Insights into the North Hemisphere daily snowpack at high resolution from the new Crocus-ERA5 product

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Abstract. This article provides a detailed analysis of the Crocus-ERA5 snow product covering the Northern Hemisphere from 1950 to 2022. It assesses the product's performance in terms of snow depth and cover compared to in situ observations and satellite data. Compared to its predecessor, Crocus-ERA-Interim, Crocus-ERA5 benefits from improved spatial resolution and better atmospheric data assimilation, resulting in more accurate snowpack estimates, especially during spring in Eurasia. The findings show a good match with observations, though biases remain, particularly in some Arctic regions, where the model tends to overestimate spring melt. In low-vegetation areas as tundra, Crocus-ERA5 may introduce biases due to its limited consideration of inter-annual vegetation changes, leading in inaccuracies in the simulation of snowmelt. The production of this snow dataset responds to the request of the continental cryosphere community. In particular the French and Canadian government institutions CNRM (National Center for Meteorological Research) and ECCC (Environment and Climate Change Canada) have been involved in monitoring Arctic snow cover as part of the "Terrestrial Snow" section of the Arctic Report Card since 2017. The Crocus-ERA5 product is freely available on a daily basis and at 0.25° resolution over the 1950-07-01 to 2023-06-30 period (Decharme et al., 2024, https://doi.org/10.5281/zenodo.14513248).

1 Introduction

The Arctic is particularly vulnerable to global climate change. Changes in atmospheric circulation can result in altered precipitation patterns affecting the amount and type of precipitation that contributes to snow accumulation (Ramos Buarque and Salas y Melia, 2018). Whereas changes in sea ice can also indirectly affect the land surface snow cover by altering the surface albedo and heat exchange processes (Pörtner et al., 2019). Over the past few decades, the Arctic has experienced warming at a rate approximately twice as fast as the global average, resulting in unquestionable alterations to the Arctic cryosphere, as documented in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Oceans and Cryosphere in a Changing Climate (Meredith et al., 2022). In addition to the above-average surface temperatures, an unprecedented (since instrumental records began) geographic spread of heat waves and warm spells occurred (Dunn et al., 2023). As a result, the rise in global temperatures linked to oceanic warming has led to a reduction in sea ice extent.

The pronounced decline in sea ice extent during late summer and early autumn increases the ocean's heat storage capacity, which in turn delays the formation of new ice at the onset of the cold season. This additional ocean heat also influences adjacent land areas, contributing to unprecedented high near-surface permafrost temperature. As a result, the active layer – the seasonally thawed layer of soil above the permafrost – is becoming deeper, with serious implications for soil stability, surface hydrology, and carbon emissions, all of which further intensify climate warming. On land, terrestrial snow cover - which now vanishes entirely from Arctic land surfaces during summer - plays a critical role in this interconnected system. Snow acts as both an insulator for the underlying permafrost and a reflective surface that regulates land surface temperatures. Its disappearance exposes the ground to direct solar radiation, accelerating permafrost thaw and deepening active layers. In late spring, early snow loss reduces surface albedo, allowing more solar energy to be absorbed and amplifying surface warming. This accelerates snowmelt and reinforces the snow-albedo feedback, a key driver of permafrost thaw, shifts in runoff patterns, changes in wildlife behavior, and heightened wildfire risk. Snow loss during this period also enhances carbon uptake in subsequent months, affecting Arctic ecosystem productivity. Moreover, snow responds rapidly to temperature fluctuations, particularly in early autumn and early spring, making it a highly sensitive and visible indicator of Arctic climate change. Variations in snow cover not only influence the timing and volume of snow melt into rivers and streams but also affect permafrost stability and the functioning of Arctic ecosystems. Together, these interlinked changes in sea ice, snow, and permafrost create reinforcing feedback loops that amplify the pace and impacts of climate change in the Arctic.

The aforementioned evidences clearly illustrates the intricate nature of these changes and the complex interactions between the various components of the Arctic climate system. In this context, the Arctic Report Card (ARC, https://arctic.noaa.gov/report-card/), published annually by the National Oceanic and Atmospheric Administration (NOAA) of the United States, enables the global scientific community to monitor and document these changes. This report presents a comprehensive and up-to-date assessment of the current state of the Arctic, based on the most recent scientific data. The ARC addresses a range of environmental aspects pertaining to the Arctic, including air and ocean temperatures, precipitation, Greenland ice sheet, sea ice extent, snow, permafrost, vegetation, etc. The objective of the report is to provide policymakers, scientists, and the general public with information about the rapid and important changes occurring in the Arctic as a result of climate warming. It identifies significant events of the past year, year-to-year variability and long-term trends, providing robust monitoring of the evolution of this critical region for the global climate. By providing accurate and timely information, the ARC plays an important role in raising awareness and supporting informed decision-making on the environmental challenges facing the Arctic.

Since 2017, the French National Center for Meteorological Research (CNRM) has been involved in the "Terrestrial Snow" contribution to the ARC through a collaboration led by the Environnement et Changement Climatique Canada (ECCC) Institute to monitor the evolution of snow cover and mass each year (e.g. Mudryk et al., 2023). CNRM's role is to provide a daily snowpack product derived from the Crocus complex snow scheme (Brun et al., 1992, 1989) contributing to the monitoring and advancement of knowledge on the snow cover and mass of the North Hemisphere (NH). In addition to its use in the ARC, from 2017 to 2020, this product has also been used in several scientific studies (Mudryk et al., 2015; Mortimer et al., 2020; Kouki et al., 2023).

Recently, our snow product has been updated using the same Crocus configuration but driven by the fifth generation of the ECMWF global atmospheric reanalysis ERA5 (Hersbach et al., 2020) , referred to as Crocus-ERA5. Although this product has been little evaluated, it has been used since 2021 in the ARC report (Mudryk et al., 2023) and in several scientific studies (Derksen and Mudryk, 2023; Mudryk et al., 2024).

