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LETTER

Recent increase in snow cover as a contributing driver to autumn cooling in central Eurasia

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Abstract

In the context of global warming, autumn air temperatures in central Eurasia have exhibited a cooling trend over the past two decades. However, the extent to which snow cover contributes to the cooling remains unclear. This study reveals that despite a general decrease in global snow cover extent, the autumn snow cover percentage over central Eurasia has increased by 5.38% per decade in the past two decades. Quantitative assessments indicate that the contribution of this increase in snow cover to the observed cooling was 21.5%. We also found that the increase in snow cover leads to a reduction in net shortwave radiation, which is the primary mechanism of the cooling effect induced by snow cover. This study advances our understanding of the evolution of the global climate system and provides scientific support for addressing climate change.

1. Introduction

Despite the unequivocal reality of global warming, extreme cold events occur frequently worldwide (Lubitz *et al* 2024). For example, during the winter of 2022–2023, bomb cyclones or epic cold waves severely impacted the United States, affecting more than 200 million people (Cuff 2023). Similarly, during the autumn of 2022, China experienced frequent cold waves, with abrupt temperature drops that adversely affected public transportation and agricultural activities. This event was listed among the top ten weather and climate events in China for 2022 by the China Meteorological Administration. Recent studies (Li *et al* 2020, Tang *et al* 2022) have revealed that a cooling trend has emerged in central Eurasia in autumn since 2004, although the driving mechanisms remain unclear. While numerous studies have focused on qualitatively addressing the coupling relationships between snow cover changes in summer and spring and temperature variations in different regions of the Northern Hemisphere (Preece *et al* 2023, Webster *et al* 2024), the quantitative contribution of snow cover changes to cooling remains uncertain (Henderson *et al* 2018, You *et al* 2020). Therefore, within the context of global warming, quantitatively assessing the feedback effect of Eurasian snow cover changes on autumn cooling can provide systematic insights for the early warning of extreme weather and climate events, as well as for disaster prevention and mitigation.

Approximately 98% of the Earth's seasonal snow cover is located in the Northern Hemisphere, with Eurasian winter snow accounting for 60%–65% of the Northern Hemisphere's total snow cover. In this study, central Eurasia refers to the vast area generally defined by 40°–65° N and 50°–130° E (figure 1). Variations in snow cover in this region have important implications for regional and global climates (Peng *et al* 2024, Mekonnen *et al* 2025).

Building on previous research advancements, the primary objectives of this study are as follows: (1) to localize the Weather Research and Forecasting (WRF) model for Eurasia and validate its simulation

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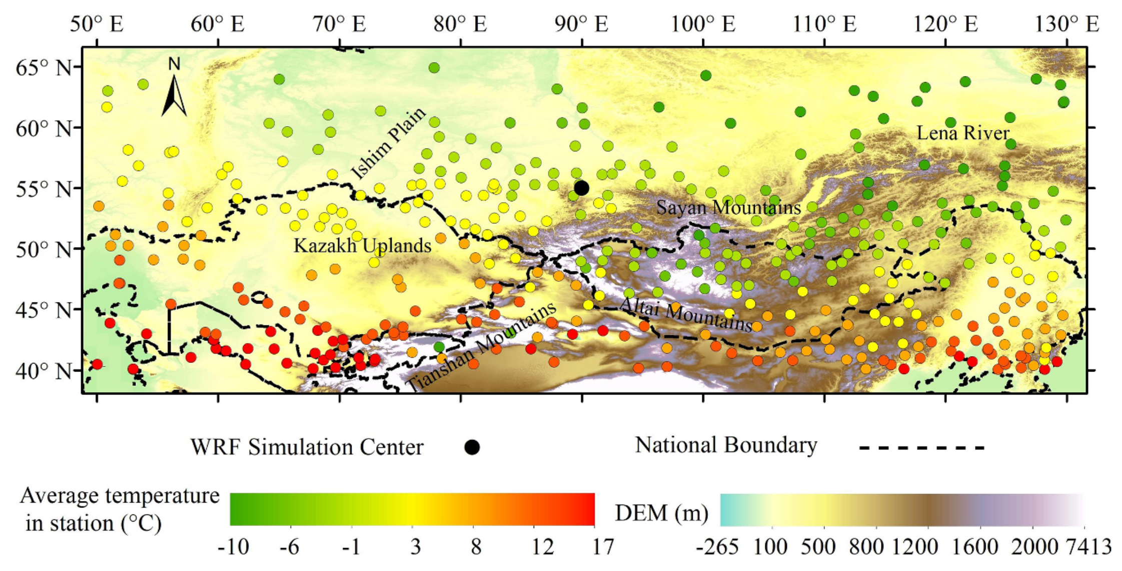

