**We thank Referee #2 for their helpful comments. Our replies to their comments are shown in bold below.**

Review of Wang et al., "Impact of topography and meteorological forcing on snow simulation in the Canadian Land Surface Scheme Including Biogeochemical Cycles (CLASSIC)"

This study examines the impact of replacing the default CLASSIC snow cover fraction (SCF) parameterization with an alternative one. The study has two objectives: 1) comparing the two SCF parameterizations and 2) examining the role of meteorological forcing on the simulation of snow. The role of meteorological forcing is highlighted by using three input datasets to force the model. The default parameterization predicts SCF from snow depth using a linear relationship for snow depth below 0.1m; above 0.1m, SCF is 1. The alternative considers the accumulation and ablation seasons separately, and also incorporates topographic information to adjust its behavior spatially based on the topographic variability within a region. The authors find that comparisons to MODIS SCF are more favorable when using the alternate SCF parameterization. In addition, other metrics related to water and energy fluxes show improvement.

General comments:

The authors state that tests changing the lone parameter (0.1) in the CTL parameterization show minimal impacts to their simulations. In contrast, in addition to a structural change, SL12 offers opportunities to improve the SCF simulation by modifying and calibrating equations 1 and 3. While the authors mention a couple of changes to the k_acc and N_melt parameters that led to positive results, they choose not to explore the parameter sensitivity in more detail "because none of the three meteorological forcing datasets used in this study are exempt from biases, there is a limit to how well optimal parameter values can be chosen for use in CLASSIC". The results shown in figure 5 of the manuscript seem to contradict this statement, as the biases seem consistent across forcings. The authors support this by stating "On the global scale, the spatial patterns of SCF bias are similar for all three meteorological forcing choices."

**Thank you for your overall positive review of our manuscript.**

I believe that this study would be improved if the authors were to pursue this path. The authors could perform a few shorter, initialized runs (e.g. from 1980 onwards) to do a sensitivity study of the N_melt parameter. They could then use these results to see if a better function for N_melt as a function of sigma_topo becomes apparent. For example, figure 5 indicates that lower SCF values in winter and spring, irrespective of forcing input, are preferred for flat regions. This implies that the N_melt equation increase too rapidly for small values of sigma_topo. This is perhaps not surprising, given that 1/x blows up as x goes to zero. A bounded function, e.g. a decaying exponential, might improve the results for flat regions, while maintaining the good results for mountainous regions. Similarly, adding a simple dependence on sigma_topo to k_acc might improve the fall bias shown in figure 5 b) without degrading other regions.

**Thank you for your suggestions. We agree that it would be ideal if the SL12 parameterization could be calibrated to improve modelled SCF in both the mountain and flat regions. Initially we tried many sensitivity experiments to try to achieve this goal. The discussion section of the paper provides some generalized results of the experiments and how this process worked (lines 685-702). However, after gaining a better understanding of the uncertainties in the meteorological forcings and observed SCF datasets, we think it is a goal impossible to achieve at present. Below are the reasons:**

**(1) Evaluation based on measurements from snow course and airborne gamma data showed that for all three choices of forcing data, modelled SWE is underestimated in the mountain and overestimated in the flat regions throughout the snow season (Fig. 4). Since SCF is directly linked to SWE in the SL12 scheme (see Eq.1 and Eq. 2), these SWE biases can exert a large impact on simulated SCF in the fall and spring seasons in the model (limited impact during the peak SWE period for SCF is usually saturated, details can be found in our reply to RC1). The consistent SCF biases shown in Figure 5 are linked to these consistent SWE biases for all three forcing choices in the model.**

**(2) SCF derived from satellite optical sensors such as MODIS represents the visible snow cover from space during cloud-free overpasses - that is, from above the vegetation canopy. In contrast, SCF from the CLASSIC model represents ground-level SCF, including snow cover beneath the canopy. As a result, MODIS-derived SCF tends to be biased low in forested regions. This limitation has been noted in previous studies (Hall et al., 2002; Hall and Riggs., 2021). Using high-resolution airborne lidar data from the western United States, Stillinger et al. (2023) found that the MODIS SCF product exhibited a consistent negative bias of approximately -0.10 under intermediate canopy cover, with the bias increasing with greater snow cover, reaching -0.25 under full snow cover conditions (peak snow season). Thus, it may not be ideal to over-tune the model to a specific observational estimate which may still have errors.**

**(3) Even if the SL12 parameterization and its associated parameters are perfectly specified, and the reference SCF for comparison was a perfect measure of ground truth, biases in the modelled SCF will still arise due to inaccuracies in the meteorological forcing data. We may revisit this if more realistic meteorological forcing datasets are available in the future.**

