

Response to Reviewers for EGUSPHERE-2026-1017

We would like to express my sincere gratitude to both reviewers for their thoughtful and constructive feedback and the Editor for considering the original manuscript. We offer our response with a number of substantive changes that remedy the editor and Reviewers' comments and concerns. We have made substantive changes to the manuscript in response to each Reviewer comment, which can be found below. We believe that the feedback we received and the new results and discussion that prompted have substantially improved the manuscript.

Reviewer comments are shown in plain text. Author responses are shown in bold text. Quotations from the revised manuscript are shown in *bold italics*. A bibliography for references cited is at the end of the document. The revised manuscript and the version of tracked changes will be uploaded with the editor's decision about the further handling of the manuscript.

Reviewer(s)' comments to Authors

Reviewer 1

General Comment

This manuscript examines the relationship between early-winter cold waves in South Korea and antecedent snow-cover variability over western Siberia. Using statistical analyses of station observations and reanalysis data, the authors identify reduced October snow cover over western Siberia as a precursor to enhanced cold-wave activity in December. They propose that associated land-atmosphere interactions and resulting circulation changes provide the physical mechanism linking western Siberian snow anomalies to cold conditions over South Korea.

Overall, the manuscript is well organized and generally easy to read. The logical flow is clear, and the discussion proceeds in a coherent and straightforward manner. The study may also have some novelty, particularly in its use of a revised cold-wave indicator for South Korea and in its focus on western Siberian snow cover, a factor that has received comparatively limited attention in previous studies of East Asian winter climate.

However, I also have important concerns precisely regarding these two aspects. The first concern is the scientific and meteorological interpretation of the newly introduced cold-wave definition. The second is the independence of the western Siberian snow-cover variability from the sea-ice variability in the nearby region. I provide more detailed comments below, but in my view, publication in this journal would be difficult to recommend unless these issues are properly addressed and the discussion is strengthened accordingly.

: We sincerely thank the Reviewer #1 for the careful evaluation of our manuscript and for recognizing its organization, clarity, and potential novelty. We particularly appreciate the reviewer's constructive comments regarding 'the interpretation of the revised cold wave definition' and 'the potential influence of nearby sea-ice variability on western Siberian

snow-cover variability'. We agree that these two issues are central to the interpretation and robustness of our study. In response to the reviewer's concerns, we have carefully reconsidered the meteorological meaning and applicability of the cold wave definition and have strengthened the relevant explanation and discussion in the revised manuscript. We have also conducted additional analyses to examine the independence of western Siberian snow-cover variability from the sea-ice variability in the nearby Barents–Kara Seas by assessing their respective associations with December cold-wave variability in South Korea.

The manuscript has been substantially revised to clarify these points and to avoid overstating the independence or causal role of western Siberian snow cover. Detailed responses to each major comments, together with the corresponding revisions and additional analyses, are provided below.

Major comment #1.

The authors have pointed out limitations in both the KMA cold day index and the cold wave advisory criteria, and then developed a revised cold day index for use in this study. I appreciate the attempt to improve the existing index. However, I think more careful consideration is needed regarding the interpretation of combining conditions (1) and (2) within a single index. As I understand it, condition (1) is intended to capture cases with a rapid temperature drop, even when the cold air itself is not particularly intense, whereas condition (2) is intended to capture cases with persistent and strong cold air. Since both types of events may have substantial social impacts, defining a warning criterion in terms of satisfying either one of the two conditions may be reasonable from an operational or public-advisory perspective.

However, from a scientific and meteorological viewpoint, the two types of events may be governed by rather different processes. For example, a day when the minimum temperature drops rapidly from 13°C to 3°C and a day when a very low temperature of around -15°C persists from the previous day are likely associated with substantially different meteorological conditions. In the present study, however, this distinction is not explicitly made. Instead, the authors construct a cold-day-based index (through the PC time series) and use it for regression and composite analyses without separating these two categories.

I therefore think that the revised cold day index requires a more careful discussion. For example, among the cold days identified by the revised criteria, what are the relative contributions of conditions (1) and (2)? My impression is that condition (2) may dominate, but if that is the case, the rationale for including condition (1) should be more clearly discussed. One possible justification might be that condition (2)-type events are relatively well represented in climate/forecast models, whereas condition (1)-type events are more difficult to capture, so including condition (1) could potentially improve prediction or forecasting. Even in that case, however, it may still be preferable to analyze conditions (1) and (2) separately.