Figure 1. Location of central Eurasia and the meteorological stations.

performance; (2) to analyze the spatiotemporal characteristics of autumn air temperature changes in central Eurasia from 2004 to 2020 based on WRF model simulations; (3) to examine the spatiotemporal variations in the snow cover percentage (SCP) and snow cover frequency (SCF) via the Interactive Multisensor Snow and Ice Mapping System (IMS) snow and ice products; (4) to quantitatively assess the contribution of snow cover changes to autumn cooling via control and sensitivity experiments with the WRF model; and (5) to elucidate the mechanisms by which snow cover changes influence autumn air temperature fluctuations from the perspectives of radiative components and energy fluxes. The findings of this study can provide significant insights into predicting future regional climate change trends and formulating adaptive strategies.

2. Data and methods

2.1. Data

Snow cover data from 1 January 2004, to 31 December 2020, were obtained from the IMS product provided by the National Snow and Ice Data Center. The data have a spatial resolution of 4 km and a temporal resolution of 1 d, offering cloud-free daily snow cover information for the Northern Hemisphere (Helfrich *et al* 2007, Frei and Lee 2010).

To validate the reliability of snow cover variation results, the autumn central Eurasian SCP presented in this study was compared with the Eurasian snow cover extent dataset published by the Rutgers University Global Snow Lab (https://snowcover.org, Robinson and Frei 2000, Estilow *et al* 2015).

The ERA5 reanalysis dataset was used as the driving data for the WRF model. ERA5 data (Hersbach *et al* 2020), released by the European Center for Medium-Range Weather Forecasts, have a spatial resolution of 0.25° × 0.25° and a temporal resolution of 1 h. These data have been widely used in temperature-related research (Ou *et al* 2020, Yang *et al* 2021). The study period covers each year from 31 August, 00:00 UTC, to 1 December, 00:00 UTC, from 2003 to 2020.

To evaluate the reliability of the WRF model simulation results, the relationship between the simulated daily air temperatures and the observed meteorological station data was analyzed. Air temperature data from meteorological stations were sourced from the National Centers for Environmental Information. Stations with more than 20% of missing temperature data for a given month were excluded. Ultimately, 408 daily meteorological observation stations within the study area (40–65° N, 50–130° E) during autumn from 2004 to 2020 were selected for analysis (figure 1).

To further validate the temperature simulation results from the WRF sensitivity experiments, the relationship between the Climate Research Unit (CRU) temperature data and the simulated temperature was analyzed. The CRU temperature data, provided by the CRU of the University of East Anglia, had a spatial resolution of 0.5° × 0.5°. The study utilized CRU TS v4.05 (CRU Time Series version 4.05) for the period 2004–2020 (https://crudata.uea.ac.uk/cru/data/hrg/).

The annual land use data for the WRF model from 2003 to 2020 were derived from the MODIS Land Cover Type product (MCD12C1), with a spatial resolution of 0.05° × 0.05°.

2.2. Methods

We employed SCP and SCF to represent changes in snow cover (text S1).

To ensure the reliability of simulation results, we conducted regional localization of the WRF model. The simulation results were validated using observational data from 408 meteorological stations and the CRU reanalysis air temperature data.

To evaluate the performance of the different experimental schemes, three performance metrics were used: correlation coefficient (CC), root mean squared error, and mean bias. The Mann–Kendall method was used to test the significance of trends in snow cover and autumn temperature changes.

Using the surface energy balance equation combined with the simulation results from the WRF model, we calculated the changes in energy flux and radiation flux caused by variations in snow cover.

