Reviewer #2:

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General:

The manuscript aims at improving the Arctic sea ice state by introducing a modulated factor for sensible heat flux (based on Davy and Gao, 2019) depending on ice lead characteristics and the atmospheric boundary stability (enhancing in winter stable conditions and reducing it in summer unstable conditions). The scheme is shown to be effective during cold climate, although its impact seems to be less in normal or warm climate. The paper is well written. Unfortunately, some important details are missing and prevent a full acceptance of the manuscript at this stage. The heat exchange is not clearly established in view of the modulating factor and the cold and warm experiments are not clearly defined.

Major comments:

1.L87: “We emphasise that in ECE3L, the ocean does not supply additional heat to warm the atmosphere” (z for emphasize?) I am still scratching my head on this. However, no substantial addition is made to clarify the statement. This manuscript clearly states that the factor is applied to surface sensible heat flux: (L77-78) “we introduced a factor Alead to the surface sensible heat flux (SSHF) within the coupled ECE3 framework, to better represent the heat exchange through leads in sea ice ». Does it mean that the heat exchange between air and ocean-ice is non conservative? According to Davy and Gao (2019), only the heat flux over open water should be amplified but I was not able to ascertain the exact method used in the manuscript**.** Also, why stopping at sensible heat? Latent heat should be also pretty high over ice leads. Some results from Davy and Gao (2019) could be added in appendix since theirs is a project report to their funding agency (i.e., not clear whether it was peer-reviewed). Moreover, the details could be moved to the main text rather than the appendix since it is the core of the paper.

We apologize for any confusion caused by our statement. When we emphasized that in ECE3L, "the ocean does not supply additional heat to warm the atmosphere," our intent was to clarify that the heat extracted from the ocean per square meter, under the same air-sea temperature difference, remains consistent according to the bulk formula, regardless of whether it's in an open ocean grid cell or a grid cell with a small fraction of open water surrounded by sea ice. This implies that the ocean is not more prone to freezing, as the same amount of heat is transferred to the atmosphere. The introduced modulating factor, Alead, primarily affects the efficiency of heat transfer received by the atmosphere through the "amplified/damped" surface sensible heat flux (SSHF) over leads surrounded by sea ice. Consequently, this sub-grid process is non-conservative. (As reply to Reviewer #1, minor comment 9)

Davy and Gao (2019) explained that the heat flux over sea ice leads (characterized as small open water fraction within the grid cell) should be amplified. Specifically, we implemented this as at SIC >70% in a grid cell, the SSHF calculated over the fraction of open water will be amplified by the modulation factor.

We acknowledge the importance of latent heat flux over ice leads. We will address this limitation in the discussion section of our revised manuscript.

”*This is a sensitivity study, with a focus on the sensible heat flux. Since we didn’t have information on how latent heat fluxes change in response to variations in lead width from the original LES simulations of Esau (2007), we chose not to make an assumption about how they would respond, but rather to quantify the sensitivity to changes in the sensible heat flux based on these LES simulations.* “

It is correct that Davy and Gao (2019) is a project report and non-peer-reviewed, while it provides a valuable foundation for our study. To address this, we will include key methodological details from Davy and Gao (2019) in the main text. We will incorporate relevant figures and findings from Davy and Gao (2019), particularly the results from the LES study as to how the fluxes from leads depend upon lead width under different atmospheric stabilities and how that was combined into a single amplification factor based on a lead width frequency distribution [Figures 1 and 4 from Davy and Gao (2019)], into the appendix to provide further context and support for our approach. We hope this will help clarify the methodology and ensure that the heat exchange process is more clearly understood.

2.L99 states that “The [cold and warm climate] simulations used constant forcing with a repeating seasonal cycle corresponding to the respective climate states ». However, I am still scratching my head on how you do this. In a coupled model, you have only variations is solar radiation at the top of the atmosphere and aerosol forcing. Nudging perhaps of one of the components? Please give more detail.

Here for the “constant forcing” of a specific year we mean to use the external forcing from CMIP6 historical forcing from the given year (including solar radiation, GHGs concentrations, aerosols and land use, ect) in the 50-year coupled simulation. The ocean and atmospheric variables still freely evolve in the simulation without being constrained.