**We discussed the impact of meteorological forcing datasets on modelled SWE in Section 5.1. We will revise the text to clearly state the link between biases in SWE and SCF. We will acknowledge the uncertainties of the MODIS SCF product mentioned above and provide a brief discussion on its impact when revising our manuscript.**

**About you other comments with regard to "…for small values of sigma_topo", note the denominator of Eq. (3) is max(10, $\sigma_{topo}$), so the maximum $N_{melt}$ parameter is 20. Attempting to develop a different SCF parametrization is beyond the scope of the study.**

**Hall, D.K., Riggs, G.A., Salomonson, V.V., DiGirolamo, N.E., & Bayr, K.J.: MODIS snow-cover products. Remote Sensing of Environment, 83(1–2), 181–194. http://dx.doi.org/10.1016/S0034-4257(02)00095-0, 2002.**

**Hall, D. K. & Riggs, G. A.: MODIS/Terra Snow Cover Monthly L3 Global 0.05Deg CMG. (MOD10CM, Version 61). Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/MODIS/MOD10CM.061. Date Accessed 06-19-2025, 2021.**

**Stillinger, T., Rittger, K., Raleigh, M. S., Michell, A., Davis, R. E., and Bair, E. H.: Landsat, MODIS, and VIIRS snow cover mapping algorithm performance as validated by airborne lidar datasets, The Cryosphere, 17, 567–590, https://doi.org/10.5194/tc-17-567-2023, 2023.**

**Stillinger, T., Rittger, K., Raleigh, M. S., Michell, A., Davis, R. E., and Bair, E. H.: Landsat, MODIS, and VIIRS snow cover mapping algorithm performance as validated by airborne lidar datasets, The Cryosphere, 17, 567–590, https://doi.org/10.5194/tc-17-567-2023, 2023.**

Specific comments:

Lines 99,100: add references for CLM5, CESM2

**Thanks for noting this, we will add references when revising our manuscript.**

Line 130: how do the four sub-areas relate to SCF?  Do the snow/snow-free areas change dynamically?

**The areal fractions of the four subareas - vegetation over bare soil , bare soil, vegetation over snow, and snow over bare soil, are calculated based on the fractional coverage of the vegetation categories and SCF.**

**Yes, the snow-covered and snow-free areas change dynamically at each time step.**

Line 144: "all vertical layers": I thought there was only 1 layer (line 132)?

**We meant for soil layers beneath the snow layer as well. We will clarify this when revising our manuscript.**

Line 160: is there reason to think k_acc should vary spatially?  If so, how might one parameterize it?  (discussed in sec 5.2).  Also, SL12 mentions that eq 1 assumes snowfall is randomly distributed in the region; is this a valid assumption?

**The SL12 parameterization was developed based on the relationship between snow depth from Snow Data Assimilation System (SNODAS) and SCF from MODIS over the continental US (Swenson and Lawrence, 2012). Topographic dependency between SCF-SND was not observed during the accumulation period. More details can be found in Swenson and Lawrence (2012).**

**About "eq 1 assumes snowfall is randomly distributed", this assumption may not be valid in mountain regions where snowfall affects preferentially high-elevation areas. We will add this when revising our manuscript.**

**Swenson, S. C. and Lawrence, D. M.: A new fractional snow-covered area parameterization for the Community Land Model and its effect on the surface energy balance, J. Geophys. Res.-Atmos., 117, D21107, https://doi.org/10.1029/2012JD018178, 2012.**

Line 173: how are the parameters 200 and 10 chosen?  How sensitive are the results to these parameters, and could they instead be calibrated?

**The parameters were determined based on observed relationship between SCF-SND, details can be found in Swenson and Lawrence (2012). We performed sensitivity experiments where 200 in the numerator of Eq. (3) were changed to 300, 100, and 50. An example of the results is discussed in Section 5.2 and another figure is included below in response to your comment on bias in flat regions.**

Line 181: does SL12 implemented in CLM5 use time of year to determine which equation to use?
**No. It is also based on whether SWE is increasing or decreasing with respect to the previous time step.**

Why is equation 4 used? Isn't W_max based on the evolution of W in the model, i.e. is it the peak SWE of each snow season?

**W_max is the accumulated maximum SWE at each time step, which is different from the peak SWE of each snow season.**

Line 262: does the resolution of the DEM affect the calculation of the standard deviation of the sub-grid terrain?

**To assess the impact of DEM resolution, we compared $\sigma_{topo}$ derived from two DEM datasets: ETOPO1 (1-arc-minute resolution, used in our study) and ETOPO2022 (15-arc-second resolution). The results show that the differences are limited in extent, primarily concentrated along the mountain edges. We also performed a test simulation using $\sigma_{topo}$ derived from ETOPO2022 and compared modelled SCF with that from a run using $\sigma_{topo}$ derived from ETOPO1. The maximum difference was less than 5%.**

**The resolution of the DEM data has limited impact on the calculation of sub-grid topographic variability and the simulated SCF.**

Line 271: 'high mountainous asia' or 'high mountain asia'?