The aim of this study is to provide a brief evaluation and insight into this Crocus-ERA5 daily snow product, which support numerous studies on the evolution of the Arctic snow cover in the coming years. This product is the result of a novel rerun of the Crocus snowpack model whose innovation is threefold: (i) the use of the improved ECMWF reanalysis ERA5 as atmospheric forcing, offering higher spatial and temporal resolution, which enhances the accuracy of snowpack simulations; (ii) comprehensive documentation of this update, highlighting both the strengths and limitations of the two most widely used variables in the community across the vast expanse of the Northern Hemisphere; and (iii) validation through comparison with fully independent references, including in-situ observations and multi-source data analysis.

The data and methods used to evaluate the new Crocus-ERA5 product are presented in Section 2. The main findings of this study are presented in Section 3. The Crocus-ERA5 product is first compared with its predecessor, Crocus forced by ERA-Interim, hereafter referred to as ERAI, to assess the progress (or lack thereof) between successive generations of these snow products. In the Arctic region, validation of the snowpack benefits of various observations and estimates, including in situ and satellite data, so Crocus-ERA is then evaluated against a range of in situ and satellite data. Finally, a brief discussion and the main conclusions are presented in section 4.

2 Data and Methods

The performance of snowpack modelling in the context of climate change, can be effectively characterized using two key variables : snow depth and snow cover. These variables are widely used as climate change indicators because of their strong interactions and feedbacks with the surface energy balance.

Snow depth plays a critical role in both seasonal and long-term evolution of frozen ground and permafrost. Changes in snow depth have significant implications in atmospheric circulation and may influence weather in other parts of the world. For instance, large snow depths in western Russia have been associated with local cyclonic circulation, where northerly flow to the west of the trough favour the advection of cold air into the regions, helping to preserve the snow cover. Locally, over regions at higher latitudes or altitudes the dynamics of snow depth may favour more prolonged snow cover periods , further modulated by local environmental conditions. Extreme weather events such as blizzards, can alsolead to rapid changes in snow depth over short time scales. Due to its climatic importance, considerable effort has been made over the years by various countries in the northern hemisphere to carry out extensive and consistent measurements of snow depth.

Snow cover extent (SCE) is an equally important climate change proxy in the Northern Hemisphere. Its seasonal cycle drives a number of important energy and water cycle processes. In Arctic regions, snow cover dynamics drive the seasonal thermal regime of the ground, with implications for the carbon cycle, permafrost, and terrestrial and freshwater ecosystems. In particular, during spring, the retrat of snow cover directly influence the magnitude of climatic warming.

Another key snow-related variable widely used by the scientific community is snow water equivalent (SWE), which represents the amount of water contained in the snowpack. SWE is particularly valuable because it provides a direct measure of the snowpack's total water content, which is crucial for hydrological applications such as water resource management and runoff prediction. In the Crocus-ERA5 model, snow depth accounts for the density of individual snow layers, while SWE is derived from both snow depth and density. Snow depth is much easier to observe through remote sensing and ground measurements, making it a valuable proxy for validating snowpack models, whereas SWE remains more difficult to measure directly. Satellite-based snow depth relies on SWE estimates and assumed or modeled snow density. This approach introduces significant uncertainties due to spatial variability in snow density, retrieval errors, and sensor limitations. These factors can lead to biases in satellite-derived snow depth estimates. In contrast, in-situ measurements offer reliable, consistent data that are essential for validating snow models like Crocus-ERA5. As a result, this study prioritizes snow depth, which provides broader and more reliable observational coverage. Accurate snow depth data are essential not only for refining SWE estimates but also for enhancing hydrological, flood, and climate models. Recognizing this importance, many Northern Hemisphere countries have maintained long-term, consistent snow depth monitoring programs.

For these reasons, in order to assess the reliability of the Crocus-ERA5 results, this study focuses on both snow depth and snow cover, comparing them with independent observations.

2.1 Atmospheric Forcings

The Crocus snowpack model is forced, in this study, to simulate snow evolution with the ERA5 atmospheric reanalysis (Hersbach et al., 2020), produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). As the latest global meteorological reanalysis, ERA5 represents a significant advancement over ERAI (Dee et al., 2011). Table 1 summarizes the main differences between ERAI and ERA5 reanalyses. One of the most notable improvements is the spatial resolution, with ERA5 offering a resolution of approximately 31 km, compared to 80 km in ERAI. Beyond the finer spatial and temporal resolution, ERA5 also benefits from over a decade of advancements in model physics, core dynamics, and data assimilation.

The ERA5 reanalysis includes an advanced land data assimilation system that has been enhanced to improve the representation of hydrological variables such as soil moisture and snow depth. Both ERAI and ERA5 use a single-layer snow scheme that assumes uniform density and temperature throughout the entire snowpack. Compared to ERAI, ERA5 improves the representation of key physical processes, including snow accumulation, melting, wind-driven redistribution as interactions with the ground by incorporating better data assimilation techniques. However, ERA5 does not account for vertical variations within the snowpack, such as temperature gradients or changes in snow properties at different depths - features typically represented in multi-layer snow models. Consequently, snow parameters derived from ERA5, including snow depth and SWE, are less detailed and refined than those produced by multi-layer models that explicitly resolve multiple snowpack layers to capture more detailed variations in snow properties.

2.2 Crocus-ERA5 Framework

Crocus is coupled to the ISBA (Interactions between Soil–Biosphere–Atmosphere) land surface model (Vionnet et al., 2012; Brun et al., 2013) and embedded in the SURFEX numerical platform (Masson et al., 2013, https://www.umr-cnrm.fr/surfex/).

Table 1. Key differences between ERA-Interim (ERAI) and ERA5 reanalysis products.

