

Summary:

This study applies an additive stochastic perturbation scheme to soil temperature and moisture (separately) in the topsoil layer of the Noah LSM in the WRF model as a means to improve background error covariances in an ensemble data assimilation system. The micro-genetic algorithm is used to calculate “optimized” amplitude, time, and length scales for different configurations of the perturbation scheme. If the perturbation scheme is working correctly (see MC1), there is some modest indication that it could act as a supplement to other perturbation schemes in the DA cycle (e.g., SPPT, SPP, etc.), since its effect on atmospheric variability is limited when applied in isolation.

There are numerous instances of unclear, incorrect, or otherwise awkward wording that need to be corrected at this stage. Additionally, there are several major questions about the application of both the SPSS and micro-GA that should be addressed before this manuscript can be accepted for publication. Further discussion of the results presented here in the context of other methods for representing land surface uncertainty (see SC2) would be helpful.

Recommendation:

Major revisions

Major Comments:

1. Figure 3 and Equation 7 do not appear to correspond to the same operation. In Equation 7, the updated state variable is computed as the sum of the random forcing and the original variable. Since the random forcing is small compared to the variables themselves, the differences between panels (7a and 7c) and (7d and 7f) are small, as expected. However, plotted values appear to be larger nearly everywhere in the “Updated” panels (except, for example, near 25N,120E in panel 7f) despite the negative values of the random forcing field. Is this supposed to be the case, if so why? Or, is this a minor figure error (e.g., panels plotted at the wrong time)? Or, is there a larger systematic error in the application of the random forcing scheme?

Response: Thank you for your comments. In Equation 7, the additive perturbations are added to soil temperature or soil moisture in every time step to forecast. Figure 11 averages the ensemble mean from 00 UTC on 4 August 2018 to 06 UTC on 7 August 2018 using a composite of the 14 cycles’ background fields, whereas Figure 3 represents the background field of the first ensemble member at 00 UTC 6 on August 2018. As a result, an individual ensemble member can be exaggerated, as shown in Figure 3; yet, the ensemble mean, which averages 27 ensembles, finally exhibits a moderate perturbation effect. To prevent confusion, we clarified Figure 3 and Figure 11’s captions as below:

“Figure 3. The 6 hour forecast field of the first ensemble member, showing the effect of RF on soil temperature (ST in K; upper panels) and soil moisture (SM in $\text{m}^3 \text{m}^{-3}$; lower panels) at 06 UTC on 1 August 2021”

“Figure 11. The averaged analysis increment (colored contours; positive in red and negative in blue) and the background error against GFS analysis (shaded) for temperature (in K) in (a) CTRL, (b) STP1, and (c) STP2 and for water vapor mixing ratio (in g kg^{-1}) in (d) CTRL, (e) SMP1, and (f) SMP2. Results are averaged from 00 UTC on 4 August 2018 to 06 UTC on 7 August 2018 with a composite of the 14 cycles’ background fields except the spin-up period and are calculated within vertical layers of 850 hPa to 1000 hPa.”

- At several points in the manuscript (e.g., Line 373), it is mentioned that the optimized perturbation length scale is related to incoming solar radiation and the spatial scale of soil texture variability, depending on time of day. It might be helpful to provide some support for this (e.g., a map of different land use categories or soil textures as a “Fig. 2b”?). If an experiment were conducted in which the soil texture/land use distribution was artificially made uniform, would the length scale of the nighttime perturbations be more similar to the daytime length scale?

Response: Thank you for your suggestion. The land use category and soil texture are shown in Figure 2 as subfigures, such as Figure 2(b)-(c), with the following description in Line 81:

“We used the Modified IGBP Moderate Resolution Imaging Spectroradiometer (MODIS) Noah dataset for the land use/land cover categories, and the USDA State Soil Geographic database (STATSGO) for soil texture. The dominant land use category and soil texture are represented in the Figure 2(b)-(c).”