3.Methodology: Some figures show the ensemble envelop (5-95% percentile), which is interesting since it gives us the statistical significance of the results. However, except for ice volume, they seem to be hardly significant (i.e., an overlap is visible), which needs to be stated in the text.

We acknowledge the importance of carefully interpreting the results. To address this, we have performed a paired *t*-test to assess statistical differences and will include a statement in the text to clarify this point. Specifically, we conducted the paired samples *t*-test in Python with Scipy library containing the ttest_rel() function. The resulting *p*-values have been provided for Fig.2, Fig.7 and Fig.9, in response to minor comments 5, 6 and 7, respectively. Additionally, we have assessed the significance for Fig. 12 as well.

4.L194-195 states that “The findings suggest that during Arctic winters, the decrease in sea ice concentration is mainly due to heat advected by the ocean from the south, rather than air-sea heat exchange through sea ice leads ». I think I see the same ice reduction in S6 for

concentration below 70% but I am not sure I understand the statement any better. Since the modulation factor is one over these regions, it must a non-local effect as mentioned by the authors. However, since we are dealing with a coupled system, it could be the ocean or the atmosphere. I am less inclined to think it is the ocean, as the authors do, since you would need to explain a change in the Arctic ability to pump more Atlantic waters northward, than a simple advection/diffusion of the warmer atmospheric boundary layer southward. So, please elaborate.
We acknowledge the reviewer's point. Combining our response to Reviewer #1, comment 13, we will revise this section.
"The findings suggest that during Arctic winters, the overall thinning of sea ice, particularly at the ice margins, is a key driver of sea ice concentration reduction. In these marginal zones, where the ice is already very thin, even small reductions in thickness can lead to significant decreases in ice extent. In contrast, in the Central Arctic, sea ice concentration can remain close to 100% during winter, despite thickness reductions of one meter or more. This thinning at the margins coincides with a significant rise in surface air temperature by approximately 2 degree (Fig. 5), indicating a warmer atmospheric boundary layer extending southwards."

Minor comments:

1.L56: Essential Climate Variables : why the capitalization here?
We have removed the capitalization of "Essential Climate Variables".

2.L248: what was the concentration threshold value used to define the ice edge? Please add.
As requested, we added *"with a 15% threshold for the sea ice edge (Goessling et al., 2016)"* to L248, in addition to its mention in L141, Section 2.3 Validation Data and Metrics.

3.L1 of Fig1 caption: please remove "compared"
It's removed.

4.L2 of Fig1 caption: "based on" I think you meant "relative to", i.e., the bars and maps are the difference between ECE3L and ECE3 base runs (?) for the two climate experiments.
Thank you for your comment. The term "based on" has been changed to "in" to clarify that only the output of the ECE3 baseline simulations is used for the analysis in the figure, rather than indicating a comparison of relative differences between ECE3L and ECE3 runs.

The figure compares surface temperature conditions between cold and warm climate states in the ECE3 model. It illustrates both the seasonal variations (Fig. 1a) and the spatial extent of sea ice cover (with SIC>70%, Figs. 1b and 1c). When (Fig. 1a) and where (Fig. 1b,c) the temperature difference is positive, an amplification factor (Alead >1) should be implemented to the ECE3L model, reflecting the reduced effect of the modulation factor in the warmer climate state.

5.Fig2: the volume does show statistical differences but not the area (at least not clearly). To be mentioned in the text.
We performed paired t-tests for Fig. 2a, b, c, and d to evaluate the statistical significance of the differences. The results will be included in the text: "*The mean differences are statistically significant, except for Fig. 2c.*"

In Fig. 2a, ExpCold-SIA differences are significant ($p = 2.25 \times 10^{-9}$);
in Fig. 2b, ExpCold-SIV differences are significant ($p = 1.60 \times 10^{-16}$).
In Fig. 2c, ExpWarm-SIA differences are not significant ($p = 0.083$), while
in Fig. 2d, ExpWarm-SIV differences are significant ($p = 0.010$).