Feature	ERAI	ERA5
Time coverage	1979–2019	1950–present
Horizontal resolution	0.75° (80 km)	0.25° (31 km)
Temporal resolution	6-hourly data	Hourly data
Vertical levels	60 levels (top at 0.1 hPa)	137 levels (top at 0.01 hPa)
Data assimilation system	4D-Var (IFS Cycle 31r2)	4D-Var (IFS Cycle 41r2)
Land surface model	TESSEL	HTESSEL (updated version)
Snowpack structure	Single-layer scheme	Single-layer scheme
Advantages	Longer-established dataset, widely validated in past studies	Higher resolution, ore detailed atmospheric processes, updated physics, improved land-surface interactions

This coupling, as described by Vionnet et al. (2012), allows Crocus to interact with other surface components such as soil, low vegetation, and atmosphere within a consistent framework. Within this setup, Crocus is forced by key atmospheric variables, including 2m air temperature, humidity, wind speed, incoming shortwave and longwave radiation, and precipitation (both rain and snow). Integrated into SURFEX, Crocus benefits from a shared surface energy balance and atmospheric forcing structure, enabling more realistic simulations of snowpack evolution in complex surface environments. A full description of the Crocus model and the technical configuration of the Crocus Northern Hemisphere Snowpack product can be found in Vionnet et al. (2012) and Brun et al. (2013), respectively.

The growing needs of the scientific community for improved snow modeling began gaining momentum in the early 2000s, driven by an increased focus on the impacts of climate change and water resources. Since the early 2010, the availability of high-resolution atmospheric reanalysis datasets has encouraged the use of one-dimensional multi-layer mass and energy balance models over large areas, improving the understanding of snowpack evolution and the simulation of snow cover and albedo. The integration of these enhanced atmospheric reanalysis forcings has further increased model accuracy, particularly in representing snow season dynamics and refining albedo estimates through explicit modeling of snow grain types.

Until 2020, the Crocus model was driven by meteorological forcing (temperature, precipitation, humidity, wind, etc.) derived from the ERAI global atmospheric reanalysis. Building on the availability of more advanced reanalysis products, the Crocus-ERA5 product was developed. A set of seven snow-related variables – snow depth, snow water equivalent, liquid water content in the snowpack, snow albedo, snow surface temperature, snowpack internal temperature, and snow cover fraction – is freely available on a daily basis at https://doi.org/10.5281/zenodo.14513248 (Decharme et al., 2024).

The CROCUS-ERA5 dataset also benefits from adopting the standards of the Coupled Model Intercomparison Project Phase 6 (CMIP6), including metadata structured according to ISO 19115. Additionally, CMIP6 data follows the Climate and Forecast (CF) metadata conventions (CF-1.7, CMIP-6.2) and complies with the Data Reference Syntax (DRS) for systematic file organization and naming, promoting interoperability.

2.3 Snowpack Modeling

The Crocus multi-layer snow model simulates snow albedo, heat transfer and phase change, snow mass, snow density, and snow grain metamorphism based on experimental laws (Brun et al., 1992, 1989). The number of layers is variable from 1 to 50 depending on snow depth and stratification.

The snowpack model does not explicitly represent forested areas. Instead, these zones are treated as low vegetation, following the approach of Brun et al. (2013). This simplification was a deliberate choice, as the model does not simulate snow-forest interactions. While this improves internal consistency, it comes with some limitations. Forests significantly impact snow processes through canopy interception, sublimation, and shading effects. Ignoring these mechanisms can lead to overestimation of snow accumulation at ground level, as it neglects snowfall interception by tree canopies and underestimates sublimation of intercepted snow driven by longwave (infrared) radiation. Forest shading also reduces surface albedo, slowing snowmelt. These interactions are complex and remain challenging to simulate accurately, which underscores the trade-off between model simplicity and physical realism. Additionally, in Crocus-ERA5, the snowpack is simulated on an idealised herbaceous surface with a climatological physiography (e.g. no inter-annual variability in leaf area index).

Rising temperatures and increasingly frequent winter thaws are reshaping snowpack structure, leading to notable changes in snow distribution. The Crocus-ERA5 snowpack model quantifies these changes by explicitly simulating snowpack processes, including snow cover fraction. It distinguishes snow-covered areas from snow-free regions, such as vegetation or bare soil within the grid, preventing unrealistic vegetation effects on snow dynamics. This precise partitioning allows for a more accurate representation of snow-melt and rain absorption processes, improving the model's reliability in capturing snow cover evolution.

To refine snowpack representation, the model dynamically divides the snowpack into layers, with a minimum of 3 and a maximum of 50, allowing it to capture thermal gradients and conserve mass and heat during melting or accumulation. Processes such solar absorption, water retention, heat transfer, and compaction are calculated based on snow density. In thin snowpacks, solar energy can penetrate to the ground, influencing albedo, whereas deep snowpacks minimize this effect, acting as insulators that reduce heat conduction, suppress turbulent transfer due to low surface roughness, and modify the net radiation budget because of snow's high albedo.

The model estimates land surface albedo by incorporating snow cover's effect on the surface radiation budget, diagnosing the effective total surface albedo (Boone et al., 2017) . This is determined by evaluating the difference between downward radiation components and total surface net radiative fluxes. In snow-covered areas, particularly those overlaying vegetation, the effective surface albedo is significantly altered due to upwelling shortwave and longwave radiative fluxes.

2.4 Analysis Methods

Evaluate changes in the estimation of the snowpack from Crocus stand alone involves variations influenced by climate change that are directly taken into account by atmospheric forcing. The two variables retained in our study, snow depth and snow cover, are strongly linked to each other and reflect the direct response of atmospheric forcing providing essential information on the performance of the snowpack modeling. For this reason, the new Crocus-ERA5 product with a horizontal resolution of 1/4° is first compared with the previous Crocus-ERAI version with a resolution of 1/2° over the period 1979-2018. The comparison focuses on the monthly variability of snow depth anomalies. It evaluates changes in Arctic snow cover variability due to changes in atmospheric forcing, and to a lesser extent, spatial resolution, separately for North America and Eurasia, as Eurasia, North America, and Greenland are affected differently by the components of the cryosphere. Within the Arctic Circle, the Eurasia pan-region includes Scandinavia (Norway, Sweden, Finland) and northern Russia, while North America includes northern Alaska (USA) and northern Canada.