: We thank the reviewer for this important comment. We agree that Criterion 1 and Criterion 2 may be associated with somewhat different short-term meteorological processes. Criterion 1 captures the rapid onset of cold conditions through an abrupt

decrease in minimum temperature, whereas Criterion 2 captures the severity and persistence of extremely low temperatures.

We acknowledge that Criterion 2 accounts for the majority of cold days identified by the revised cold day index, with Criterion 1 comprising approximately 7% of total cases. To examine whether the two criteria are indeed governed by fundamentally different processes, we performed the same correlation analysis using PC1 time series derived separately from Criterion 1-type and Criterion 2-type December cold days with October western Siberian snow cover. Criterion 1 showed a similar spatial pattern to Criterion 2, with both analyses producing negative correlation patterns over western Siberia, as shown in Fig. S4 (added in the supplementary), suggesting that the two criteria reflect complementary manifestations of cold-wave occurrence that share a common large-scale forcing.

Furthermore, despite accounting for a small proportion of the total cold days identified by the revised cold day index, Criterion 1 exhibits a statistically significant increasing trend during December over the study period, significant at the 90% level, suggesting that rapidly developing cold waves have become more frequent in recent decades. Sudden temperature drops are also known to be critical for human health (Ni *et al.*, 2025), and Criterion 2 alone cannot capture this category of events, which has shown a distinct increasing trend in recent decades. We therefore consider the revised cold day index, which integrates both criteria, to be more appropriate for comprehensively representing December cold wave variability in South Korea.

We also note the reviewer's suggestion that Criterion 1-type events may be more difficult to represent in climate and forecast models compared to Criterion 2-type events. While a detailed model evaluation is beyond the scope of our study, this observation further supports the importance of retaining Criterion 1 in an observation-based index intended to capture cold-weather hazards that may be systematically underrepresented in model-based analyses.

Regarding the reviewer's suggestion to analyze the two criteria separately, we note that Criterion 1 alone yields a limited number of cases during the study period, which would constrain the statistical robustness of regression and composite analyses. Nevertheless, the correlation maps derived separately for each criterion are provided in the revised manuscript as supplementary material to allow direct comparison, which is shown in Fig. S4. We have also documented the proportion of cold days satisfying each criterion and incorporated these statistics into the revised manuscript. We have further clarified in the revised text that the revised cold day index serves as a comprehensive indicator that integrates complementary characteristics of cold-wave occurrence in South Korea.