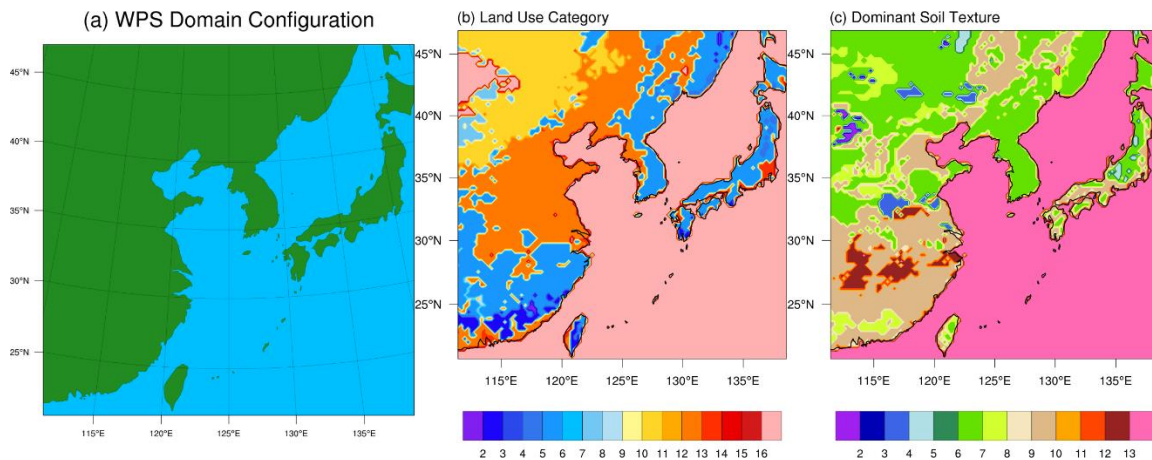


Figure 2. (a) WPS domain configuration, (b) land use category: 1-evergreen needleleaf forest, 2-evergreen broadleaf forest, 3-deciduous needleleaf forest, 4-deciduous broadleaf forest, 5-mixed forests, 6-closed shrublands, 7-open shrublands, 8-woody savannas, 9-savannas, 10-grasslands, 11-permanent wetlands, 12-croplands, 13-urban and built-up, 14-cropland/natural vegetation mosaic, 15-snow and ice, 16-barren or sparsely vegetated, and 17-water, and (c) dominant soil texture: 1-sand, 2-loamy sand, 3-sandy loam, 4-silt loam, 5-silt, 6-loam, 7-sandy clay loam, 8-silt clay loam, 9-clay loam, 10-sandy clay, 11-silty clay, 12-clay, 13-organic material, and 14-water.

As for the artificially uniform soil texture and land use distribution, we can’t be certain without experiments. In this manuscript, we simply compared how the optimized length scale was related to the other length scale. Because the optimization experiment using

uniform soil texture and land use categories takes a long time to test, it can be done as a future study to investigate the effect of the length scale on soil temperature and soil moisture perturbation.

3. Were the optimal perturbation parameters derived over only the two 6-hour periods listed on Lines 226–228? Would using additional periods to optimize these parameters (perhaps averaging over multiple optimization values) improve or degrade performance? Related to this, is it possible to calculate the percent increase in computational time that optimizing the perturbation parameters adds to the DA process, since re-optimizing the parameters in the cycling system is suggested on Lines 301–302 (of course, this will vary depending on a user's specific model/resource configuration)?

Response: Yes, we selected the representative for daytime and nighttime. Of course, the optimization during the DA cycles can contain the exact error information during the whole experiment period; however, it takes longer under our configuration. Below is the expected computational time of optimization in the DA process:

In our configuration for the optimization,

- Optimization with a 6 h forecast and 27 ensembles requires about 30 min in 1 generation (5 cpu/1 ensemble)
- Each generation repeats up to 100 generations: 30 min x 100 generations = 3,000 min
- Four experiments (OSTP-D, OSTP-N, OSMP-D, and OSMP-N): 3000 min x 4 = 12,000 min (200 h = 8.3 days)
- We can do parallel runs in two experiments: 12,000/2 min = 6,000 min = 4.17 days

In our configuration for verification in the DA cycles,

- 1 cycle with a 6 h forecast and 27 ensembles requires about 30 min. (4 cpu/ 1 ensemble)
- Total 25 cycles: 30 min * 25 cycles = 750 min (12.5 h = 0.5 days)
- Four experiments (STP1, STP2, SMP1, and SMP2) = 750 min x 4 = 3,000 min (50 h = 2.08 days)

In summary, if we use the DA cycling system to optimize the RF tuning parameters, we require about 104.2 days for optimization. Moreover, the verification for DA cycling systems requires about 2.08 days.

Ex) 750 min x 100 generations x 4 experiments/2 = 104.2 days

4. There are numerous language and grammar errors that should be revised for clarity and precision. While most of these issues are not severe enough to detract from understanding the research presented in the manuscript, they do interrupt the reader's experience. The manuscript should be thoroughly reviewed for grammar and scientific language, many of these issues are identified in the "technical comments" section.

Response: We carefully checked the grammar errors according to the "technical comments". Thank you for your detailed opinion.

Specific Comments:

1. Line 52: Replace “the less” with “reduced,” however, neither choice seems consistent with the discussion of stochastic representations of model uncertainty in this paragraph, since these schemes improve (increase) ensemble spread. Please clarify.