In this study, the assessment of the Crocus-ERA5 daily snow depth is done against the harmonized dataset of in-situ observations across North America and Eurasia providing a comprehensive view of historical snow conditions. In Brun et al. (2013), this *Crocus-ERAI* daily snow product was validated against local observations from over 1000 monitoring stations in northern Eurasia. Assessing the timing of snow onset and melt simulated by large-scale models is especially challenging due to the rapid and highly variable response of snow to temperature fluctuations. The ability of the Crocus-ERA5 to map snow depth (or mass, related to depth by the density) is thus evaluated against these in-situ observations in terms of time-average and local daily variability. To identify particular errors in the biases of Crocus-ERA5, statistics were calculated for diagnostics derived from continuous snow depth information, such as duration and first/last day of continuous snow following the method described in many previous studies (Brun et al., 2013; Schellekens et al., 2017; Decharme et al., 2016, 2019). Additional diagnostics include the averaged and annual maximum snow depths, the date of maximum snow depth (expressed as days since January 1st) as the number of snow-covered days per year.

Over the years, significant advancements in SCE analysis, particularly through multi-sensor approaches, have greatly improved mapping by reducing the uncertainties associated with sparse, single-sensor data. Issues related to mismatches in temporal and spatial scales - which historically made large-scale validation increasingly reliant on modeling frameworks and gridded interpolations - have thus been reduced.

The use of SCE provides a distinct advantage, as it represents a cumulated variable that can be reliably derived from satellite observations over large regions. Additionally, expressing snow cover as a percentage (%) offers a valuable advantage for validation purposes, providing a simple, spatially explicit measure of snow presence or absence over a given area. SCE and snow cover percentage can thus be directly compared with satellite-derived estimates, making them practical and robust metrics for evaluating the spatial accuracy of snowpack models.

In this study, SCE is characterized by representing its monthly standardized anomalies for 2000-2022, which directly addresses the main objective of validating the seasonality and inter-annual variability of snow cover changes over large areas.

2.5 Observational Data

The in-situ dataset includes over 2,000 stations with daily observations spanning the period from 1950 to 2012. Most measurements are taken at synoptic stations following World Meteorological Organization (WMO) standards, typically representing bare ground or open areas with regular grass cutting (Schellekens et al., 2017, https://doi.org/10.5194/essd-9-389-2017-supplement).

This extensive dataset that was carefully processed to ensure consistency and minimize elevation-related biases offers valuable spatial and temporal coverage, providing robust insights into historical snow depth variability and trends. Decharme et al. (2019) described the processing to this dataset namely outlined specific selection criteria, including: (i) a local-model elevation of less than 100 m, (ii) a minimum of 100 days with a non-zero depth measurement over the full period and, (iii) at least eight snowy days per year.

The ability of the Crocus-ERA5 to map snow cover is evaluated against the Interactive Multisensor Snow and Ice Mapping System (IMS) satellite data (U.S. National Ice Center, 2008, https://nsidc.org/data/g02156/versions/1). The IMS snow cover analysis incorporates estimates from NOAA AVHRR, MODIS, VIIRS, and Sentinel satellites, alongside in-situ observations and NCEP model data (Helfrich et al., 2007). By integrating time-sequenced satellite imagery, IMS enhances the differentiation between snow and cloud (Estilow et al., 2015), ensuring superior spatial and temporal coverage for more precise and reliable snow cover estimate. The adoption of advanced multi-sensor fusion techniques in 2020 has set IMS apart, allowing it to combine multiple satellite sources and models for an all-weather, day-and-night analysis. This makes IMS more robust and comprehensive than other snow cover analyses, which often lack the same level of real-time updates and multi-source data integration. Additionally, in this study, the period covered by IMS complements that of in-situ observations (1950–2012). To align as closely as possible with model resolution, IMS snow cover data is used at a spatial resolution of 24 km for the period 2000–2022.

3 Crocus-ERA5 assessment

While Crocus-ERA5 provides valuable insights into snowpack dynamics, it faces limitations in accurately representing different land cover types. Forests are not explicitly represented in Crocus. Although this simplification affects average snow depth estimates, it has a limited impact on inter-annual variability. In forested areas, snow generally melts slightly earlier, but this timing shift does not significantly alter year-to-year trends. Beyond forests, Crocus-ERA5 faces limitations in open areas with low vegetation, such as grasslands and tundra, where it may not accurately capture wind-driven snow redistribution. This can introduce biases in snow depth and duration estimates, affecting the dataset's applicability in regions where blowing snow and drift processes play a dominant role in snowpack evolution.

Despite these challenges, Crocus-ERA5 enhances snow cover simulation by explicitly modeling snowpack processes and distinguishing snow-covered and snow-free areas, surpassing the capabilities of satellite observations alone. While satellites rely on indirect measurements and assumptions, Crocus-ERA5 uses physically based simulations to represent snowpack dynamics more accurately. Its detailed physical representation, combined with increasing spatial and temporal resolution, improves snowpack dynamics simulation, enhances accuracy, and extends dataset applicability across diverse landscapes

3.1 Comparison with the Crocus-ERAI product

The variability of monthly snow depth is highlighted by the changes in its monthly anomalies over time, displayed annually and seasonally, for both the North American and Eurasian regions (Figure 1). Anomalies are calculated in relation to the average for the period 1979-2018, which encompasses both products in order to ensure its temporal and spatial consistency. Negatives anomalies indicate lower snow depth, while positive values indicate higher snow depth. In the Northern High latitudes, the snow depth typically increases during the winter months as a result of the accumulation of snowfall. The snow depth from both the Crocus-ERA5 and Crocus-ERAI products are generally well in phase for both the North American and Eurasian regions. In Eurasia, the decrease in snow depth that started at the beginning of the 21st century is very similar for both simulations, however Crocus-ERA5 shows more pronounced negative anomalies (brown), particularly for 2000-2010. In North America, however, the similarity between the snow depth anomalies of both simulations is more nuanced, and there is a significant inter-annual variability throughout the full data series.