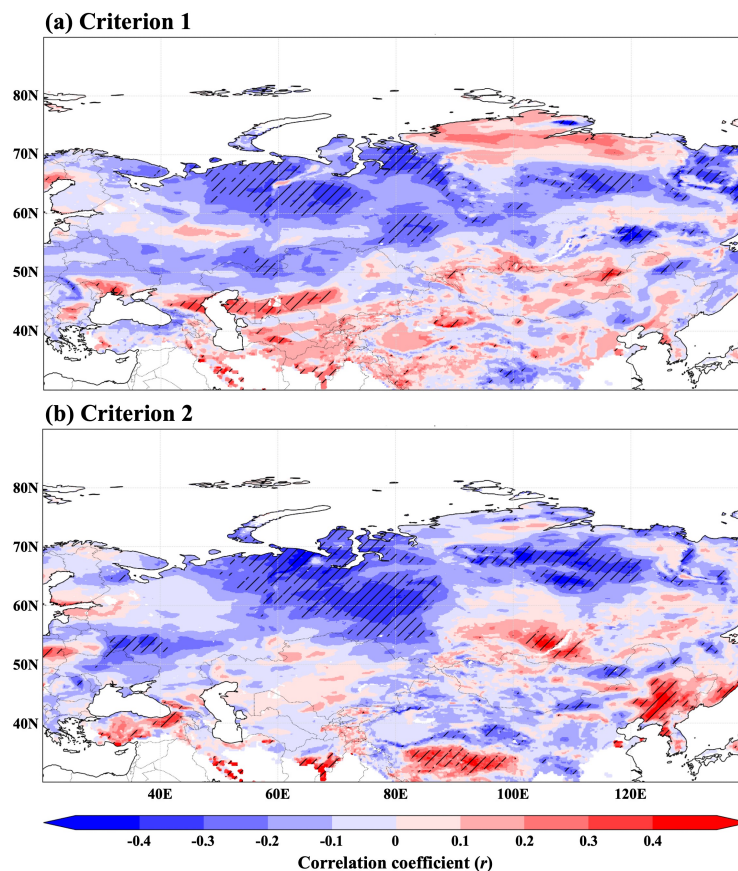
In L129, we have added

Although Criterion 1 represents a relatively small proportion of the cold day cases identified by the two criteria (7%), its December frequency exhibits a statistically significant increasing trend at the 90% confidence level. Also, both criteria were retained, as the combined single

index which more effectively captures the relationship between December cold wave variability and its large-scale atmospheric forcing than either criterion alone.

And in L276:

To examine whether the two criteria are governed by fundamentally different atmospheric processes, the same correlation analysis was also performed using PC1 time series derived separately from Criterion 1-type and Criterion 2-type December cold days with October snow cover. Criterion 1 showed a similar spatial pattern to Criterion 2, with both analyses producing negative correlation patterns over western Siberia, suggesting that the two criteria reflect complementary manifestations of cold wave occurrence that share a common large-scale forcing (Fig. S4).



Supplementary Figure S4. Correlations of October snow cover with (a) Criterion 1 and (b) Criterion 2 PC1 of the revised cold day index, respectively. Hatched areas indicate regions statistically significant at the 90% confidence level.

Major comment #2.

I find it interesting that this study focuses on western Siberian snow-cover variability, since relatively few previous studies have examined its relationship with East Asian winter climate. In fact, the analysis of the surface energy budget presented here clearly shows enhanced upward

heat transfer from the land surface to the atmosphere over regions of reduced snow cover in northern western Siberia during October, which strongly suggests an active role of land-surface processes.

: We thank the reviewer for this positive comment. We agree that the enhanced upward heat transfer over regions of reduced October snow cover provides strong support for the active role of land-surface processes.

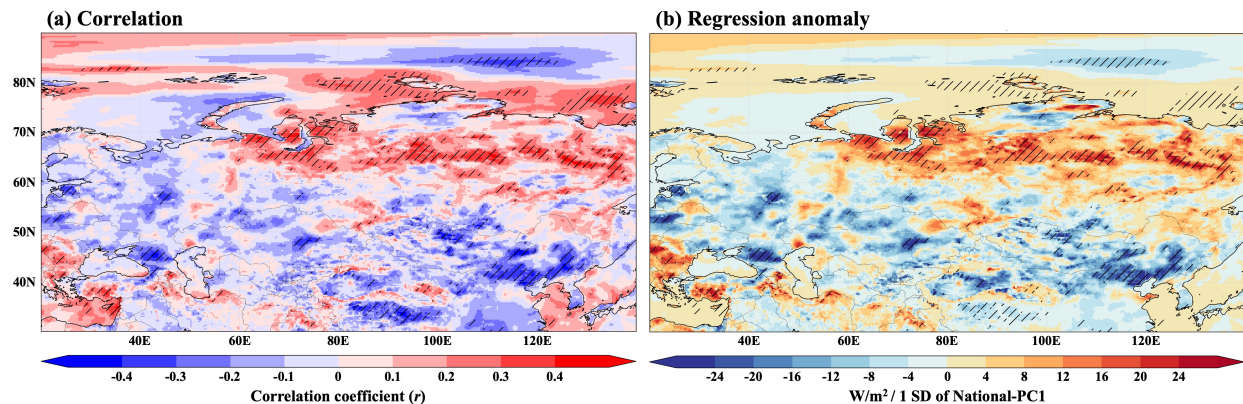
At the same time, however, this active region is located close to the Barents–Kara Seas (BKS), where sea-ice reduction from autumn to winter is among the largest in the Arctic. For this reason, I think the manuscript needs a more careful discussion of the extent to which the proposed role of western Siberian land processes is independent of, or coherent with, variability in nearby sea ice. In fact, a large number of previous studies have suggested that sea-ice reduction in the BKS can lead to cold conditions over East Asia. In addition to the studies already cited by the authors, several mechanisms have been proposed, such as the northward shift of cyclone tracks (Inoue et al., 2012), a stationary Rossby wave response to surface heating (Honda et al., 2009), and a shift toward the negative phase of the AO regime (Nakamura et al., 2015). Although these mechanisms differ in detail, they all involve enhanced anticyclonic circulation over Siberia (i.e., strengthened Siberian High) as a pathway toward East Asian cooling. In this respect, the mechanism proposed in the present manuscript appears analogous to those earlier interpretations.