Response: Thank you for your comment. We revised Lines 51-52 as below:

“Because it is strongly coupled to the atmospheric state at certain times and in certain places, the reduced land-surface uncertainty may lead to better atmospheric forecasts”

2. Lines 53–58; 61: The sentence starting on line 54 “For example...” could be removed, since the focus of the present study is on soil state perturbations. It would also help to elaborate (in 1–3 sentences) on some of the relevant references included in these lines to show how soil state uncertainty has been represented in recent literature and forecast systems, beyond the already mentioned sensible and latent heat fluxes.

Response: Thank you for your comments. The examples of the land parameters in Lines 54–56 have been removed. We included how soil state uncertainty has been represented as follows:

“In particular, the soil states directly affect the near-surface temperature and humidity forecasts through the sensible and latent heat fluxes response (Kim and Hong, 2007; Deng et al., 2016; Lin and Pu, 2020; Sutton et al., 2006; Wang et al., 2010b). If the surface is heated during the daytime, sensible energy transfers to the atmosphere and moisture evaporates from the soil; thus, exact soil states are important within the planetary boundary layer (PBL), influencing convection and precipitation (Sutton et al., 2006).”

References:

Sutton, C., Hamill, T. M., and Warner, T. T.: Will perturbing soil moisture improve warm-season ensemble forecasts? A proof of concept. *Mon. Weather Rev.*, 134, 3174–3189, <https://doi.org/10.1175/MWR3248.1>, 2006.

Wang, Y., Kann, A., Bellus, M., Pailleux, J. and Wittmann, C.: A Strategy for perturbing surface initial conditions in LAMEPS. *Atmos. Sci. Lett.*, 11, 108–113, <https://doi.org/10.1002/asl.260>, 2010b.

3. Line 85: Please revise the non-scientific text “and so on.” Consider changing the in-text list of variables calculated by the Noah LSM to a table.

Response: Thank you for your comment. We revised the non-scientific expression in Lines 84-85 as below:

“It calculates land surface variables such as soil temperature, soil moisture, surface skin temperature, canopy water content, snowpack water equivalent content, and snowpack depth in the 4 soil layers”

We added Table 1, which listed the state variables for Noah LSM, and we cited Table 1 in Line 86 as below:

“Among the prognostic variables in Noah LSM (Table 1),...”

Table1. List of state variables in Noah LSM (NCAR, 2020b). Soil temperature, total and unfrozen soil moisture are considered in the multiple soil layers.

State variables	Unit
Canopy moisture content	m
Ground/canopy/snowpack effective skin temperature	K
Soil temperature	K
Total soil moisture content	Volumetric fractions ($\text{m}^3 \text{m}^{-3}$)
Unfrozen soil moisture content	Volumetric fractions ($\text{m}^3 \text{m}^{-3}$)
Actual snow depth	m
Liquid water-equivalent snow depth	m
Surface albedo including snow effect	Unitless fraction
Surface exchange coefficient for heat and moisture	m s^{-1}
Surface exchange coefficient for momentum	m s^{-1}

Reference: NCAR: WRF Version 4.2 [code], <https://github.com/wrf-model/WRF/releases/tag/v4.2>, (last access: 23 April 2023), 2020b.

4. Line 127: The description of the decorrelation time scale is somewhat unclear. As it is written, “determine how long the perturbed errors will be sustained,” implies that the perturbations will be held fixed for the duration of the decorrelation time. It may be more clear to say something like, “determine how quickly perturbations evolve in time”

Response: Thank you for your suggestion. We redefined the length and time scale in Lines 126-127 as follows:

“the horizontal decorrelation length scale (L) determines how errors propagate in an isotropic horizontal direction before the spatial autocorrelation function (ACF) of the perturbation field reaches e^{-1} ; the decorrelation time scale (τ) determines how quickly perturbations evolve in time before the temporal ACF of the perturbation field reaches e^{-1} .”

5. Figure 3: Please add a date/time to the caption or figure panels.

Response: We added a date and time in Figure 3’s caption as below:

“The 6 hour forecast field of the first ensemble member, showing the effect of RF on soil temperature (ST in K; upper panels) and soil moisture (SM in $\text{m}^3 \text{m}^{-3}$; lower panels) at 06 UTC on 1 August 2021: (a) Original ST, (b) RF for ST (with $\sigma = 0.13 \text{ K}$, $L = 2900 \text{ km}$, and $\tau = 120 \text{ s}$), and (c) updated ST (i.e., original + RF); (d) original SM, (b) RF for SM (with $\sigma = 0.0003 \text{ m}^3 \text{m}^{-3}$, $L = 250 \text{ km}$, and $\tau = 900 \text{ s}$), and (f) updated SM.”

6. Line 147–148: Please add a citation in the sentence that begins with “A previous study...”

Response: We add a citation at the beginning of the sentence as follows:

“Krishnakumar (1990) showed that the small population could sufficiently reach the entire search space by crossover alone.”