The snow depth on the ground is closely related with the extent of snow cover, particularly in terms of its spatial distribution. Furthermore, the anomaly of snow cover varies considerably depending on the geographic location and local climate conditions. In the late spring (April to June), a decrease in snow thickness is observed as temperatures rise, leading to snow melt as in autumun (September to November), the return of colder conditions favours the onset of new snow accumulation, marking the beginning of the seasonal increase in snow cover. Figure 2 shows the standardized anomalies in snow cover extent for land areas situated within the Arctic Circle (latitudes > 60° N) from 1979 to 2018, for both the North American and Eurasian Arctic regions. Solid black and red lines depict 5-yr running means, providing a smoothed trend of variability, whereas filled circles highlight standardized anomalies relative to the last year 2018. Across both regions, the Crocus-ERA5 and the Crocus-ERAI snow cover products exhibit a closely similar inter-annual variability, with an overall declining trend throughout late spring and early autumn months. However, after the early 2000s, North American Arctic anomalies for Crocus-ERA5 in May and June appear less negative. In Eurasia, around 2012, a particularly pronounced reduction in snow cover occurred during late spring and early summer (April-June), preceded by another noticeable decline in the autumn months (September-November) around 2009. These patterns highlight the ongoing and broad seasonal impacts of Arctic warming on snow cover dynamics. The inter-annual variability in Crocus-ERA5 and Crocus-ERAI is very similar. However, over Eurasia in late spring, Crocus-ERA5 anomalies are slightly more pronounced, in contrast to the North American Arctic, where Crocus-ERAI anomalies are less pronounced. In autumn, differences in the inter-annual variability are less evident. The yearly standardized anomalies relative to 2018 (filled circles) display a broadly similar pattern with consistent inter-annual variability. They illustrate how the monthly snow cover state in each year compares to 2018 and deviates from the smoothed long-term climate trend. These deviations from the long-term mean are generally larger during the onset of accumulation, particularly in Eurasia (Figure 2, panels g-l). This highlights that early-season snow cover is more sensitive to short-term atmospheric variability, whereas late-spring snow melt is more strongly influenced by long-term climate trends.

The April-May standard deviation of snow depth from its mean on the land surface on the period 1979-2018, highlight the variability of both products (Figure 3). There is a clear stability in snow depth distribution, i.e. deviation varies similarly around the mean, for both regions Eurasia andNorth America. In Eurasia, the shift of the CROCUS-ERA5 distribution toward higher values of both the mean and standard deviation suggests a proportional relationship, where greater snow depth corresponds to increased variability. In North America, while the CROCUS-ERA5 standard deviation also increases with the mean, the relationship is less pronounced. In April, the mean monthly snow depth is higher for Crocus-ERA5 compared to Crocus-ERAI by about 15% (from 0.44 to 0.52 m) in Eurasia and by 8% (from 0.42 to 0.46 m) in North America. The standard deviation also increases by similar proportions, with a rise of approximately 15% (from 0.24 to 0.29 m) in Eurasia and 7% (from 0.24 to 0.26 m) in North America. This significant changes in the statistics, mean and standard deviation, in same proportions suggests that Crocus-ERA5 shifts towards larger values. In May, the Crocus-ERA5 snow depth is higher by about 26% (from 0.17 to 0.23 m) in Eurasia and 16% (from 0.21 to 0.25 m) in North America. The standard deviation likewise increases, with a rise of approximately 24% (from 0.21 to 0.28 m) in Eurasia and 10% (from 0.24 to 0.26 m) in North America. For North America, this increase in mean coupled with a smaller rise in standard deviation suggests that the data is becoming more consistent around higher values, with lower values showing less variability. This significant increase in the Crocus-ERA5 statistics (mean and standard deviation) in similar proportions, with the same spread of points and clusters, aligns with increased snow accumulation and reduced melting. These are linked, respectively, to higher precipitation - particularly in mountainous and mid-to-high latitude regions - and colder temperatures in ERA5 (Wang et al., 2019). Another indirect conclusion is that wind redistribution, which primarily affects snow depth, does not change significantly, as snow depth variability remains stable.

3.2 Snow depth

The annual cycle of snow depth is characterized by a gradual accumulation of continental snow from October to March, followed by a rapid ablation of the snowpack during the spring (Figure 1). The snow that persists at the advent of spring incorporates precipitation that occurred during the preceding winter, thereby reflecting the atmospheric variability of winter conditions. To represent the onset of the spring period, the amount of snow is verified by calculating the time-averaged snow depth on 10 March for two climatological periods for both the Crocus-ERA5 and the in-situ observations products. Two tier of climatic normals have been highlighted: the period 1950-1980 is used to define the past climate and the period 1980-2012 is used to define the present-day climate (Figure 4). The present-day period cover the start of the acceleration in global warming and particularly the rapid warming of the Arctic that has led to the thawing permafrost.