6.Fig.7: can the authors add the spread? I am worried that the significance is less than visually shown.

We have added the spread to Fig. 7. The ensemble means show significant differences for both Arctic sea ice area ($p = 1.47 \times 10^{-10}$) and sea ice volume climatologies ($p = 3.35 \times 10^{-17}$).

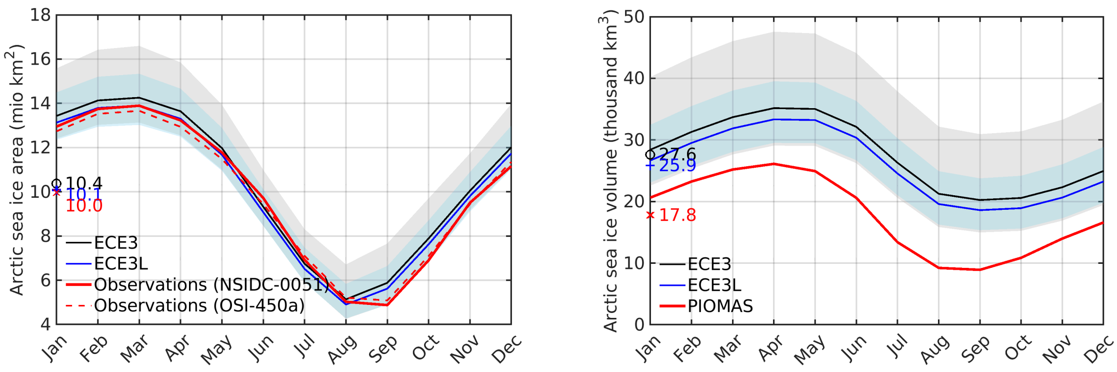

Figure 7. Comparison of seasonal cycle in the transient climate (1980-2014) between ECE3 (black) and ECE3L (blue) for (a) Arctic sea ice area and (b) Arctic sea ice volume. Thick lines represent the ensemble means, while the shaded areas indicate the spread between the 5th and 95th percentiles across 20 ensemble members, grey for ECE3 and light blue for ECE3L. Observations for the sea ice area include NSIDC and OSI-450a datasets, both remapped to the NSIDC-0051 grid. Sea ice volume is based on PIOMAS domain criteria (thickness > 0.15 m).

7.Fig.9: The plots do not show a statistically different mean (the two envelops overlap).

We assessed the statistical differences. The results will be included in the revised version. "*In Fig. 9a, the ensemble means for September Arctic sea ice extent are significantly different ($p = 2.61 \times 10^{-11}$), and in Fig. 9b, the means for March sea ice volume also differ significantly ($p = 4.99 \times 10^{-17}$). These differences are primarily driven by external forcing. After removing linear trends, the residuals for both September SIE and March SIV are no longer significantly different ($p > 0.05$).*"

Additionally, in Figure 12, the time series of Integrated Ice Edge Error (IIEE) shows significant differences for both March (p-value = 1.78e-15, $p < 0.05$) and September (p-value = 2.27e-08, $p < 0.05$). No significant trends were detected in the time series.

8.L1 of Fig.10: ECEL should be ECE3

We corrected it as noted.

9.Fig.11: the solid circle appearing in the key of the map is misleading. Its interior should be lightly colored as the area covered.

We adjusted the figure legend to Fig.11, as suggested.