**Thanks for noting this typo.**

Line 297: IMS data could be converted to 1 degree fractional values, then treated similarly to MODIS; is that how IMS data is processed?

**The IMS dataset provides binary snow/no snow information: if more than 50% of the 4 km pixel is covered by snow, it has a value of 1, otherwise 0 (snow free). If we aggregate the 4km IMS snow/no snow data into SCF at 1 degree, the derived SCF would have an uncertainty range from 50% to 100%.**

**In our study, daily IMS data were converted to monthly snow cover duration fraction (SCF = total number of days with snow cover in a month divided by the number of days in the month), which we found more comparable with SCF from MODIS. This method was used in previous studies (Brown et al., 2010; Wang et al., 2014).**

**Brown et al. 2010, https://doi:10.1029/2010JD013975.**

**Wang et al., 2014, https://doi.org/10.1175/JHM-D-13-086.1.**

Line 315: SND is related to SWE via snow density; how is snow density calculated in CLASSIC?

**The density of fresh snow density ($\rho_{s,i}$) is determined as an empirical function of the air temperature (Ta). For Ta <= 0ºC, an equation presented by Hedstrom and Pomeroy (1998) is used. For Ta > 0ºC, a relation following Pomeroy and Gray (1995) is used, with an upper limit of 200 kg $m^{-3}$:**

$\rho_{s,i} = 67.92 + 51.25 \exp[Ta/2.59]$ Ta < 0ºC
$\rho_{s,i} = 119.17 + 20.0Ta$ Ta ≥ 0ºC

**Over time, snowpack density ($\rho_s$) increases due to the effects of crystal settlement and metamorphism in the snowpack, sublimation, wind packing, melt, and refreezing. CLASSIC models this using an empirical relationship with time:**

$\rho_s (t) = \rho_s (t - 1) \exp(-B\Delta t)$

**Where Δt is the time step and B = 0.01/3600 is a constant. More details can be found in Verseghy (1991) and Bartlett et al. (2006).**

**Verseghy, D. L., 1991, https://doi.org/10.1002/joc.3370110202.**
**Bartlett et al., 2006, https://doi:10.3137/ao.440301.**

Line 363: are there 21 datasets, or 7 datasets?

**A unique feature of AMBER is that it uses multiple reference datasets when available to evaluate the same variable. In the AMBER results shown in our study, seven variables were evaluated using 21 reference datasets (shown in Table 1).**

Figure 2: add units to (d) colorbar

**Thank you for noting this, we will add units when revising our manuscript.**

Figure 3: please label figures with NH or HMA. Also adding a dashed line to indicate zero for each y-axis would be helpful.

**Thank you for your suggestions. We will modify the figure as suggested when revising our manuscript.**

Figure 4: why only show NH, but not HMA like other sections? Does HMASR not provide SWE?

**In situ SWE measurements are not available for the HMA region. Though HMASR provides SWE, it is still model outputs with unknown uncertainties, not the same as those from snow course and airborne gamma data shown in Fig.4.**

**We feel the temperature and precipitation comparison in Fig. 3b and the number of wet days shown in Fig. 10 are sufficient to explain the differences in simulated SCF over the HMA region.**

Figure 4: perhaps replace 'mount' and 'flat' with 'Mountainous Regions (sigma > 200m)' and 'Flat Regions (sigma < 200m)'

**Thanks for your suggestions. We will change the title to 'Mountainous Regions' and 'Flat Regions' and include the definition for mountain/flat regions in the caption, to be consistent with other figures.**

Figure 4: how do errors compare to magnitude of SWE, e.g. figure 2 d), which shows maximum values of 115?

**The maximum SWE is up to 2000 mm in the mountain regions. We will replot Figure 2d to show more range for SWE.**

Line 403: CTL and SL12 do not cause any albedo feedbacks to cause changes in SWE (via surface energy balance)?

**Thanks for noting this. Yes, there is snow-albedo feedback, which affects simulated SWE in the model. We will modify the sentence when revising our manuscript.**

Figure 5: improvements mainly in 2nd half of snow season for mountainous regions; is this due to the ablation part of the SL12 parameterization?

**Yes. The parameterization for ablation in SL12 accounts for sub-grid topographic variability.**

Figure 5: SL12 shows similar results in the NA and EA flat regions (the flat region biases begin early in the season (around Dec/Jan)), can that be improved by calibrating with the parameters in eqn 3?

