Authors' Response to Reviewers

Phenology and Surface Energy Balance Changes Across Northern Lands

August 2026

We thank both Reviewers for their thoughtful and constructive evaluation, as well as their careful reading of our manuscript. The main revision addresses the justification and robustness of our sensitivity analysis settings, raised by both Reviewers. We ran the analysis across alternative LAI thresholds (20%, 40%) and window widths (±15, ±25 days) and present results by PFT and surface energy balance variable in a new Section 3.5 (Figure 7, Supplementary Figure A6, and Table A1 in the revised manuscript). The reference settings (30% threshold, ±20-day window) consistently fall within one standard deviation of the mean across alternative settings, confirming methodological robustness.

We respond point-by-point to all comments below. Reviewer text appears in *blue italic*; our responses are indented. Verbatim changes to the manuscript are indicated in the tracked-changes version provided alongside these responses.

Response to Reviewer 1

We thank Reviewer 1 for the detailed and constructive comments. We address each comment below.

Major Comments

R1.1 *SOS and EOS are defined using a single threshold of 30% of annual maximum LAI across all vegetation types and latitudes (L78–80). For tundra or deciduous forests with strong seasonal amplitude this may work reasonably well, but for evergreen needleleaf forests—where intra-annual LAI variation is small—the same threshold likely captures noise rather than a real phenological transition. PFT-specific biases in phenological detection could plausibly explain part of the spatial heterogeneity the authors observe in energy balance sensitivities, but this possibility is never examined. A sensitivity test with alternative thresholds (e.g., 20% and 40%) would help, or at minimum the authors should acknowledge this as a source of spatially-structured uncertainty.*

We agree that the choice of LAI threshold influences the estimated timing of SOS and EOS and therefore introduces uncertainty into our analysis of surface energy balance sensitivities. The optimal threshold to derive phenological transition dates is still a topic of research, with an accepted range between 20–50% of maximum annual LAI, but without a universally agreed standard. We selected a 30% threshold as a compromise within this accepted range, applied consistently across all vegetation types to ensure methodological comparability. Furthermore, the fixed temporal window around SOS and EOS encompasses a time range beyond the exact threshold-crossing date, which partly reduces sensitivity to the precise transition date.

Following the reviewer's suggestion, we performed a sensitivity analysis with thresholds of 20% and 40%, complemented by alternative window widths of ±15 and ±25 days (see also R1.5). We demonstrate the mean, median, standard deviation, and distribution of significant spatial sensitivities for each surface energy balance variable and plant functional type (Figure 7 and Supplementary Figure 6); evaporative fraction is omitted from these figures because it is derived from the latent and sensible heat fluxes that are already evaluated. Overall, our results at the reference settings (30% threshold, ±20-day window) are robust: the reference mean generally lies near the centre of the distributions obtained from the alternative settings, and within one standard deviation of the overall settings mean (Table A1 in the manuscript), while the sign of the response is maintained. We discuss these robustness findings in the new Section 3.5. Regarding PFT-specific bias, we did not find a systematically elevated uncertainty for evergreen needleleaf forests, but we did find a larger sensitivity to our analysis settings in mixed forest, as highlighted in Section 3.5. We inlcude here the new in: Figure 1 (Figure 7 in the manuscript).

R1.2 *The partial correlation analysis uses ERA5 surface temperature as a covariate to control for confounding (L125–128). When ERA5 LE and H are the response variables, this is problematic because ERA5 skin temperature and ERA5 turbulent fluxes are products of the same land surface model, where energy balance closure is imposed—they are not independent. The issue is most acute in Section 3.4 where ERA5 LST serves as both the response variable (Figure 6) and the partial correlation covariate. The authors should acknowledge this explicitly and note that ERA5-based partial correlations need to be interpreted carefully. Results from FLUXCOM and GLEAM provide a more independent basis for inference here.*

We thank the reviewer for raising this important methodological point. ERA5 latent heat, sensible heat, and skin temperature are all outputs of the same integrated land-surface–atmosphere model and therefore share internal physical consistencies rather than being statistically independent. Partial correlations between ERA5 LE or H and ERA5 skin temperature as a covariate may therefore contain residual within-product dependencies that could inflate or deflate the apparent phenology–flux association.