The analysis of climate element trends in time series primarily utilized a univariate linear equation between climate elements and time series to reflect the temporal variation characteristics of the climate elements (text S1).

3. Results

First, to localize a WRF model suitable for the unique geographical conditions and complex terrain of Eurasia, 12 parameterization schemes were designed based on previous research findings (text S1 and table S1). The performance of these parameterization schemes was evaluated using observed temperature data from 408 meteorological stations and CRU reanalysis data, considering both temporal and spatial perspectives. The optimal parameterization scheme was identified via this evaluation (tables S2 and S3, and figures S1–S3).

Temporally, the simulated autumn mean air temperature (2004–2020) of the WRF model exhibited highly significant correlations ($P < 0.001$) with the observed air temperature and CRU temperature data, with CCs of 0.948 and 0.978, respectively (figure 2(a)). Spatially, the CCs between the simulated and observed air temperatures, and between the simulated and CRU temperatures, were 0.985 and 0.974, respectively (figure 2(b)). These results indicate that the localized WRF model can accurately capture the spatiotemporal characteristics of autumn air temperature variations in the study area.

To further investigate the impact of snow cover changes on air temperature variations, control and sensitivity experiments were designed based on the localized WRF model (text S1 and table S4). In the control experiment (CTL), the actual autumn temperature variations in the study area from 2003 to 2020 were simulated, whereas in the sensitivity experiment (SEN), autumn temperatures from 2004 to 2020 were simulated solely with snow cover changes. The results of the SEN experiment reflected the temperature variations attributable solely to snow cover changes.

Second, we analyzed the spatiotemporal characteristics of autumn temperature variations. Temporally, the simulated autumn mean temperature in central Eurasia from 2004 to 2020 exhibited a non-significant declining trend, with a rate of change of −0.867 °C per decade (figure 2(c)). Notably, during 2004–2016, the autumn temperature showed a significant ($P < 0.05$) declining trend, with a rate of change of −2.15 °C per decade.

To further validate the control experiment results, a comparative analysis was conducted between the simulation results of this study and the findings of existing research (Li *et al* 2020). The results revealed a significant ($P < 0.05$) cooling trend from 2004 to 2018, with a rate of change of −1.425 °C per decade, which is consistent with prior findings. Spatially, from 2004 to 2020, the areas in central Eurasia with declining temperatures accounted for 98.21% of the total study area (figure 2(d)).

Third, we analyzed the spatiotemporal variations in autumn snow cover. From 2004 to 2020, the multiyear mean SCP in central Eurasia during autumn was 29.75%. The mean autumn SCP in central Eurasia from 2004 to 2020 exhibited a significant ($P < 0.05$) increasing trend, at a rate of 5.38% per decade (figure 2(e)), whereas the SCP during the other seasons showed a decreasing trend (figure S4). Moreover, the variations in autumn central Eurasian SCP during 2004–2020 demonstrated strong consistency with trends in Eurasian fall snow cover extent, exhibiting a statistically significant correlation ($R = 0.93$, $P < 0.001$).

Spatially, the distribution of SCF from 2004 to 2020 revealed significant variability across central Eurasia (figure S5). Generally, the SCF demonstrated clear latitudinal zonality, thereby increasing with latitude, and higher SCFs were observed in regions with relatively high elevation. Statistical analysis indicated that in most areas of central Eurasia, the SCF was less than 40%, covering 2.98×10^5 km^2 (accounting for 66.33% of the total area). Regions with SCF values exceeding 60% were primarily concentrated in high-altitude areas, such as the Tianshan Mountains, Altai Mountains, Sayan Mountains, and the Lena River Plateau, with a total snow-covered area of 0.19×10^5 km^2 (accounting for 0.04% of the total area).