: We agree that the proximity of the western Siberian land region to the Barents–Kara Seas makes it necessary to consider whether the identified snow-cover signal is independent of, or dynamically coherent with nearby sea-ice variability. We also agree that the anomalous anticyclonic circulation over Siberia identified in our study resembles the circulation responses reported in previous studies of Barents–Kara sea ice reduction, including changes in cyclone tracks, stationary Rossby wave responses to surface heating, and a shift toward the negative phase of the AO. At Line 394, we added new lines. Please refer below.

Therefore, the authors should discuss much more carefully whether the snow-cover variability over western Siberia acts independently of sea-ice variability, or whether the two vary coherently and jointly contribute to the atmospheric response. For example, in Fig. 5, it may be useful to calculate regression anomalies with respect to one standard deviation of the National-PC1 time series, using ERA5 also over the ocean, so that the magnitudes of surface flux anomalies over land and ocean can be directly compared. If this is done, how large is the land contribution relative to the oceanic flux anomalies that may be associated with sea-ice loss?

: We thank the reviewer for this constructive suggestion, which allowed us to more rigorously quantify the relative contributions of western Siberian snow cover and Barents–Kara Sea ice variability. Following the reviewer's suggestion, we performed a regression analysis between the National-PC1 time series and October turbulent heat flux from ERA5, extended over both land and ocean, and calculated the flux anomaly associated with one standard deviation of National-PC1 (Supplementary Figure S5).

The results reveal that statistically significant positive flux anomalies are more spatially coherent and of greater magnitude over the western Siberian land surface than over the BKS. Specifically, the regression analysis shows upward turbulent heat flux anomalies exceeding 20 W/m^2 per 1 SD of National-PC1 over inland western Siberia, whereas anomalies over the BKS Sea remain less than 4 W/m^2 per 1 SD of National-PC1. Although this analysis does not allow us to fully disentangle the interacting effects of snow cover reduction and sea ice loss, but it provides quantitative evidence that the snow cover reduction in western Siberian is more strongly associated with December cold-wave variability in South Korea than sea ice variability in the BKS.



Supplementary Figure S5. (a) Correlation analysis between National-PC1 and October ERA5 upward turbulent heat flux. (b) Regression anomaly of October ERA5 upward turbulent heat flux with respect to 1 standard deviation of National-PC1. Hatched areas indicate regions statistically significant at the 90% confidence level.

More directly, it may also be useful to add to Fig. 3b a time series of October snow-cover area over western Siberia, together with an index of BKS sea-ice area in September or October, and then examine their correlations with the National-PC1 and cluster time series. If the authors can demonstrate either that western Siberian snow-cover variability is largely independent of sea-ice variability, or that even if they vary coherently, the land-atmosphere interaction proposed here amplifies the impact in a physically meaningful way, then the value of this study would become much clearer.

In this context, previous approaches may be useful as references. For example, statistical removal of the component coherent with sea-ice variability (McCusker et al., 2016) or climate-model experiment designs that isolate the sea-ice impact (Nakamura et al., 2019) may provide helpful guidance. At the very least, the manuscript should discuss its results in light of such previous studies.

: Thank you for the suggestion. As noted by the reviewer, we conducted additional analyses to examine whether the relationship between western Siberian snow cover and December atmospheric circulation could be distinguished from variability in Barents–Kara Sea ice (Supplementary Table S1).