We note that Figure 6 presents a sensitivity analysis (regression slope of ERA5 skin temperature against SOS/EOS), not a partial correlation, so ERA5 temperature is not simultaneously used as both response and covariate here. Nevertheless, the shared ERA5 model structure means that

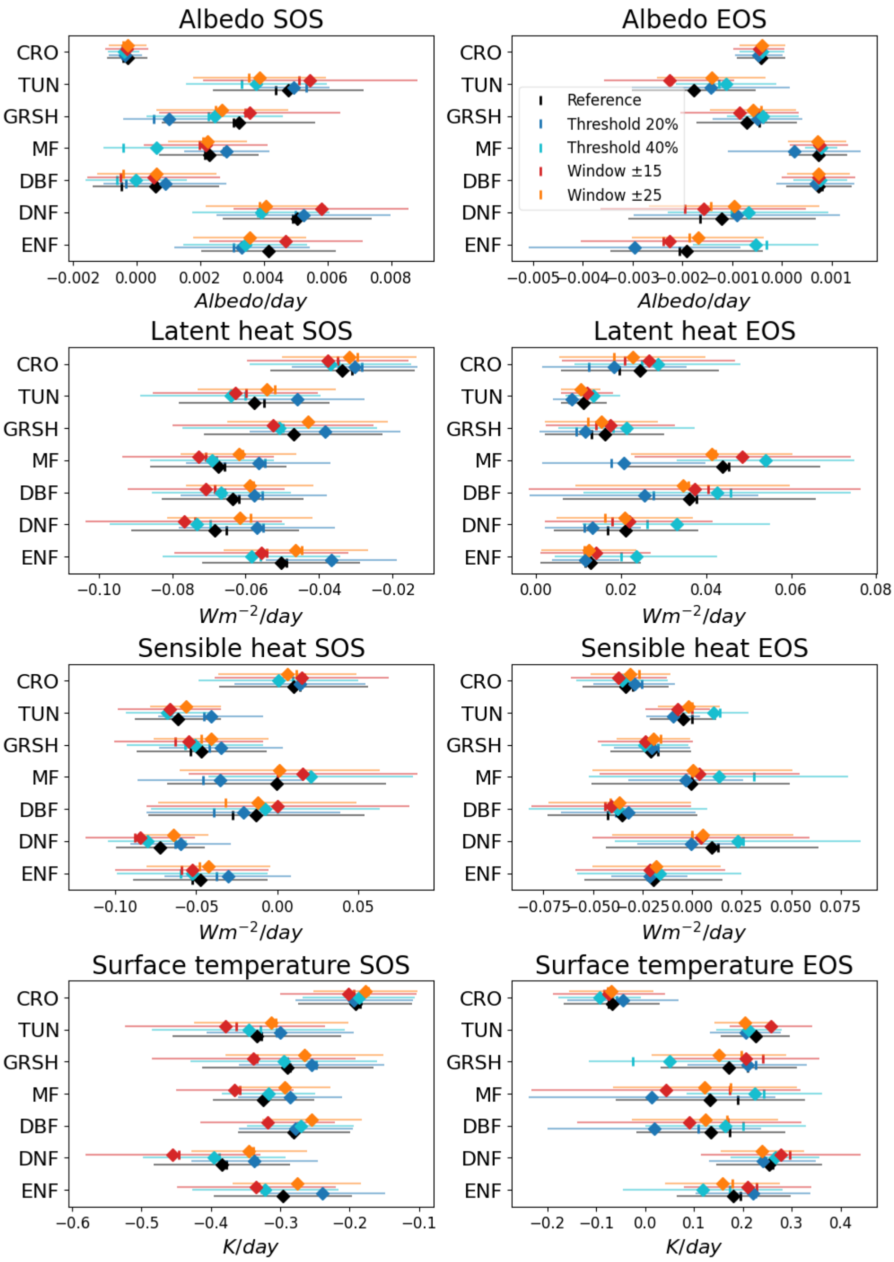

Figure 1: Statistical distribution of sensitivity slopes for the different analysis settings by plant functional type and surface energy balance variable. The reference analysis uses a 30% threshold of the annual maximum LAI and a temporal window of ±20 days around the mean SOS/EOS. The alternative settings include a 20% threshold, a 40% threshold, a ±15-day window, and a ±25-day window. In each sensitivity analysis, only one parameter (threshold or window width) is varied, while the other is kept identical to the reference analysis. Results are shown for albedo, latent heat, sensible heat, and surface temperature. For each variable and plant functional type, the mean (diamond), median (vertical line), and standard deviation (horizontal error bar) of the significant sensitivity slopes are shown for evergreen needleleaf forest (ENF), deciduous needleleaf forest (DNF), deciduous broadleaf forest (DBF), mixed forest (MF), grass and shrubland (GRSH), tundra (TUN), and croplands (CRO).