Based on the spatial distribution of these trends (figure 2(f)), the area showing an increasing trend in the autumn SCF from 2004 to 2020 was 4.02×10^5 km^2 (accounting for 89.32% of the total area), of which 0.56×10^5 km^2 (12.56%) exhibited a significant increasing trend ($P < 0.05$). These significant increases were primarily concentrated in regions

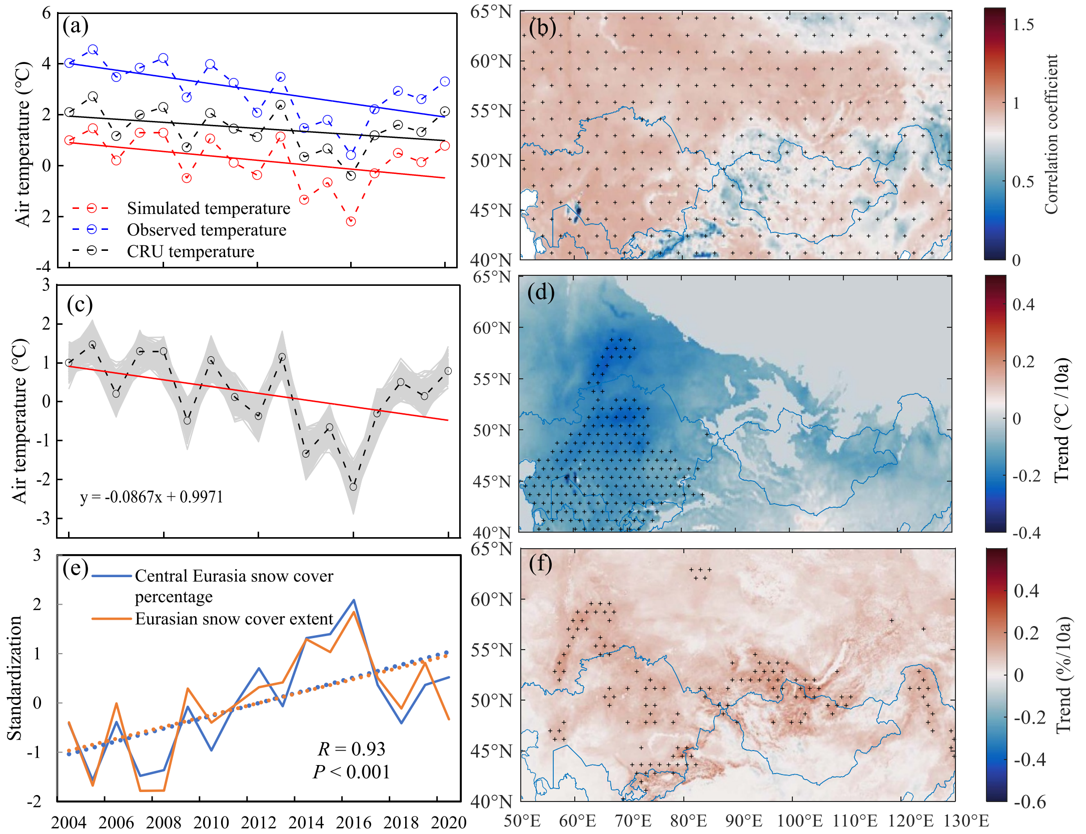

Figure 2. Comparison of autumn temperature time series in central Eurasia (2004–2020) between the simulated temperature of the control experiment, CRU temperature, and station-observed temperature (a); correlation coefficients between the simulated and CRU temperatures ((b), the black dots denote coefficients passing the significance level at $P < 0.05$); temporal variations in the simulated mean autumn temperature (2004–2020) ((c), the grey lines indicate the mean temperature time series from 1% ($n = 870$) of randomly selected grids (300 iterations) in the study area; the black line indicates the average of the grey lines; the red line indicates the linear trend of the black line data) and spatial trends ((d), the black dots denote trends passing the significance level at $P < 0.05$); temporal trends of the snow cover percentage or extent during 2004–2020 (e); and spatial trends of the snow cover frequency ((f), the black dots denote trends passing the significance level at $P < 0.05$).

such as the Tianshan Mountains, Altai Mountains, Sayan Mountains, parts of the Kazakh Hills, and Ishim Plain. In contrast, the area with a decreasing trend in the SCF was 0.35×10^5 km^2 (7.78%), which was located mainly in the Caspian lowlands, Turpan Basin, and its surrounding areas. However, regions with a significant decreasing trend ($P < 0.05$) accounted for only 0.06% of the total area.