7. Line 224: First use of OSTP and OSMP acronyms. Please define these in the text.

Response: Thank you for pointing this out. We defined the experiments’ acronyms.

“(1) Optimization of the RF tuning parameters for Soil Temperature Perturbation at Daytime (OSTP-D); and (2) the corresponding one at Nighttime (OSTP-N); (3) Optimization of the RF tuning parameters for Soil Moisture Perturbation at Daytime (OSMP-D); and (4) the corresponding one at Nighttime (OSMP-N).”

8. Line 244–246: Please define acronyms when they first appear in the text (STP1, STP2, SMP1, SMP2).

Response Lines 244-247 have been altered to better clarify the experiments:

“Therefore, we performed the following DA cycling experiments to investigate the effect of SPSS on each soil temperature and soil moisture perturbation: (1) Soil Temperature Perturbation 1 (STP1) perturbs soil temperature using the daytime tuning parameters obtained from OSTP-D, and (2) STP2 perturbs soil temperature using the diurnally-varying tuning parameters obtained from OSTP-D and OSTP-N; (3) Soil Moisture Perturbation 1 (SMP1) perturbs soil moisture using the daytime tuning parameters obtained from OSMP-D, and (4) SMP2 perturbs soil moisture using the diurnally-varying tuning parameters obtained from OSMP-D and OSMP-N; (5) These were compared to the control experiment (CTRL), representing the current WRF-GSI/EnKF system.”

9. Table 1, Lines 161–162, and Line 231:
- Please add relevant references (e.g., “previous studies” on line 161) and further discussion to how these ranges were defined.

Response: Thank you for your comments. We included the relevant references and include why we choose these ranges in Line 161:

“First, μ -GA randomly initializes RF tuning parameters from the assigned ranges. We assumed potential tuning parameter ranges for the length scale and standard deviation based on three general scales of tuning parameters (Leutbecher et al., 2017). As for the time scale, however, it was redefined for the SPSS because typical ranges (e.g., 6 hours, 3 days, and 30 days) caused excessive perturbations.”

- The numbers of candidate values (Line 231) do not need to be in exponential form. 64, 64, and 16 provides better clarity to the reader.

Response: We corrected the exponential form to an integer as follows:

“A coupled system of μ -GA and SPSS found a potential solution of RF tuning parameters within the assigned ranges (Table 1) by randomly choosing the candidate value among 64, 64, and 16 cases for amplitude, decorrelation length and time scale, respectively.”

- Table 1 indicates that a decorrelation time of 0s was included in the tested ranges – would perturbations with this time scale simply behave as temporally uncorrelated noise?

Response: Yes, we also considered noise that disappears after the initial perturbation is

generated.

10. Line 274–283 and Figure 6: There is no time and date information in the caption for Figure 6. Are these means and spreads averaged over the entire experimental forecast period (for all 6-hour background forecasts)? Or are they for a single 6 hour forecast? Line 277 refers to “a 6 hour forecast.” Please clarify this both in the text and in the figure caption/labels.

Response: Thank you for pointing this out. Figure 6 represents the averaged ensemble means and spreads for all background (i.e., 6-hour forecasts) over the entire experimental forecast period. We included a detailed description in the manuscript and caption.

In the manuscript, we add following sentences in Lines 275-277:

“We examined the zonal mean temperature and water vapor mixing ratio of the ensemble mean error and ensemble spread for all background (i.e., 6 hour forecasts) over the entire experimental DA cycling period (Fig. 6): the former is the RMSE of the ensemble mean against 0.5° GFS analysis, and the latter is the ensemble spread.”

We revised Figure 6’s caption as below:

“The zonal mean ensemble mean error (left panels) and ensemble spread (right panels) for temperature (K; top panels) and water vapor mixing ratio (g kg^{-1} ; bottom panels) as for the 6 hour forecasts of CTRL over the land. Results are averaged from 06 UTC on 1 August 2018 to 06 UTC on 7 August 2018 with a composite of the 25 cycles’ background fields (i.e., 1 cycle per 6 hour).”

11. Line 305; 316; 323–324: There are several occasions where the impact of the tuning parameters on ensemble spread is discussed. On Lines 305 and 323-324, a smaller length scale with a longer timescale increases ensemble spread. On line 316, a larger length scale and larger amplitude scale yield a larger spread. To improve clarity and reduce confusion, it may be better to simply omit the length scale on these lines, since its influence appears to be secondary to the configuration of the time and amplitude scales [which is consistent with SPPT experiments by both Bouttier et al. (2012) and Lupo et al. (2020)].