ERA5-based partial correlations of LE and H warrant caution. We note that the rationale for using temperature as a covariate remains physically motivated regardless of data product: both latent and sensible heat are influenced by temperature, so partial correlations with temperature as covariate are used to assess the phenology–flux association while accounting for this confounding influence. We have added an explicit caveat to the Results preamble (Section 3) noting the ERA5 dependency limitation, while also highlighting that the results are supported by independent correlations from the FLUXCOM and GLEAM datasets.

Minor Comments

R1.3 *(L10–12): The abstract states the findings "indicate a negative feedback loop that may partially dampen surface warming." The paper itself acknowledges (L239–242) that causal attribution is not possible from these observations. The abstract should reflect that—something like "are consistent with" would be more accurate.*

We agree with this concern and thank the reviewer for highlighting the inconsistency. We have revised the final sentence of the abstract to read: *"These findings are consistent with a phenology-driven negative feedback on surface warming through enhanced evaporative cooling, although causal attribution from observational analyses alone is not possible."* This wording aligns with the more cautious framing already present in the body of the manuscript (L239–242) and with the parallel revision requested in R2.1.

R1.4 *(L60–65): The paper describes using "daily temporal resolution data," but MODIS and FLUXCOM are 8-daily. The interpolation from 8-day to daily for GLASS LAI (L74–75) produces smoothed estimates that are not independent observations. This matters for how precisely SOS/EOS dates are actually being constrained, and should be noted.*

We thank the reviewer for pointing out that the uncertainty associated with deriving daily phenological transition dates from the interpolated GLASS LAI dataset was not sufficiently discussed. The provision of continuous daily observational datasets at global scale is currently limited by sensor characteristics. We use GLASS LAI, which provides gap-filled estimates at 8-daily resolution linearly interpolated to daily resolution, as one of the few available options for joining meteorological and phenological datasets over long periods at global scale. We have revised the manuscript to explicitly acknowledge that the interpolated daily values should be interpreted as temporally approximated estimates rather than independent daily observations, and that this constrains the precision with which SOS and EOS can be determined.

R1.5 *(L120–124): The $\pm$20-day fixed window around mean SOS/EOS does not account for inter-annual variation in transition duration. Some justification for this choice, or a brief check of sensitivity to window width, would be helpful.*

We recognise that the choice of window width introduces additional uncertainty, as it determines which values of the surface energy balance variables are included in the sensitivity analysis. The fixed $\pm$20-day window was chosen to capture the surface energy balance dynamics in response to phenological shifts, which may not manifest instantaneously at the exact transition date, while maintaining a consistent analysis period across years that encompasses the natural inter-annual spread of transition dates.

We have performed the sensitivity analysis with window widths of $\pm$15 and $\pm$25 days, alongside the alternative LAI thresholds described in R1.1. Results confirm an overall robustness: the reference mean lies within the standard deviation of the alternative settings mean (Table A1 in the manuscript), and the trend direction is maintained. These results are presented in the new Section 3.5, Figure 7 (by PFT and surface energy balance variable), and Supplementary Figure 6 (aggregated across PFTs by surface energy balance variable) (see also R1.1 and R2.3).

R1.6 *(L180–185): "Back-of-the-envelope" is a bit informal for a methods section. Reframe as a first-order estimate, and state the assumptions more explicitly.*

We agree that this phrasing is too informal. We have replaced "back-of-the-envelope" with "first-order estimate" and added an explicit statement of the underlying assumptions: (1) the downward shortwave radiation is treated as approximately time-invariant over the study period; (2) the multi-decadal ERA5-Land average for May–June over northern lands ($> 30°$N) is used as a representative flux value; and (3) the albedo change is assumed to act uniformly across the spatial domain used to derive the sensitivity. These assumptions are now stated explicitly in the revised manuscript.