Fourth, we quantitatively evaluated the contribution of snow cover change to autumn cooling. In terms of temporal variation, the trend in autumn temperature fluctuations caused by changes in snow cover (as determined in the sensitivity experiment; figure 3(a), at a rate of −0.187 °C/decade, closely matched the temperature variation simulated in the control experiment (figure 2(c)), with a CC R of 0.65 ($P < 0.05$). Spatially, snow cover changes induced a general cooling trend across the study area, and the spatial pattern of the cooling trends resembled that of the control experimental results (figure 3(b)). These findings suggest that changes in autumn snow cover in Eurasia can partially explain the observed variations in autumn temperatures. To minimize the potential influence of the selected study period on the results, we quantitatively assessed the contribution rates of snow cover changes to autumn temperature trends across different periods (2004–2016, 2004–2018, and 2004–2020). The results revealed that the contribution rates of snow cover changes to autumn temperature trends ranged from 21.54% to 24.59% across different periods (figure 3(a)).

In terms of the spatial temperature correlation (figure S6), the regions where the autumn temperatures obtained in the sensitivity and control experiments passed the significance test ($P < 0.05$) exhibited high correlations ($R > 0.6$). These regions were primarily concentrated in the central part of the study area (45–55° N), which accounted for 54% of the total study area. The relatively high CCs indicate that the autumn temperature changes obtained in the sensitivity experiment could better explain the temperature variations observed in the control experiment.

Fifth, we analyzed the feedback mechanism of snow cover changes during cooling. First, we examined the relationships between the autumn temperatures simulated in the control experiment and