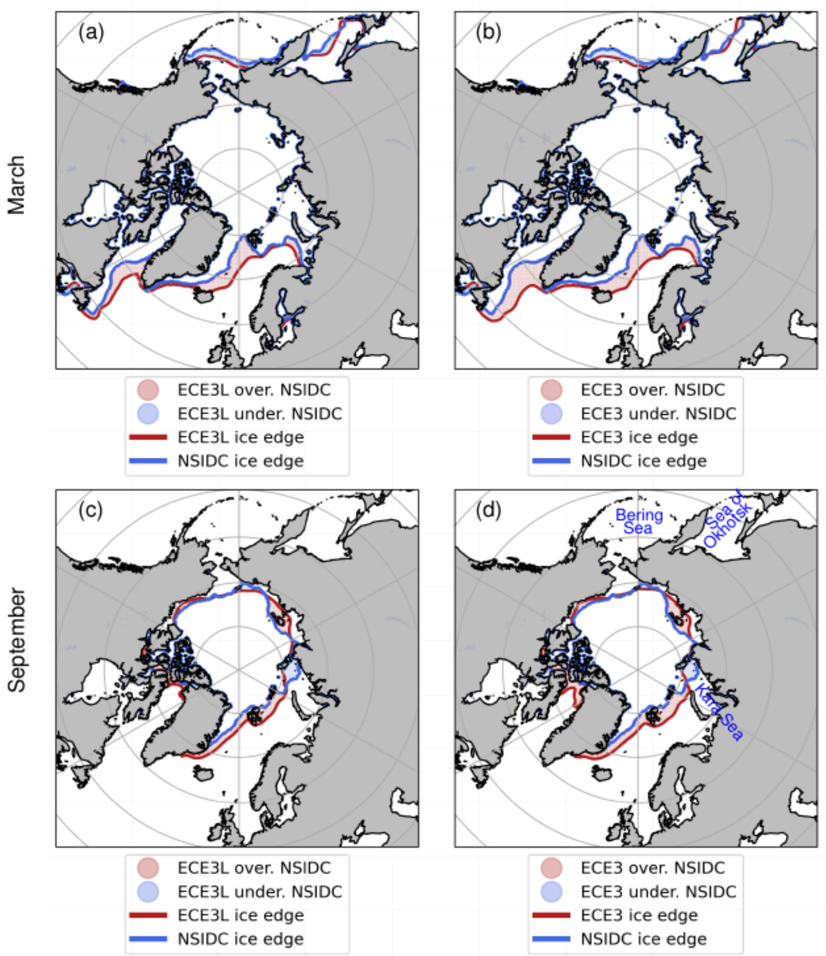

Figure 11. Integrated Ice Edge Error (IIEE, defined in section 2.3) maps of ECE3L (a) and ECE3 (b) vs. NSIDC-0051 for March sea ice climatology (1980-2014). Red and blue indicate whether the model's ensemble mean overestimates or underestimates the ice edge prescribed by NSIDC-0051, respectively. (c) and (d) as in (a) and (b), but for September sea ice. Sea ice edge is defined by the 15%-sea ice concentration contour.

10. Fig.13 and L291-295: Despite the authors' vigorous statement that ECE3L Arctic temperature trend is better than ECE3, both modelled trends are still quite far from the observed one. So, we are still missing out on the amplification factor in climate simulations. I realize that it is touched upon in the previous paragraph L287-290 discussing S10 but I must say that the S10a was not showing clearly this underestimation (but it is clearer in Fig.13), unless we are talking about something subtle hidden behind the spread of the ensemble? Why would there be a compensation between a global overestimation and the Arctic underestimation? Can you elaborate on this please, and possible in view of what the authors intent with the supplement (see below)?

Using the time series from Fig. S10a, we applied CDF to both visually and statistically assess the differences in variability and central tendency between the two ensembles (ECE3 and ECE3L) for the Arctic region (north of 66.5°N). As shown in Fig. 13, the Greenland-Iceland- Norwegian Seas (GIN: 40°W-15°E, 66.5°N-82°N) and the Barents and Kara Seas (BAKA: 15°E-100°E, 70°N-82°N) exhibit relatively remarkable changes in temperature trends and amplification ratio, compared to the rest of the Arctic domain. We applied CDF to the two key sub-regions.