R1.7 *(L254–255): Winkler et al. (2026) is a companion preprint with overlapping authorship, cited here as supporting evidence for the feedback mechanism. This should be flagged clearly as a companion paper under review rather than independent supporting literature.*

We thank the reviewer for this important point. We have added an explicit statement at both citation locations identifying Winkler et al. (2026) as a companion paper currently under review with overlapping authorship, and therefore not an independent line of supporting evidence. We have also expanded the supporting literature by adding Lian et al. (2022) and Forzieri et al. (2020) as independent lines of evidence in the Conclusions (see also R2.4); both are already cited in the Introduction and provide modelling and observational support, respectively, for a LAI/phenology-driven latent cooling feedback.

R1.8 *(L260–264): The SOS–EOS interaction is mentioned as a limitation too briefly. An earlier SOS may deplete summer soil moisture and directly affect autumn energy balance—this is not just a gap for future work, it could be actively confounding the EOS–LE results. Worth a few more sentences in Section 3.2 or 3.4.*

We agree that this is not merely a future research gap but a potential active confounder in our EOS results. An earlier SOS extends the period of active transpiration (and also canopy interception), which can progressively deplete soil moisture reserves over summer. Reduced soil moisture entering autumn would suppress stomatal conductance and transpiration regardless of canopy presence, meaning that our observed EOS–LE sensitivities may partly reflect the legacy moisture deficit from an earlier growing season rather than a direct response to delayed senescence. This interpretation is consistent with the weaker and more spatially heterogeneous EOS–LE sensitivities we report compared to SOS, and with the negative EOS–LE sensitivities found in some regions by GLEAM, where explicit soil moisture constraints on evaporation are represented. We have expanded the discussion of this limitation in Section 3.2 (latent heat) and Section 3.4 (EF and surface temperature) accordingly.

Response to Reviewer 2

We thank Reviewer 2 for the careful reading and constructive suggestions. We address each comment below.

Specific Comments

R2.1 *Abstract: The last, concluding, sentence appears somewhat disconnected or even contradictory given the second-to-last sentence and the preceding text. While the LE maps are very consistent, also the EF maps contain areas that are spatially coherent, lending some support to the indication of a negative feedback loop. I suggest expanding the abstract somewhat to express the motivation for the conclusion of a negative feedback more clearly.*

We thank the reviewer for this observation. We have revised the final sentences of the abstract to build more explicitly on the LE and EF results before drawing the conclusion. The revised text reads: *"Across datasets, earlier SOS is consistently associated with increased latent heat flux, and the concurrent evidence from evaporative fraction suggests a shift towards enhanced latent cooling. These findings are consistent with a phenology-driven negative feedback on surface warming through enhanced evaporative cooling, although causal attribution from observational analyses alone is not possible."* This revision also addresses the concern raised in R1.3 regarding consistency with the caution expressed at L239–242 of the manuscript.

R2.2 *Please clarify if detrending is done on all variables including satellite-derived LAI (as stated on L62)? This is unclear since detrending is explicitly described for the surface balance variables (L116–117) but not explicitly for the LAI data.*

We thank the reviewer for pointing out that this was not sufficiently clear. Only the surface energy balance variables are detrended; LAI intentionally retains its long-term trends. The detrending of surface energy balance variables is performed to reduce the influence of long-term climate trends (principally global warming) on the sensitivity analysis, ensuring that the regression slopes reflect interannual variability rather than shared long-term trends. LAI is not detrended because its long-term changes in response to climate warming on top of interannual variability, and their effects on the surface energy balance, are the central object of study. We have revised the Methods section to make this distinction explicit.

R2.3 *Please provide motivations of the technical choices of a 20-day window and phenology thresholds of 30%.*

We have added explicit justifications for both choices to the Methods section, as detailed in our responses to R1.1 and R1.5. Briefly: the 30% threshold was selected as a widely used and methodologically consistent choice within the accepted 20–50% range; the ±20-day window was chosen to capture the surface energy balance response in the period surrounding the phenological transition, accounting for the fact that biophysical responses may not be instantaneous. A full sensitivity analysis across alternative thresholds (20%, 40%) and window widths (±15, ±25 days) is now presented in Section 3.5 and added as Figure 7 in the revised manuscript (Figure 1 here).