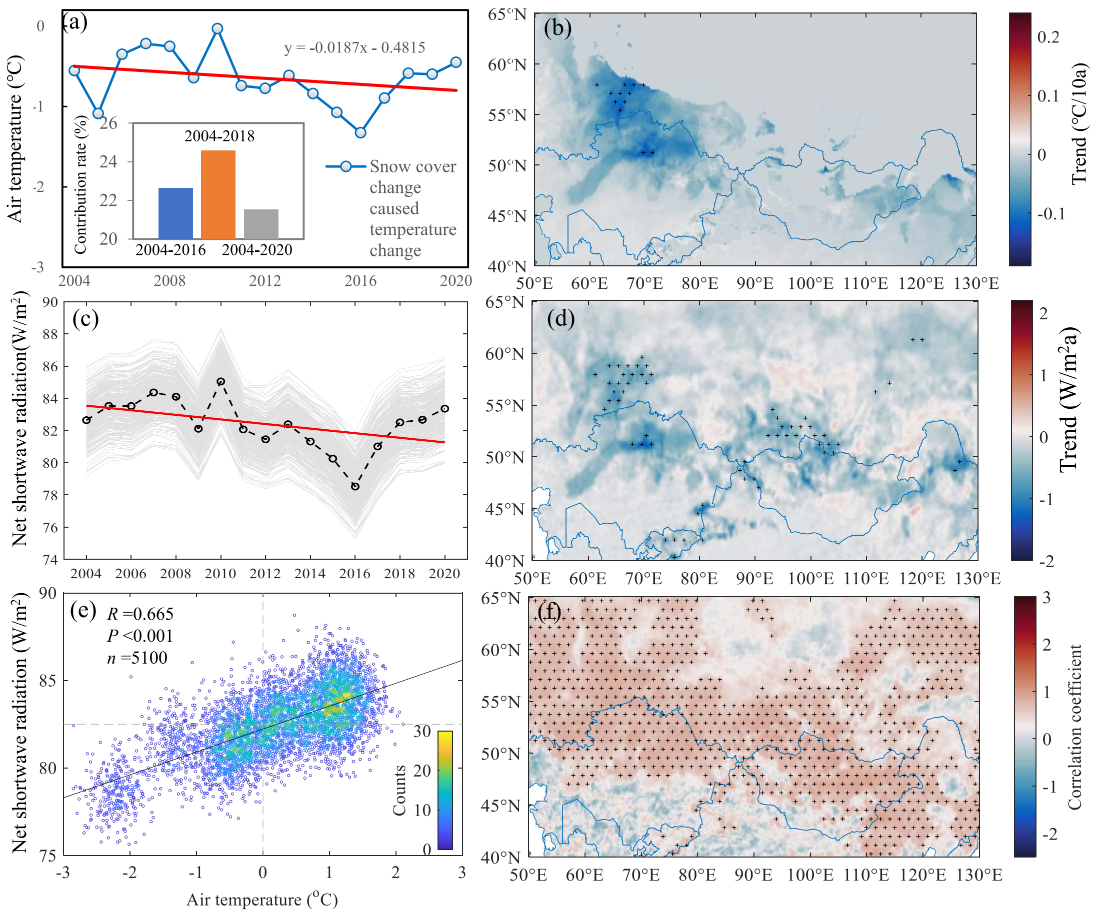

Figure 3. Trends in temperature changes induced by snow cover (sensitivity experiment) and the contribution of snow cover changes to temperature variations across different periods (a); spatial trends of temperature changes induced by snow cover (sensitivity experiment) (b); trends in net shortwave radiation changes induced by snow cover based on 300 random samples (1% of all grid points) (c); spatial trends of net shortwave radiation changes induced by snow cover (d); scatter plot of the net shortwave radiation versus the actual temperature (e); spatial correlation map of net shortwave radiation with the actual temperature at corresponding grid points (f).

various radiation components obtained in the sensitivity experiment (induced by snow cover changes). The results for the 2004–2020 period revealed that the mean temperature was significantly negatively correlated with upward shortwave radiation ($R = -0.85$, $P < 0.001$) and significantly positively correlated with upward longwave radiation ($R = 0.55$, $P < 0.05$), net shortwave radiation ($R = 0.87$, $P < 0.001$), net radiation ($R = 0.73$, $P < 0.001$), soil heat flux ($R = 0.75$, $P < 0.001$), latent heat flux ($R = 0.59$, $P < 0.05$), and sensible heat flux ($R = 0.85$, $P < 0.001$).

To identify the primary factors influencing temperature changes, stepwise regression analysis was performed to construct a regression model between temperature and various radiation fluxes. The results indicated that only the net shortwave radiation was included in the model. This finding suggests that the reduction in net shortwave radiation due to increased snow cover is the primary mechanism behind the snow-induced cooling effect, accounting for 70% of the total contribution to snow cover changes.

Changes in snow cover resulted in a decreasing trend in net shortwave radiation (figure 3(c)), with a rate of -0.16 W $m^{-2}\cdot a$. To minimize the potential influence of changes in net shortwave radiation in specific regions on the results, a random sampling of 1% ($n = 870$) of all grid points was conducted 300 times. The results revealed that the net shortwave radiation across Eurasia exhibited a consistent decreasing trend, with fluctuations similar to those in temperature changes. Spatially, the spatial trends in net shortwave radiation were also broadly consistent with the cooling trends (figure 3(d)).

To further examine the relationship between temperature and net shortwave radiation, random sampling (1%, $n = 870$) was conducted 300 times for autumn temperatures and net shortwave radiation each year. The relationship between mean autumn temperature and net shortwave radiation from 2004 to 2020 was then calculated. The results revealed a CC of 0.665 ($n = 5100$, $P < 0.001$), confirming the influence of net shortwave radiation on cooling (figure 3(e)). Spatially, 56.9% of the study area exhibited a significant correlation ($P < 0.05$) between the temperature and net shortwave radiation (figure 3(f)).