Response: Thank you for your suggestion. We removed the length scale description in Lines 305, 316, and 323-324 as below:

(Lines 304-305) “Although the amplitude of the soil moisture perturbations was the same at daytime and nighttime (e.g., $0.0003 \text{ m}^3 \text{ m}^{-3}$), SMP1, with a longer time scale (e.g., 900 s), produced a larger ensemble spread than SMP2.”

(Lines 315-316) “Because STP1 used a larger amplitude (e.g., 0.13 K), it produced a larger impact on temperature (Fig. 9b).”

(Lines 323-324) “In particular, SMP1 generated an apparent overestimation by using a larger time scale (e.g., 900 s) under the same amplitude.”

12. Line 318–319: The sentence starting with “Because...” is unclear and should be revised.
- “...it indirectly changed the temperature...” Does this refer to SPSS indirectly

modifying the air temperature? Please clarify.

Response: Yes, so we revised Lines 318-319 as below:

“Because SPSS indirectly modifies the air temperature through the soil temperature perturbation, the responses in the atmospheric layers were relatively weak compared to the soil.”

b. “...soil temperature perturbing...” This should probably be “soil temperature perturbation,” Please revise.

Response: We corrected it (Please see the above response).

13. Line 320: Please clarify “underestimated temperature.” In the present phrasing, it is unclear if this refers to underestimated temperature spread or a cold bias.

Response: We revised Lines 319-321 to explain the underestimated ensemble spread of temperature as below:

“When a standard stochastic perturbation method (such as SPPT) cannot resolve the underestimated ensemble spread of temperature below the PBL, the SPSS can be used as a supplementary method to inflate the ensemble spread.”

14. Line 327–333: The first and last sentences of this paragraph imply that the number of observations assimilated (or discarded) could be shown here. Elsewhere in the paragraph, the wording seems more related to the ensemble spread including the observed value at station 31873 (Fig. 10). Please consider making a more clear distinction between the uses of “including more observations” in this paragraph. If possible, consider also computing and showing the number of assimilated observations here.

Response: SPSS contributes to include more observations during the DA cycles; however, the change in number of conventional data from PrepBUFR into the ensemble data assimilation (EDA) system is not significant, as shown in Figure S1, which is the time series of the differences in the number of observations used in DA between SPSS (e.g., STP1 or SMP1) and CTRL. We agree with the reviewer to distinguish between the total number of observations and the single station; thus, we revised the paragraph in Lines 327-333 with a supplementary figure as below:

“We expected the BEC inflation to include more observations in the EDA system; thus, we compared the ensemble spread and observation (e.g., rawinsonde) at station 31873 near 1000 hPa, where SPSS showed the greatest impact. For temperature (Fig. 10a), the ensemble spread in CTRL (black shading) was narrow, so it was hard to contain the observation information. The ensemble spread, however, was increased in STP1 (blue shading) and STP2 (red shading), so the EDA system could include more observations. For specific humidity (Fig. 10b), the ensemble spreads in SMP1 (blue shading) and SMP2 (red shading) have weakly increased -- still including more observations. Most stations showed an increasing trend in the number of observations due to SPSS; it is evident that SPSS can increase the number of observations to be assimilated, though not remarkable (Figure S1).”