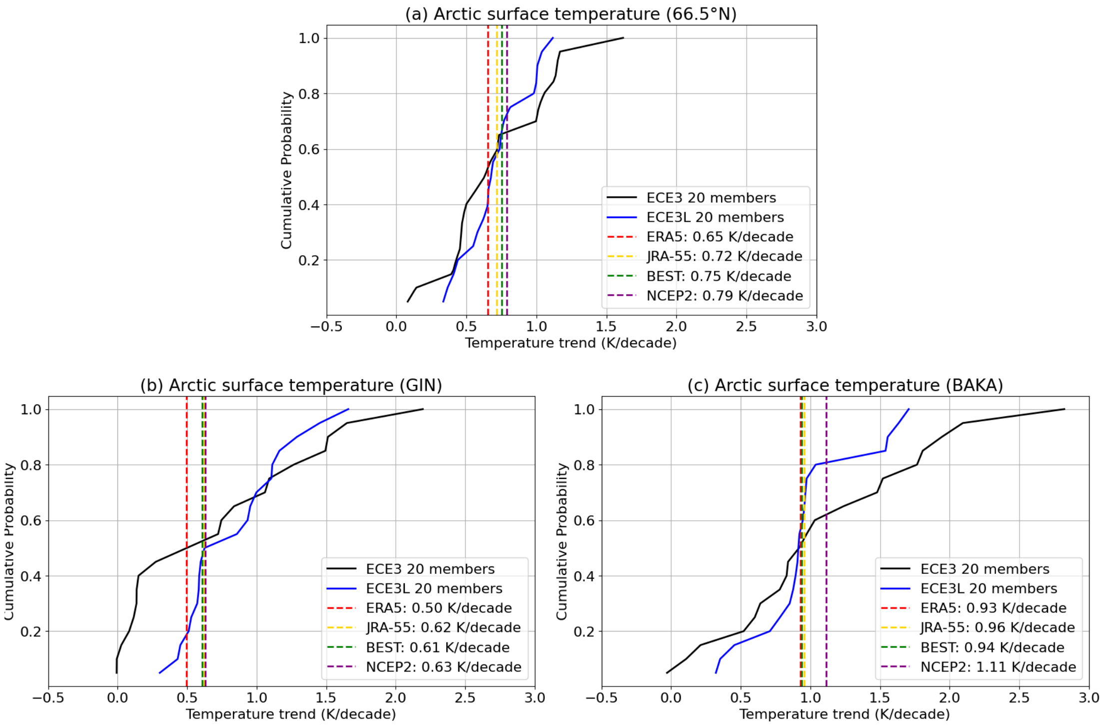

Figure S10. Cumulative Distribution Function (CDF) plots for surface air temperature trend from ECE3 and ECE3L ensembles: (a) in the Arctic region (north of 66.5°N), (b) the Greenland-Iceland-Norwegian Seas (GIN: 40°W-15°E, 66.5°N-82°N), and (c) the Barents and Kara Seas (BAKA: 15°E-100°E, 70°N-82°N). Observations are from ERA5 (Hersbach et al., 2020), Berkeley Earth (BEST, Rohde and Hausfather, 2020), JRA-55 (Kobayashi et al., 2015) and NCEP2 (Kanamitsu et al., 2002).

In the Arctic, ECE3L simulates trends that are not only closer to the observed values but also with less variability compared to ECE3. This indicates that ECE3L more accurately captures the overall warming in the Arctic. In GIN, ECE3L exhibits a narrower distribution of temperature trends, demonstrating a closer alignment with the reference observational datasets. ECE3, in contrast, shows greater variability and tends to predict slightly higher warming trends than the observed references. In BAKA, ECE3L performs better than ECE3 by closely aligning with the observed warming trends. While some ECE3L estimates exceed 1.0 K/decade, it still provides a more accurate and consistent representation of temperature trends in this region compared to ECE3. Overall, these results suggest that ECE3L improves the representation of Arctic warming trends, particularly in terms of reduced variability and better alignment with observed data across key Arctic regions.

Because Fig.S10b shows indistinguishable differences of global mean T2m anomaly between ECE3 and ECE3L, we decided to remove the original Fig.S10a,b and replace them with the CDF plots.

Appendix:

11.L480: units are missing from a1 and a2.

We added units: a1 in units: m^2K^{-1} and a2 in units m.

12.L481: is it not too large for winter Arctic Atmospheric Boundary Layer? Maybe add the expected and reasonable values for comparison.