**Yes, that can be improved by tuning parameters in Eq. (3), details and an example of results (Fig. AR1) can be found in our reply below for a related comment. However, we choose not to use the tuned parameters in CLASSIC, please see our reply above to your main comments.**

Figure 6: I would use a colormap that was not white in the middle for panels a) and b). Perhaps simply linear white-to-blue?

**Thanks for noting this, we will use a different colorbar in the revised manuscript.**

Figure 7: SWE evaluation for HMA in section 4 would help understand differences in forcing data. Is the cruja/era5 overestimate due to a SWE high bias, or does it come from the SCF parameterizations?

**Given that the same CTL/SL12 schemes were used across all model runs, the substantial difference in simulated SCF in the run forced by GSWP3W5 (compared to the other two) indicates that the primary cause of the discrepancy is the difference in the forcing data. To improve clarity and logical flow, we will include the above sentence when revising our manuscript.**

**In addition, high SWE bias in ERA5 was well documented in previous studies (Liu et al., 2022; Orsolini et al., 2019), which suggested that excessive snowfall in ERA5 contributed to overestimation of SND, SWE, and SCF across HMA (also in Line 672-675).**

Line 441: SL12 is shown to perform slightly worse than CTL in fall (SON) in mountainous regions but not flat regions in NA.  What might cause this?  Is it more due to the accumulation equation or the ablation equation?

**Thank you for your comments and suggestions. This is mainly due to the accumulation formula, which can be improved by increasing the $k_{acc}$ parameter in Eq. (1), details can be found in Section 5.2 (L685-694).**

For the flat regions, the spring bias is similar for both SL12 and CTL.  What does that say about SL12, i.e. would a more rapid SCF decrease improve the results?  Does that imply that equation 3 is not optimal for flat regions, and the 1/sigma_topo behavior might be too large for small sigma_topo?

**We conducted sensitivity experiments by varying the value of 200 in the numerator of Eq. (3) to 300, 100, and 50. Among the tested configurations, the following combination produced the smallest overall SCF bias (Fig. AR1): for grid cells with $\sigma_{topo} \geq$ 100m, a numerator of 200 was used; for cells with $\sigma_{topo}$ < 100m, a numerator of 50 was applied. The map on the right (using the modified $N_{melt}$) shows reduced positive bias in flat regions compared to the one on the left (using the default $N_{melt}$).**

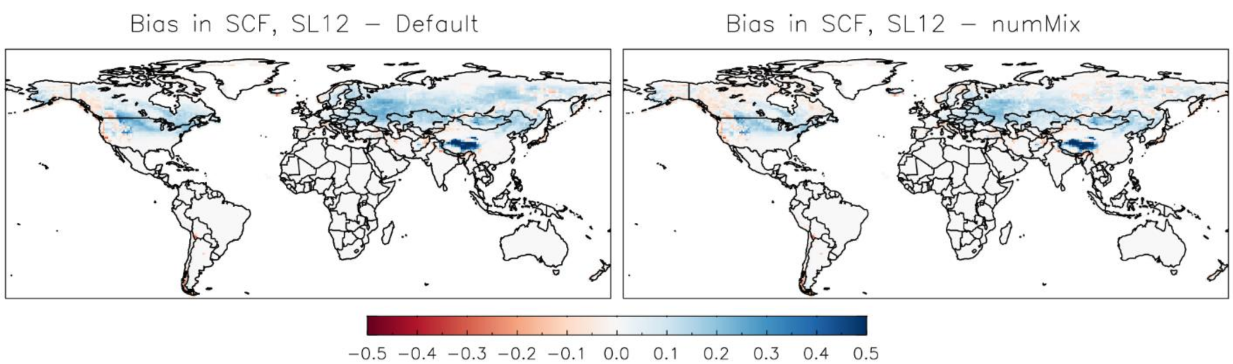


**Figure AR1. Bias in simulated SCF using the SL12 scheme with the default parameter (left) and the modified parameter (right). SCF from MODIS was used as the reference.**

**However, we choose not to use the tuned parameters in CLASSIC, please see our reply above to your main comments.**

Line 664: does the 'wet day' dependence indicate that one of the accumulation / ablation equations in SL12 has a bigger impact on the SCF evolution?

**The number of wet days influences the frequency of new snowfall, thereby directly affecting SCF during the accumulation period (Eq. 1). It also determines the amount of snow stored on the ground, which in turn impacts SCF through the ablation processes (Eq. 2). The dominant process controlling SCF evolution likely depends on the regional climate. In cold regions, where melting is rare during the accumulation season, SCF evolution is primarily governed by the accumulation**

**process. In contrast, in intermediate and warmer climates where accumulation and melt cycles are more frequent, both accumulation and ablation processes may contribute comparably to SCF evolution.**