Overall, Crocus-ERA5 generally reproduces the snow depth pattern well, as indicated by the similarity between modeled (shaded pattern) and observed (circles) values. Regions where the colors closely match suggest strong agreement between the two datasets. The long-term mean of snow depth on 10 March exceeds 0.3 m for latitudes above 60° in Eurasia and above 45° in North America , with localized variations reflecting regional climatic influences. Crocus-ERA5 tends to slightly overestimate snow depth, particularly in localized areas of the central Russian Plain, east of the Ural Mountains, as well as in parts of the Central Siberian Plateau. In Eurasia, maximum of snow depths are found in the north-eastern regions of European Russia and the central Siberian plateau, and minimums in the eastern part of Siberia. Crocus-ERA5 slightly overestimates the snow depth in the central part of the Russian plain to the east of the Ural mountains. For the present period, two stations with strong values (> 0.75 m) differ strongly from Crocus-ERA5, one at the end of the Ural Mountains and the other at the mouth of the Ob Gulf. Otherwise there is good agreement on both sides of the Ural Mountains and on the Siberian Plain for both periods, where also some stations show strong values (> 0.75 m) compared to Crocus-ERA5 (< 0.50 m) in the modern period. Weak snow depths (< 0,30 m) are well simulated by Crocus-ERA5 on the Verkhoïansk and Tcherski mountains, where the large decline in snow depth during the summer months is well represented. This performance has been already highlighted by Brun

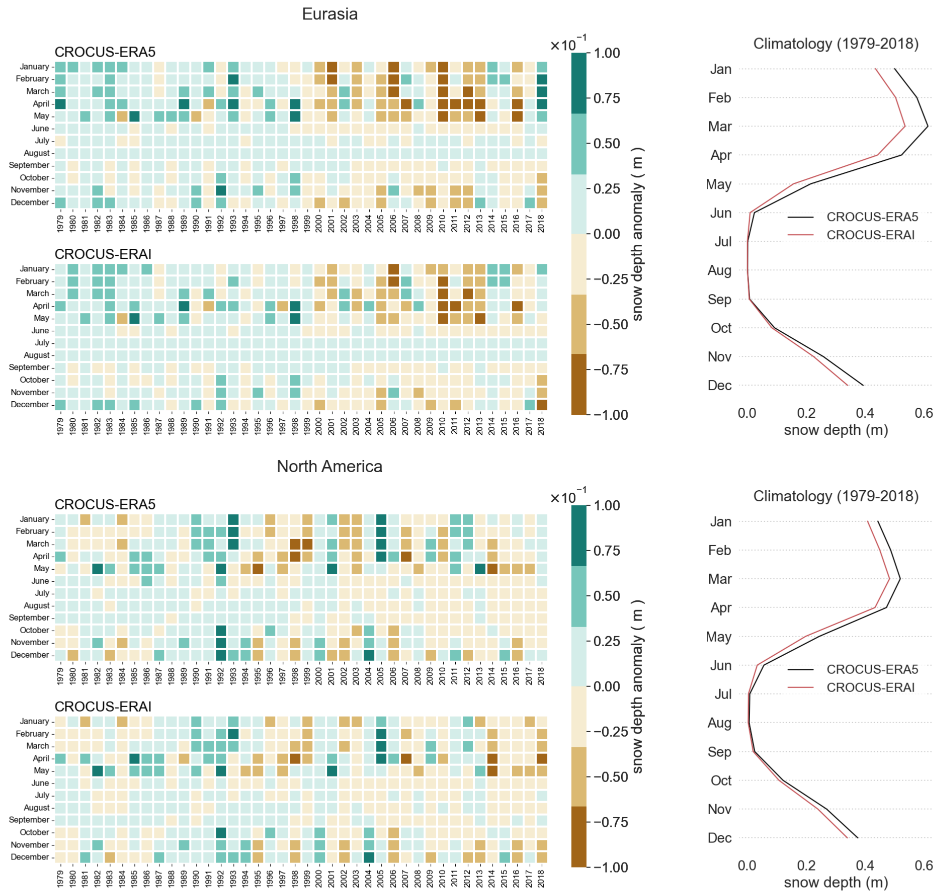

Figure 1. (Panels left)Time series of monthly snow depth anomalies from January 1979 to December 2018, calculated relative to the mean snow depth for 1979-2018. Positive anomalies are shown in blue-green, while negative anomalies are shown in brown. Adapted from Figure 1 in Mudryk et al. (2020). (Panels right) Monthly climatology of snow depth anomalies for Crocus-ERA5 (black line) and IMS (red line). The x-axis represents climatological values, while the y-axis lists months from January (top) to December (bottom).

et al. (2013) with the previous Crocus-ERAI product in terms of low density, which is explained by the ability of Crocus to simulate the metamorphism of the snowpack layers into depth hoar under extreme temperature gradients. Further west, in the East Siberian lowlands, deviations from observations occur at very low values. Wherever the relief is not significant, in the plain but around the mountain terrain, the observed snow depth compares reasonably well with in situ observations. This was highlighted by Mudryk et al. (2024) in its evaluation of gridded snow water equivalent (SWE) products for their ability to represent climatology, variability and trends in regions spanning the Northern Hemisphere.

The upper part of Figure 5 shows the spatial distribution of the time-averaged snow depth in early spring, as simulated by Crocus-ERA5 for the period 1950-2022. The figure depicts the long-term daily snow depth on 10 March for both the Canadian and Eurasian domains. The bottom panels show the results for a selection of stations representing diverse geographical regions.