We will add an explanation for the two extreme conditions in the appendix. *"This range of λCBL was derived from the original LES simulations which were tested on extreme cases of strongly stable stratification (30.7 K/km) to weak stratification (9.7 K/km). We therefore concluded that this was not an unreasonable limit to the resultant values for λCBL as we did not find more strongly stable stratifications than this in the lowest model level."*

13.Supplement figures: What is the goal of them: do the authors intent to keep them there (please revise the captions then with attention), or ultimately discard them?

Thank you for the suggestion. We will revise the figure captions to highlight the purpose of supporting materials and withdraw unimportant figures.

Fig. S1: We will add "*The figure illustrates the modulation of turbulent heat fluxes over sea ice, showing remarkable seasonal variation and such effect in different magnitudes between ExpCold and ExpWarm scenarios, particularly in regions with sea ice thicker than 1 m."*

Fig. S2-S3: As response to reviewer #1, major comment 2, we merged Fig.S2 and S3 to one and added the transient (r5) simulation (historical + SSP2-4.5, red) experiments from 1965-2065, to illustrate the effect of initial sea ice states and external forcing. We will add "Figure S2. *Yearly mean Arctic sea ice area (a), Arctic sea ice volume (b) and global 2-meter air temperature (c) from 1965 to 2065, comparing the ECE3 (black), ECE3L (blue), and transient (r5) simulation (historical + SSP2-4.5, red) experiments. Results from the 1985-forcing experiments are shown for the period 1985–2035, while results from the 2015-forcing experiments cover the period 2015–2065.*

The changes in sea ice area and volume from ECE3 to ECE3L shows notable differences between the ExpCold and ExpWarm setups, revealing the sensitivity of sea ice evolution to initial seat ice conditions and external forcing, with relatively more sea ice reduction in ExpCold. The paired simulations are stable over the 50 year period in both forcing experiments, with no significant warming trends attributable to initialization artifacts. This stability is reflected in the absence of noticeable temperature drift in both forcing periods. In contrast, the transient simulation (r5), driven by historical and SSP2-4.5 external forcings, shows a clear warming trend over time. The small fluctuations in ECE3 and ECE3L are consistent with internal variability, indicating that the model does not exhibit any pronounced initialization-induced warming."

Figure S4: We will add "*In summer the regions experiencing the greatest SIT reduction remain consistent with those identified in the winter, as shown in Fig. 3: from the eastern Arctic in the thicker ice regions in ExpCold shifting to the western Arctic in the thinner ice regions in ExpWarm."*

Figure S5: We will add "*In summer the regions experiencing the greatest SIC reduction remain consistent with those identified in the winter, as shown in Fig. 4. These are primarily in the thinner ice regions, typically along the ice margins, with up to 30% reduction in ExpCold compared to less than 20% in ExpWarm.*"

Figure S6: We will add "*The regions showing the greatest SIC reduction in March and September climatologies are similar to those observed in ExpCold (Figs. 4a,b and S5a,b), though the magnitude of the reduction is lower compared to ExpCold.*"

Figure S7: We will remove this figure, as the comparison with OSI-450a observations leads to the same conclusion as Fig. 11.

Figure S8: We will remove this figure for the same reason as Figure S7.

Figure S9: We will remove this figure for the monthly comparison of IIEE time series, as ECE3L consistently shows lower errors in sea ice edge representation across all seasons. We think Fig.12 is sufficient to present the IIEE for September and March, highlighting the errors during the sea ice minimum and maximum conditions.

Figure S10: As reply to comment 10, we will replace the figure of annual mean evolution of Arctic and global T2m anomalies from ECE3 and ECE3L ensembles with the CDF plots for the Arctic, the GIN seas and the BARA seas.

The CDF analysis visually and statistically captures differences in the variability and central tendencies between the two ensembles. In the Arctic (a), ECE3L shows a closer match to observed trends, reflecting reduced variability and a more accurate central tendency compared to ECE3. In the GIN and BAKA seas (b&c), showing relatively pronounced changes in Fig.13, the CDF analysis highlights regional differences in ensemble performance, with ECE3L again demonstrating better alignment with observations. These plots provide insight into how each ensemble simulates warming trends in both the Arctic as a whole and in key sub-regions, helping to understand spatial variations in model performance.

Reference:

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