We first calculated area-averaged October ERA5-Land snow cover over western Siberia (55–90° E, 55–70° N, SC-WS) and ERA5 sea-ice concentration over the Barents–Kara Seas (40–100° E, 70–85° N, SIC-BKS). Using the original and non-detrended time series, respectively, October SC-WS showed a statistically significant negative correlation with the National-PC1 time series ($r = -0.371$, $p < 0.05$). October SIC-BKS also showed a negative correlation with National-PC1, but the strength was weaker ($r = -0.268$, $p < 0.10$).

Because October SC-WS and SIC-BKS may covary, we further conducted a partial correlation analysis to determine whether the relationship between SC-WS and December atmospheric circulation remained after statistically controlling for SIC-BKS. For this analysis, linear trends were removed from October SC-WS, October SIC-BKS, and December 500 hPa geopotential height (Z500) before the calculations. December Z500 was spatially averaged over the region encompassing the western Siberian anticyclonic anomaly shown in Figure 6 (55–100° E, 55–75° N). Specifically, detrended SC-WS and detrended Z500 were separately regressed onto detrended SIC-BKS, and the partial correlation was calculated between the residuals from the two regressions.

The detrended October SC-WS and SIC-BKS time series were significantly correlated ($r = 0.350$, $p < 0.05$). However, after controlling for detrended October SIC-BKS, the partial correlation between detrended October SC-WS and detrended December Z500 remained significant ($r = -0.280$, $p < 0.10$). This value was similar to the correlation before controlling for SIC-BKS ($r = -0.296$, $p < 0.05$), indicating that accounting for SIC-BKS variability only slightly weakened the relationship between SC-WS and Z500.

Supplementary Table S1. Correlation and partial-correlation analyses among October western Siberian snow cover (SC-WS), Barents–Kara Sea sea ice concentration (SIC-BKS), December 500 hPa geopotential height (Z500), and the December National-PC1 time series.

Analysis	Variables	Controlled variable	Data treatment	r	p-value
Pearson correlation	October SC-WS vs National-PC1	—	Original time series	-0.371	**
Pearson correlation	October SIC-BK vs National-PC1	—	Original time series	-0.268	*
Pearson correlation	October SC-WS vs October SIC-BK	—	Linearly detrended	0.350	**
Pearson correlation	October SC vs December Z500	—	Linearly detrended	-0.296	**
Pearson correlation	October SIC vs December Z500	—	Linearly detrended	-0.101	<i>n.s.</i>
Partial correlation	October SC vs December Z500	October SIC	All variables linearly detrended	-0.280	*

** $p < 0.05$, * $p < 0.1$, *n.s.* $p > 0.1$

These results show that the relationship between October SC-WS and December Z500 remains after statistically accounting for SIC-BKS. We have therefore revised the manuscript to clarify that western Siberian SC variability is associated with December

atmospheric circulation beyond the linear variability shared with nearby SIC along with the discussion as follows.

L394: *It is noteworthy that the anticyclonic anomaly identified in this study is similar to the atmospheric responses associated with Barents-Kara Sea (BKS) sea ice loss discussed in previous studies. Reduced BKS sea ice is known to be linked with a northward shift of cyclone tracks (Inoue et al., 2012), a stationary Rossby wave response to anomalous surface heating over the Arctic Ocean (Honda et al., 2009), and a shift toward the negative phase of the Arctic Oscillation (Nakamura et al., 2015). Although the detailed mechanisms differed among these studies, they commonly showed similar enhanced anticyclonic circulation patterns over Siberia and subsequent cooling over East Asia. Therefore, the circulation pattern identified in this study may be partly similar to the atmospheric response to BKS sea ice loss. However, our results indicate that thermodynamic changes associated with reduced SC over the western Siberia may also contribute to the anticyclonic anomaly.*

As western Siberian SC and BKS sea ice are geographically close and may be associated with similar atmospheric circulation patterns, their variability may not be fully independent. We therefore examined their respective relationships with December cold wave variability in South Korea. The results showed that October Western Siberian SC showed relatively stronger correlation with December cold wave variability than October BKS sea ice concentration (Supplementary Figure S5). In addition, the relationship between western Siberian SC and December atmospheric circulation remained statistically significant even after controlling for the linear influence of BKS sea ice concentration using partial correlation analysis (Supplementary Table S1). The results indicate that western Siberian SC is associated with December cold wave variability even after accounting for the variability shared with BKS sea ice concentration. However, these analyses cannot fully separate the effects of SC reduction and sea ice loss or determine the causal relationship between them. Further studies using nonlinear causality analysis and climate model experiments are therefore needed to clarify the individual and combined effects of western Siberian SC and BKS sea ice loss on early-winter cold waves in South Korea.