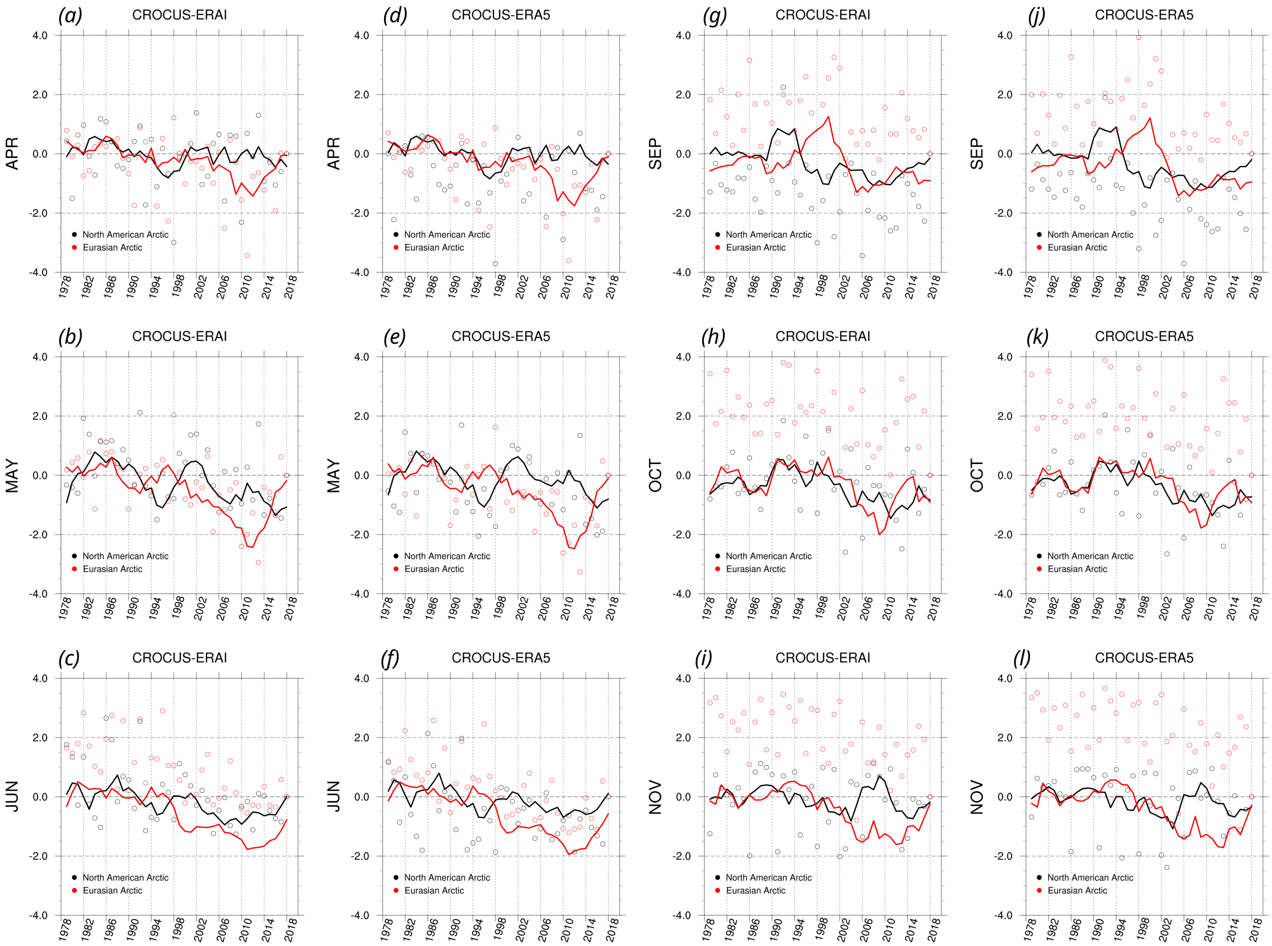

Figure 2. Monthly time series of snow cover extent (SCE) shown as standardized anomalies relative to the period 1979-2018. Spring and Autumn are represented respectively for months of April-May-June, from (a) to (f), and September-October-November, from (g) to (l). Land surface averages for North America and Eurasia refer to latitudes above 60° N. Solid black and red lines depict 5-yr running means providing a smoothed trend of variability. Filled circles are used to highlight anomalies relative to the last year 2018. Adapted from Figure 1 in Mudryk et al. (2023).

The first Canadian station on Figure 5 (station S2) is situated at an elevated altitude (1323 m) in the vicinity of the Canadian Rocky Mountains. Others stations are located in the Canadian Shield region, which is characterised by numerous hills and glacier-carved lakes. The observed and simulated time series of snow depth on 10 March are in very good agreement over the Canadian Rocky Mountains for the present-day period (station S2), which is characterised by a high variability. In the northern continental part, between 65° and 70° latitude (stations S29 and S25), snow depths exhibit less variability around 0.4 m but also show excellent agreement with observations. In the northern Hudson Bay Lowlands (station S12), there is also a high degree of agreement between the two time series, although less agreement is revealed for the past climate (before 1980).

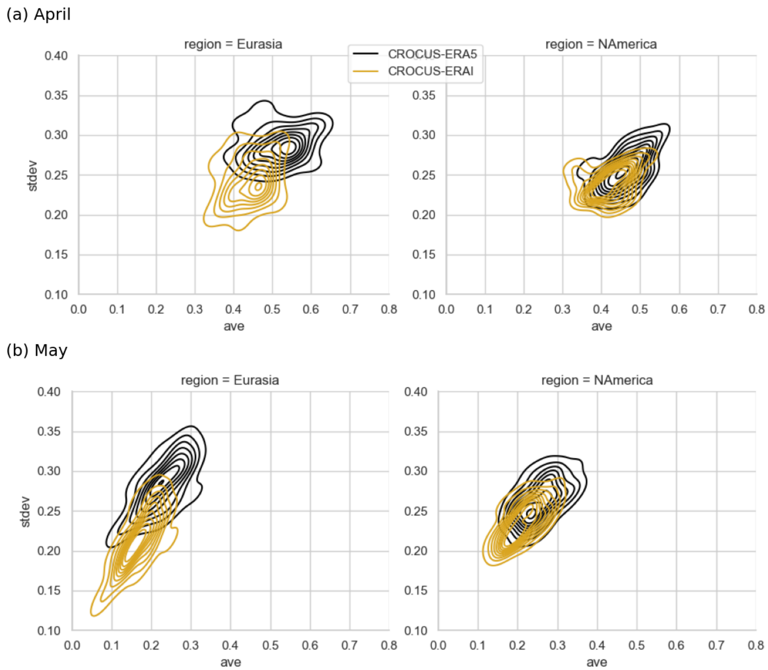

Figure 3. Monthly standard deviation of snow depth from its mean on the land surface for Eurasia (left) and North America (right) with respect to latitudes above 60° N. Representation of the months **(a)** April and **(b)** May.