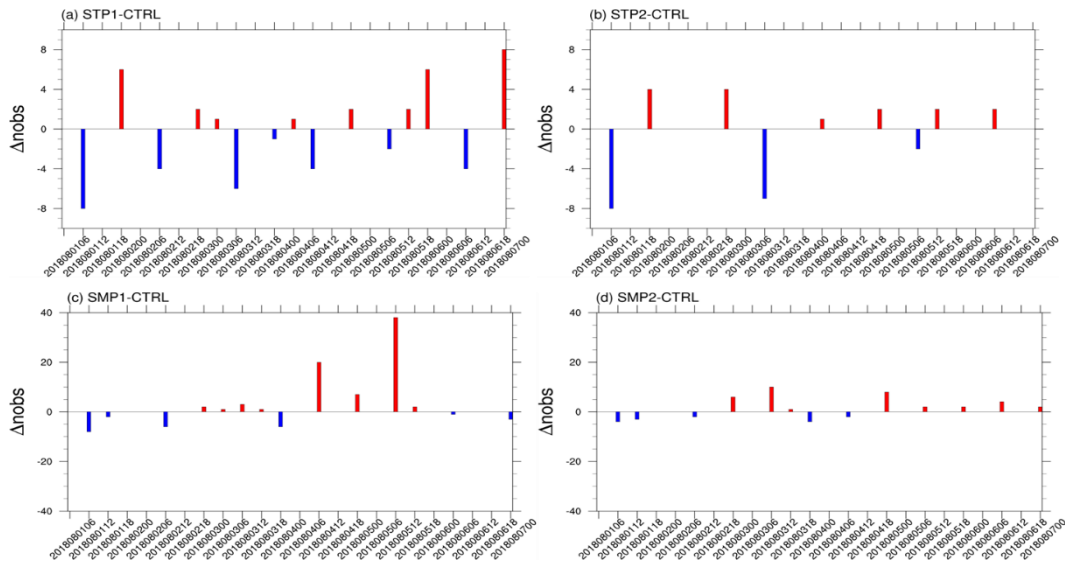
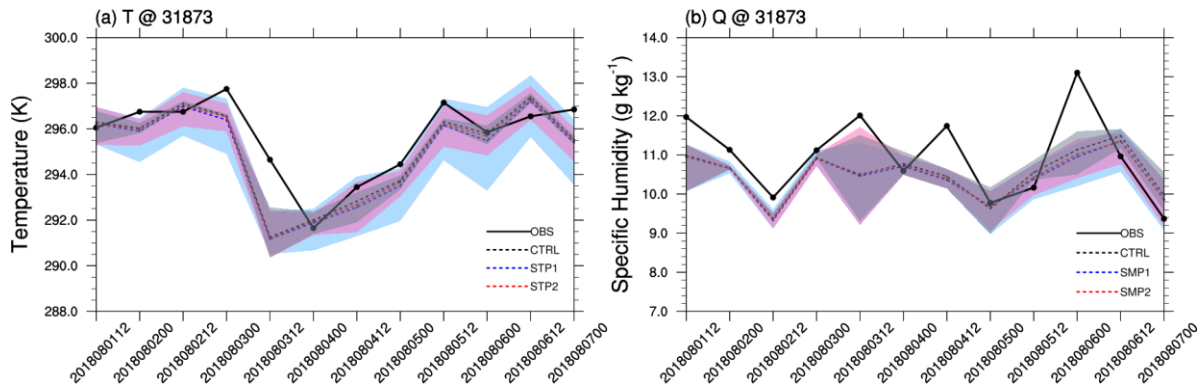


Figure S1. Time series of the difference of the number of observations (Δn_{obs}) for (a) STP1-CTRL, (b) STP2-CTRL, (c) SMP1-CTRL, and (d) SMP2-CTRL.

15. Figure 10: Could the shaded areas in Fig. 10 be made partially transparent? This may be helpful at times when the CTRL spread is similar to the STP1 and STP2 spread (e.g., between 20180800212–2018080512 in Fig. 10b.)

Response: Thank you for your suggestion. Figure 10 was modified in transparent.



16. Line 369–379: It could be worth mentioning here that the amplitude scale of the daytime soil temperature perturbations is an order of magnitude larger than the night time perturbations, which could be a reason why the daytime-only perturbations more effectively propagated to the atmospheric variables. In its current form, the text here focuses more heavily on the length scale and time scale parameters.

Response: Thank you for your suggestion. We added the following discussion regarding amplitude scale in Lines 369-379 below (Revised sentences are written in blue font):

“First, soil temperature had the amplitude optimized according to the diurnal variation because soil temperature has a diurnal variation greater than soil moisture. [Since the amplitude scale of the daytime soil temperature perturbations \(e.g., 0.13\) is an order of magnitude larger](#)

than the scale of the nighttime perturbations (e.g., 0.01), daytime-only perturbations propagate more effectively to atmospheric variables. Second, the length scale depended on the characteristics of soil variables and target time. During the daytime, the length scale was 2900 km, similar to the domain size, because soil temperature was affected by the solar radiation varying with the latitude. During the nighttime, the length scale was 100 km, which was affected by the soil texture distribution. As for soil moisture, the length scale was 250 km and was classified as a mesoscale convection system due to rainfall effects in the daytime, while the length scale was 700 km due to less convection at nighttime. Lastly, the time scale was inversely proportional to the length scale. As a result, SPSS with diurnal variations in the EDA system depicted a reasonable ensemble spread for soil states, but the propagation to atmospheric states through the sensible and latent heat flux was less effective than the daytime-only tuning parameter. In detail, the soil temperature perturbations in the EDA system reduced the ensemble mean error of temperature in PBL by generating a proper analysis increment during the data assimilation cycles.”

17. Line 374: Please rephrase “classified as a mesoscale convection system.” The length scale and soil moisture itself is not an MCS, but may be similar in scale. If there are indeed mesoscale convective systems active in the domain at the time of the optimization cycle, it would be helpful to see these on a map, since the optimization appears to be only over a single 6-hour period (e.g., perhaps as a Fig. 2b or 2c).