4. Discussion and conclusion

We localized the WRF model and it successfully simulated autumn air temperatures across Eurasia. The model revealed a unique phenomenon of autumn cooling in Eurasia against the background of global warming. Additionally, against the backdrop of a general decline in snow cover around the world (Li *et al* 2022, Wu *et al* 2023, Gottlieb and Mankin 2024), only the autumn SCP over central Eurasia has shown an increasing trend over the past 20 years. Allchin and Déry (2019, 2020) also found that increased snow cover extent over large areas of Eurasia during September to December (1972–2017) is primarily attributed to stronger southerly winds driving northward moisture advection, resulting in progressively earlier snow cover onset. We quantitatively evaluated the contribution of increased snow cover to autumn cooling in central Eurasia from 2004 to 2020, thereby estimating a contribution rate of 21.5%. Finally, the feedback mechanism of snow cover changes on autumn temperature fluctuations was elucidated from the perspective of radiative components and energy fluxes. On the one hand, with increasing snow cover, the surface albedo increases (figures S7 and S8), leading to more shortwave radiation being reflected and less absorption by the surface (Sun *et al* 2021, Zhang *et al* 2023), thereby reducing the net shortwave radiation and causing cooling. However, the low thermal conductivity of snow impedes heat exchange between the atmosphere and the ground (Che *et al* 2019, Hao *et al* 2023), resulting in decreases in the sensible heat flux, latent heat flux, and soil heat flux (figures S8 and S9). This study deepens our understanding of the evolution of the global climate system and provides scientific support for climate change mitigation and adaptation.

The mechanisms by which atmospheric circulation drives initial snow deposition primarily involve three aspects. (1) The positive phase of the Pacific Decadal Oscillation (PDO) deepens the East Asian trough (Li *et al* 2020), intensifying cold air activity and providing low-temperature conditions for snowfall. (2) Altered zonal gradients in geopotential height north of the Himalayan Mountains enhance southerly moisture advection northward, supplying moisture conditions for snowfall (Allchin and Déry 2020). (3) The strengthened westerly jet under PDO amplification (Li *et al* 2020) interacts with orographic uplift at the Ural Mountains and Siberian Plateau (Allchin and Déry 2020), generating dynamic lifting conducive to snowfall. These processes collectively demonstrate the interactive roles of PDO and snow cover in driving cooling.

The feedback mechanisms between snow deposition, air temperature, and atmospheric circulation are manifested in two aspects: (1) observations in central Eurasia suggest that snow-temperature interactions may establish a self-reinforcing feedback mechanism. Increased SCP reduces surface net shortwave radiation, which not only explains the direct cooling effect but also creates favorable conditions for sustained snowpack through two pathways. First, enhanced surface albedo prolongs snow duration by reducing melt energy (Miao *et al* 2024). Second, induced near-surface cooling suppresses the decay of the snow-albedo feedback. (2) Persistent radiative cooling over snow-covered areas strengthens near-surface temperature inversion layers, promoting the development of cold high-pressure systems. The intensified Siberian High drives moisture-laden cold air convergence along its periphery, synergizing with the PDO to enhance snow deposition and regional cooling.

The mechanisms by which snow cover suppresses soil heat flux involve two aspects (Déry and Brown 2007, Flanner *et al* 2011): (1) snow, as a low thermal conductivity medium, reduces diurnal soil temperature variations by weakening heat conduction between the soil and atmosphere. (2) The melt–freeze cycles at the base of the snowpack consume latent heat, slowing the downward propagation rate of the soil freezing front. Additionally, snow-induced suppression of soil heat flux alters surface energy partitioning, thereby modulating atmospheric circulation such as the Siberian High. For example, early autumn snow cover inhibits soil heat flux, which traps cold air near the surface. This not only prolongs the soil freezing period but also promotes the development of near-surface cold high-pressure systems, subsequently regulating the intensity of the Siberian High and creating favorable conditions for cooling.

This study, along with existing research (Li *et al* 2020), indicates that the factors influencing autumn cooling in central Eurasia over the past two decades include increased snow cover and the intensification of the PDO and Siberian High. In summary, the primary drivers and mechanisms of autumn cooling in Eurasia have been largely elucidated. However, the coupling effect between atmospheric circulation, snow cover and air temperature and other factors still require further investigation.

The results are derived from simulations using the WRF model. It is acknowledged that variations in parameterization schemes and model resolution introduce uncertainties into the findings. Future studies should focus on identifying key sensitive parameters in snow–atmosphere coupling, improving model resolution, and reducing the impacts of model dependency.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

Baofu Li, Weijun Sun and Minghu Ding designed the study. Dong, Lian, Pan, Sun, Chen, Wang, and Qin analyzed the data. All authors analyzed and discussed the results.

Conflict of interest

The authors declare that they have no conflict of interest.

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