Minor comments

- I did not notice any obvious problems with the English.
- The references appear generally appropriate and consistent with the citations in the text.

: Thank you for the double check.

- When presenting maps of regression or correlation coefficients, such as in Figs. 4d–f, 5, and 8, it may be (in some cases) more informative to show regression coefficients corresponding to one standard deviation of the explanatory variable.

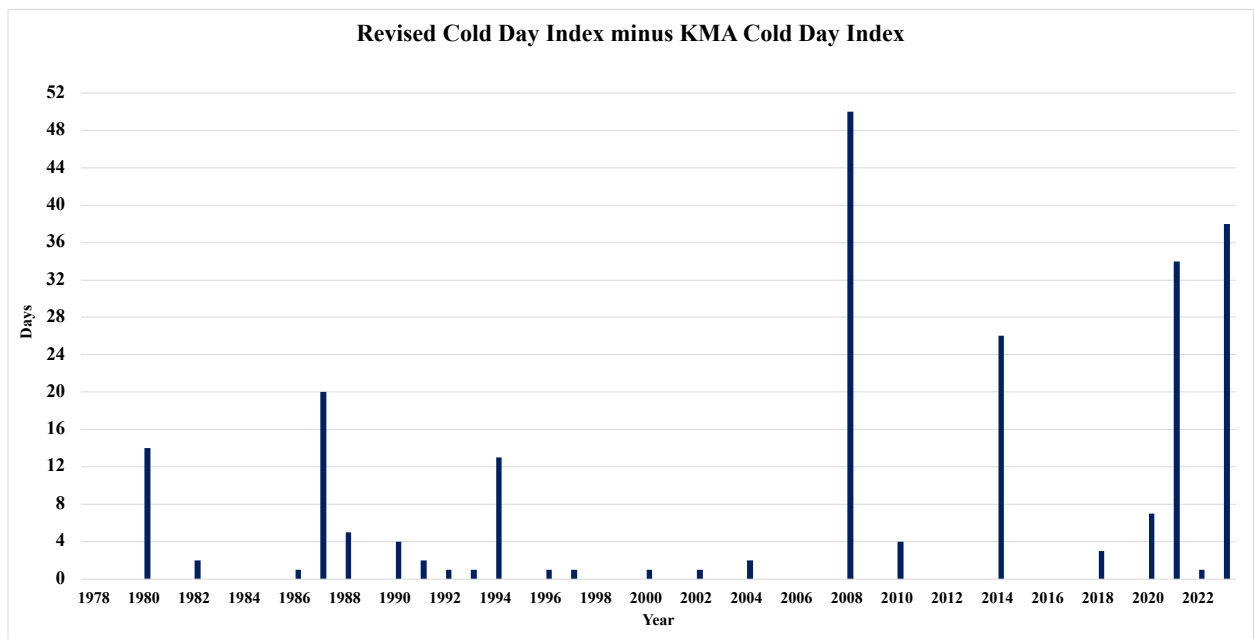
: Thank you very much for the suggestion. We've added the regression coefficient map for Fig 5c and for Figs 4d-f in the supplementary material.

- The benefit of applying the k-means cluster analysis is not entirely clear to me. I wonder whether this part could be moved to the Supplementary Material.

: Changed accordingly.

- In Table 1, how different are the three definitions (the two previous ones and the revised one) in terms of, for example, time series?

: The revised cold day index could be understood as mixture of KMA cold day index and cold wave advisory criteria. However, as mentioned in Section 2.2.1, we could not directly calculate cold wave advisory criteria for two reasons. First, we could not calculate the climatological normal (seasonal average), and criterion 3 depends on forecasters' subjective judgements. Therefore, we only compared with the cold day index defined by the KMA (Responding Figure R1). The results show the differences of the revised cold day index, based on the number of Criterion 1-type cold days, from the KMA cold day index in South Korea.



Responding Figure R1. Differences of December cold day between revised cold day index and KMA cold day index in South Korea.

References

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