Response: Thank you for your suggestion. Since soil moisture is not exactly an MCS, we revised it as you suggested in Lines 373-375. Indeed, there was MCS at the optimization time (e.g., 06 UTC on 1 August 2018 and 18 UTC on 1 August 2018), we added the supplementary figures showing the satellite image.

“In contrast, soil moisture, revealed different length features; in the daytime, the length scale was 250 km --- similar to the scale of a mesoscale convective system (MCS) --- reflecting the rainfall effect by the MCS (Fig. S2a); in the nighttime, the length scale was 700 km with less effect of the MCS (Fig. S2b). In fact, the MCS was active in the afternoon in southern part of the domain (south-central China) on the date the optimization was performed (see Fig. S2a).”

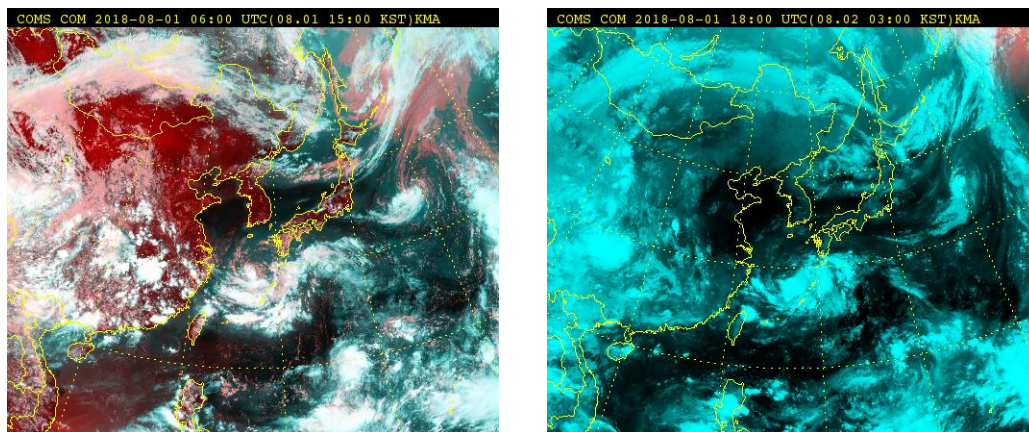


Figure S2. Satellite image at (a) 06 UTC and (b) 18 UTC on 1 August 2018.

Technical comments:

1. Line 8: Word “respectively” isn’t necessary here. This could be a good place in the abstract to specify that soil temperature and soil moisture are perturbed in separate experiments, though, since this is not stated clearly in the abstract.

Response: We removed "respectively" and clarified the separate experiments that perturb soil temperature and soil moisture, respectively.

“It perturbs soil temperature and soil moisture by adding the random forcing to inflate the ensemble spread. In this study, we investigated the effects of separately perturbed soil temperature and soil moisture in each experiment.”

2. Line 29: Remove unnecessary “The” starting the sentence.

Response: Thank you for pointing this out. We removed “The” as below:

“Sufficient ensemble sizes can moderately remove the sampling error...”

3. Line 32: Replace “out” with “outside”

Response: We corrected it as below:

“The former does not use observations outside of a cutoff distance from a state variable, ...”

4. Line 36–38: This sentence would probably be more clear if the colon on line 37 was removed. Either make this into two separate sentences or combine to remove the colon.

Response: We removed the colon and made the original sentences into two separate sentences, as follows:

“As one of the inflation methods, the stochastic perturbation scheme represents the model uncertainty by perturbing the tendencies or parameters in the physical parameterization schemes (Buizza et al., 1999; Shutts, 2005; Palmer et al., 2009). It assumes that the NWP model contains inevitable uncertainties in the physical processes by simplifications and approximations.”

5. Line 49: “This...representations” number inconsistency. Please revise.

Response: We changed it to “These stochastic representations of model uncertainty...”

6. Equations 4 and 5: Are the vertical bars ‘|’ used here to group terms? If so, it is a little confusing when first reading these equations since they look like operators. Consider removing or replacing the vertical bars.

Response: We removed the vertical bars in Equations 4 and 5.

7. Line 113: “resolve the” doesn’t seem like the most correct word choice here. “represent” may be more clear.

Response: We changed “resolved the” to “represent”.

8. Line 124: “depend on the characteristics being applied” is unclear. Please revise.

Response: We revised Lines 124-125 as below:

“The RF tuning parameters that create a perturbation are defined as follows”

9. Lines 129–131: This short paragraph could be merged with the previous one.

Response: We merged the two paragraphs.

10. Line 210: “widely used in the mesoscale model” is somewhat awkward phrasing.

Consider revising to “widely used in mesoscale modelling”

Response: Thank you for your suggestion. We revised it to “widely used in mesoscale modeling”.