R2.4 *The conclusion (L254–255) refers to global modelling studies for supporting the conclusion of negative feedback but only provides a reference to the companion paper (?) by Winkler. Please provide examples of other independent studies.*

We thank the reviewer for this important point, which is in agreement with R1.7. We have explicitly identified Winkler et al. (2026) as a companion paper under review with overlapping coauthorships. We have added two independent supporting references to the conclusions: Lian et al. (2022), who found using a modelling framework that earlier SOS enhances evaporative cooling across northern vegetated regions; and Forzieri et al. (2020), who provide large-scale observational evidence that LAI-driven increases in transpiration have reduced the Bowen ratio. While the latter study does not look into phenology explicitly, it provides evidence for the relationship between increased LAI and increased transpiration, along the lines of the phenology-driven latent cooling feedback we report.

R2.5 *A substantial part of the results and conclusions of the paper are based on interpretation of the maps. However, the limited size and the chosen colour scales limits their interpretability. At least, the size of the maps can be expanded to fit the full text width. The colours are sometimes insufficiently graded, e.g. Fig A1, where it is difficult to match the colours with the actual values in the legend. A separate colour scale for each map would improve legibility. In Fig 2, the colours are saturated with a maximum of 0.002 while values in the box plots below go up to 0.006, resulting in one single colour for the whole northern belt.*

We thank the reviewer for these constructive suggestions to improve the interpretability of the figures. We have updated the color scales to cover the full range of values (minimum to maximum), using discrete color bins. Each bin contains an equal number of positive or negative data points, with zero serving as the boundary between the two color ramps, ensuring comparability between SOS and EOS panels while improving legibility. In addition, we have increased the width of all spatial map figures (Figures 2–6 and Supplementary Figures A1–A5) to the full text width to maximise map resolution and legibility.

R2.6 *The results are presented per climate dataset. While this provides a good structure, the results section could benefit from a final paragraph where the effects of all these variables are summarised per land cover class.*

We agree that the PFT-specific effects are not discussed in detail in the original manuscript and could provide an additional interesting perspective on surface energy balance dynamics. We have added a new Section 3.5 with a comprehensive figure showing all PFTs for each surface energy balance variable, allowing for easier inter-variable comparisons and facilitating assessment of sensitivity to the different analysis settings for each PFT (Figure 7 in manuscript; here Figure 1). So, we include the new Figure 7 in the revised manuscriopt rather than a detailed variable-by-variable PFT description and in Section 3.5 we highlight only the most notable PFT patterns and dynamics across the surface energy balance variables.

Typographical Comments

R2.7 *L200: Central America → Central North America*

We thank the reviewer for this correction. The text has been updated to "Central North America."

R2.8 *Line 217: "Southern Canada and the central United States…" A bit difficult to see from the map if the region touches Canada; maybe rather "Central and south-eastern North America"?*

We agree and have adopted the suggested wording "Central and south-eastern North America."

R2.9 *Line 222, 223: two missing section numbers (see Section) (Section)*

The missing section references have been added.

R2.10 *L208–209: The two sentences appear contradictory. Please rephrase.*

We have rephrased these sentences to distinguish clearly between our large-scale and regional-scale interpretation of the sensitivities.

R2.11 *Fig 2, Fig 3, Fig 4 all captions: MF mixel forest → MF mixed forest; CRO coplands → CRO croplands*

The typographical errors in the figure captions have been corrected.

R2.12 *FigA2, caption: albendo → albedo*

Thanks for spotting the typo. Corrected.

R2.13 *Fig A4, title: Sensile heat → Sensible heat*

Thanks for spotting the typo. Corrected.

References

Forzieri, G., Miralles, D. G., Ciais, P., Alkama, R., Ryu, Y., Duveiller, G., Zhang, K., Robertson, E., Kautz, M., Martens, B., Jiang, C., Arneth, A., Georgievski, G., Li, W., Ceccherini, G., Anthoni, P., Lawrence, P., Wiltshire, A., Pongratz, J., Piao, S., Sitch, S., Goll, D. S., Arora, V. K., Lienert, S., Lombardozzi, D., Kato, E., Nabel, J. E. M. S., Tian, H., Friedlingstein, P., and Cescatti, A. (2020). Increased control of vegetation on global terrestrial energy fluxes. *Nature Climate Change*, 10(4):356–362.

Lian, X., Jeong, S., Park, C.-E., Xu, H., Li, L. Z. X., Wang, T., Gentine, P., Peñuelas, J., and Piao, S. (2022). Biophysical impacts of northern vegetation changes on seasonal warming patterns. *Nature Communications*, 13:3925.

Winkler, A. J., Kranz, J., Graf, A., et al. (2026). The phenology-climate feedback loop: Current understanding and future directions. *ESS Open Archive*.