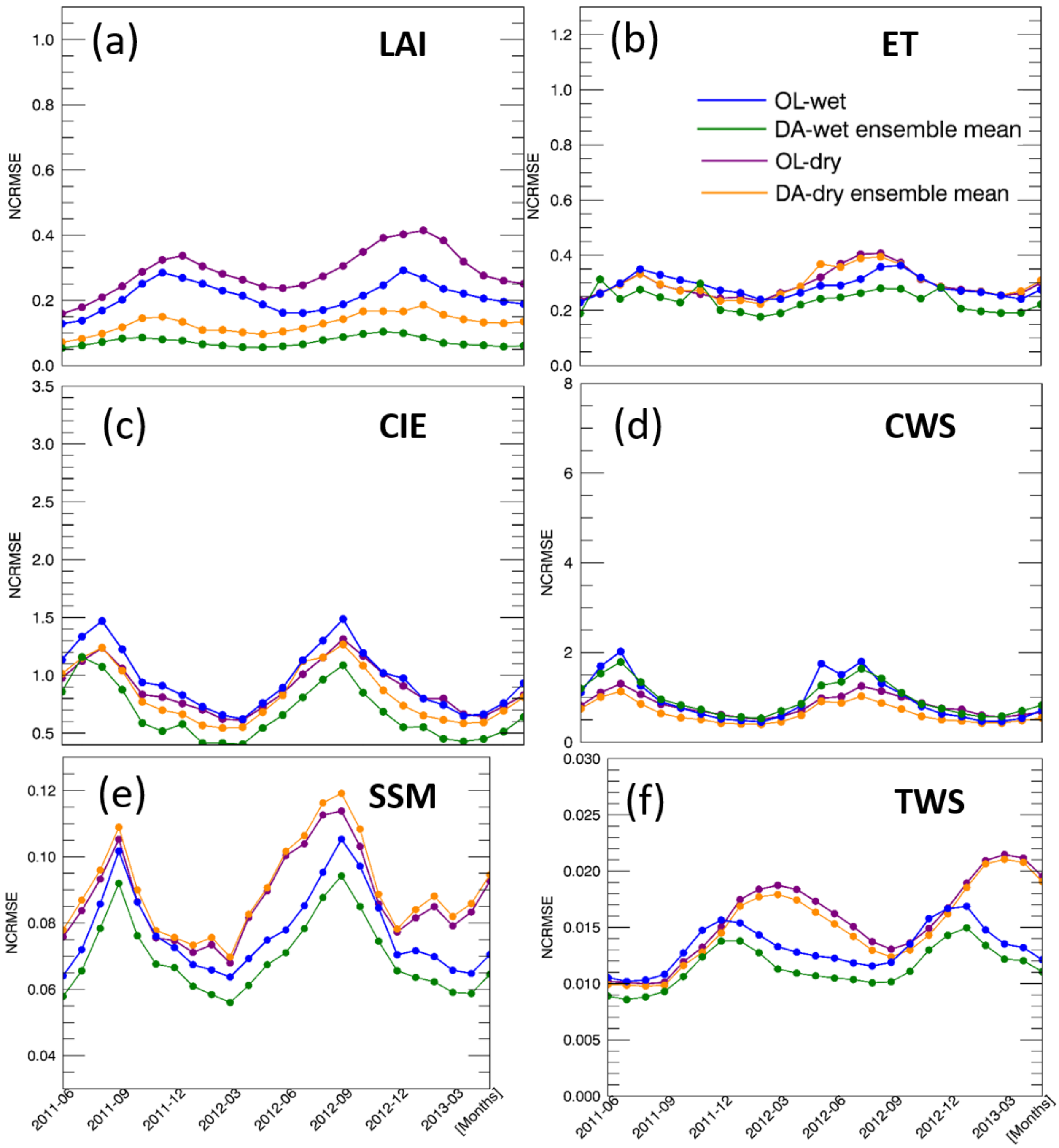


Figure 6. Same as in Figure 5, but for the Southern hemisphere.