11. Line 211–212: “is” “are” number inconsistency, please revise.

Response: This sentence indicates the initial and lateral boundary conditions; thus, we changed the original sentence to plural as “Because they are based on the GFS with Noah LSM, ...”

12. Line 215: “...the interpolation uncertainties” – “the” is unnecessary, please remove. Also consider rephrasing to “interpolation uncertainties are avoided”

Response: Thank you for your comments. We revised Lines 215-216 as below:

“Since the number of soil layers and soil depth in GFS analysis are identical to Noah LSM, interpolation uncertainties are avoided”

13. Line 219: “It included...” – Pronoun “It” is inconsistent in number with the antecedent “observations” or “data” in the previous sentence. Consider revision to “These observations included...”

Response: Thank you for your comments. We revised the pronoun in Line 219 as below:

“These observations included...”

14. Line 221: Unnecessary “The” starting the sentence. Consider revision to “Satellite radiances were...”

Response: Thank you for your comments. We revised Line 221 as below:

“Satellite radiances were not assimilated in this study”

15. Line 229: “i.e.,” is more appropriate here than “e.g.,”. Please revise.

Response: We revised it to “i.e.,”.

16. Line 230: Parenthetical “e.g.,” is probably unnecessary and can be reworded. Consider revision to “a potential solution of RF tuning parameters”

Response: Thank you for your comments. We revised Line 230 as below:

“A coupled system of μ -GA and SPSS found a potential solution of RF tuning parameters within the assigned ranges (Table 1)...”

17. Line 277: Missing space after period between “...(Fig. 6).For temperature...”

Response: Thank you for pointing this out. We added the space between two sentences.

18. Line 296–308: Numerous instances of awkward or confusing wording, or typos in this paragraph that should be revised.

a. Line 298: Revise phrasing “it went...”

Response: We revised Lines 298-299 as below:

“At the beginning of the cycle, the ensemble spread of soil moisture was less than the RMSE, but as the DA cycles progressed, it became excessively greater than RMSE.”

b. Line 300: Revise phrasing “when happened underestimated...”

Response: We revised Lines 299-301 as below:

“Because we optimized the RF tuning parameters using the underestimated ensemble spread at 06 UTC on 1 August 2018, the excessive inflation was applied during the DA cycles.”

c. Line 301: Revise phrasing “it is recommended optimizing...”

Response: We revised Lines 301-302 as below:

“Hence, in order to maintain the proper balance between ensemble spread and ensemble error during DA cycles, it will be necessary to optimize the RF tuning parameters within the DA cycling system.”

d. Line 303: “necessary” should be “necessity”

Response: We corrected it.

e. Line 306–307: Remove “As for the” and “, they”

Response: We revised Lines 306-307 as below:

“Surface variables such as 2 m temperature, 2 m water vapor mixing ratio, and 10 m horizontal winds also showed...”

f. Line 308: Revise phrasing “weakly decreased RMSE” to “a small RMSE reduction”

Response: We revised Lines 306-308 as below:

“Surface variables such as 2 m temperature, 2 m water vapor mixing ratio, and 10 m horizontal winds also showed an increased ensemble spread and a small RMSE reduction in both experiments (not shown).”

19. Line 330: Replace word “tried.”

Response: We revised Lines 330-332 as below:

“For specific humidity (Fig. 10b), the ensemble spreads in SMP1 (blue shading) and SMP2 (red shading) have weakly increased --- still including more observations.”

20. Line 337: Add missing words “of the” after most.

Response: We revised Lines 336-338 as below:

“For temperature, there was a warm bias in north China (NC), northeast China (NE), and most of the Korean Peninsula (KP) in CTRL, STP1, and STP2, while there was a cold bias in east China (EC), the southern region of South Korea (SSK), and most of Japan (JP).”

21. Line 379: Replace “strengthened” with “increased”

Response: We corrected it in Lines 379-380 as below:

“The soil moisture perturbations, however, increased the ensemble mean error of water vapor mixing ratio in PBL by producing an inappropriate analysis increment.”

22. Line 381: “As further studies” is awkward phrasing. Consider revising to “in future research”

Response: We corrected it.

References:

Bouttier, F., B. Vié, O. Nuissier, and L. Raynaud, 2012: Impact of Stochastic Physics in a Convection-Permitting Ensemble. *Mon. Wea. Rev.*, **140**, 3706–3721, <https://doi.org/10.1175/MWR-D-12-00031.1>.

Lupo, K. M., R. D. Torn, and S. Yang, 2020: Evaluation of Stochastic Perturbed Parameterization Tendencies on Convective-Permitting Ensemble Forecasts of Heavy Rainfall Events in New York and Taiwan. *Wea. Forecasting*, **35**, 5–24, <https://doi.org/10.1175/WAF-D-19-0064.1>.