Nevertheless, confidence in the Crocus-ERA5 snow depth in past climates is however supported by its close phase with in situ observations in the Arctic region (S37 and S38). However, in these very high-latitude regions, snow depths are overestimated by Crocus-ERA5, particularly in the north of Baffin Island which is divided into numerous peninsulas (S30).

In Eurasia (left panels of Figure 5), in the part of the Ural Mountains near the Kara Sea (station S19), time series of snow depth on 10 March show an overestimation of Crocus-ERA5 in the past climate (1960-1984) with a phase close to the observations. However, in the subsequent present period (1984-2012), Crocus-ERA5 and the in situ observations demonstrated a high degree of agreement. Near the city of Norilsk (station S28), Crocus-ERA5 exhibits three distinct behaviours: an overestimation for the period 1950-1967, followed by an underestimation for 1968-2000, ending with an excellent agreement in phase and magnitude for 2000-2012. On the Central Siberian Plateau, in a station located in a latitudinal valley near the city of Toura (station S16, 277 m), Crocus-ERA5 overestimates snow depth but is remarkably in phase for the entire period of 1950-2015. This significant overestimation of Crocus-ERA5 in relation to observations associated to a remarkable agreement in phase is also shown in the data from the S8 station (682 m), located in the Kolyma mountain. In regions along the Laptev and Siberian Seas (stations S34 and S39), where snow depth varies below 0.5 m, Crocus-ERA5 exhibits a slight tendency to overestimate observations. However, both the model and observations remain in relatively close alignment. Finally, there is a noticeable match in phase and magnitude to the west of the Kamchatka Peninsula (station S2), where deep snow depths generally exceed 1m. Figure 6 compares the Crocus-ERA5 and observations for the period 1950-2012 in terms of average duration, maximum,

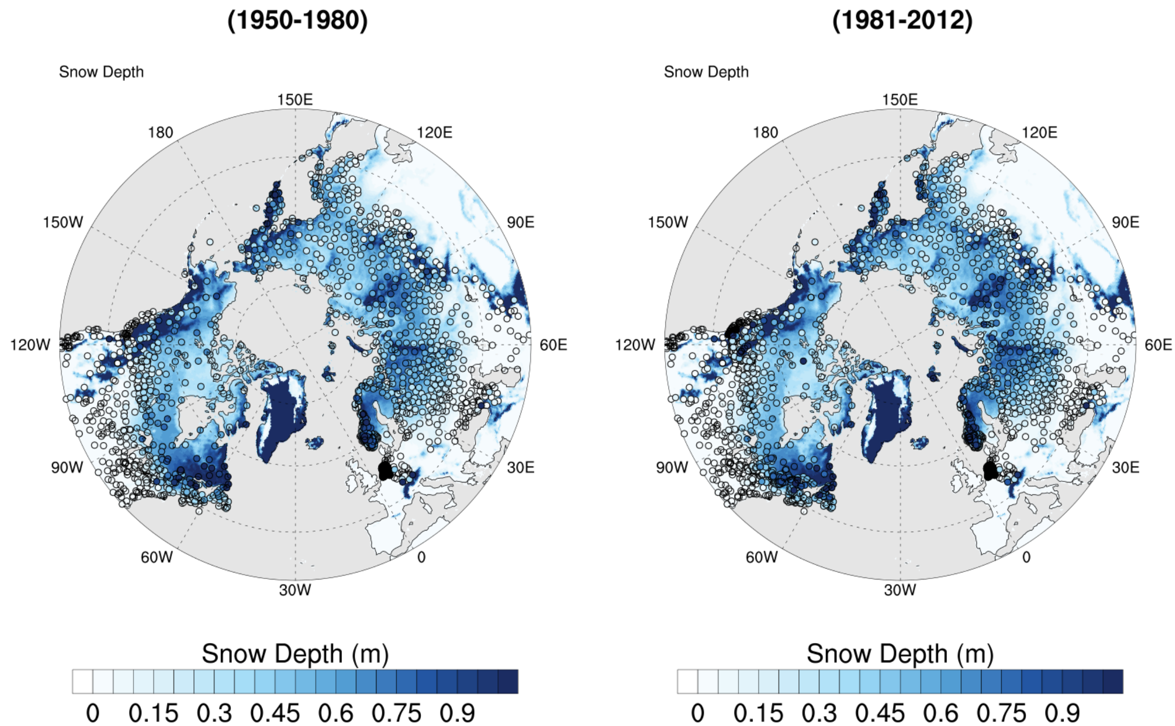

Figure 4. Time-averaged snow depth from Crocus-ERA5 (2D field) for the two climatological periods 1950-1980 and 1981-2012 on 10 March superimposed on the corresponding time-averaged observed snow depth (circles).

first and last day of continuous snow on the ground. A day with snow on the ground is defined as a day with more than 1 cm of snow (Brun et al., 2013; Decharme et al., 2019). Overall, Crocus-ERA5 demonstrates a satisfactory level of concordance with the observations. This underlines the efficacy of the model in replicating the seasonal snow cycle in the northern hemisphere, despite the persistence of certain biases. Crocus-ERA5 simulates predominately a shorter snow season in the Arctic compared to observations, while in the sub-Arctic plains it predicts a longer snow season. However, these biases are relatively small in both regions (~2 days, Figure 6.a). Two regions differ significantly from the observations. Around the Rocky Mountains, the Crocus-ERA5 show many more continuous snow days than observations. Additionally, in Norway, the biases alternate strongly between positive and negative values (~20 days). The biases in the first and last snowy days of the continuous snow period indicate that the snow season generally starts later and ends earlier in the Crocus-ERA5 estimates (Figures 6.c and 6.d). The largest discrepancies in snow peak between Crocus-ERA5 estimates and measurements are scattered in the Arctic region, where ERA5 has difficulty producing accurate estimates due to incomplete or sparse observational data. In the western part of Eurasia below 60° latitude, the bias in the maximum date of snowfall is small, approximately 2 days (Figure 6.b and Table 2), allowing accurate estimation and forecasting of changes in snow cover.

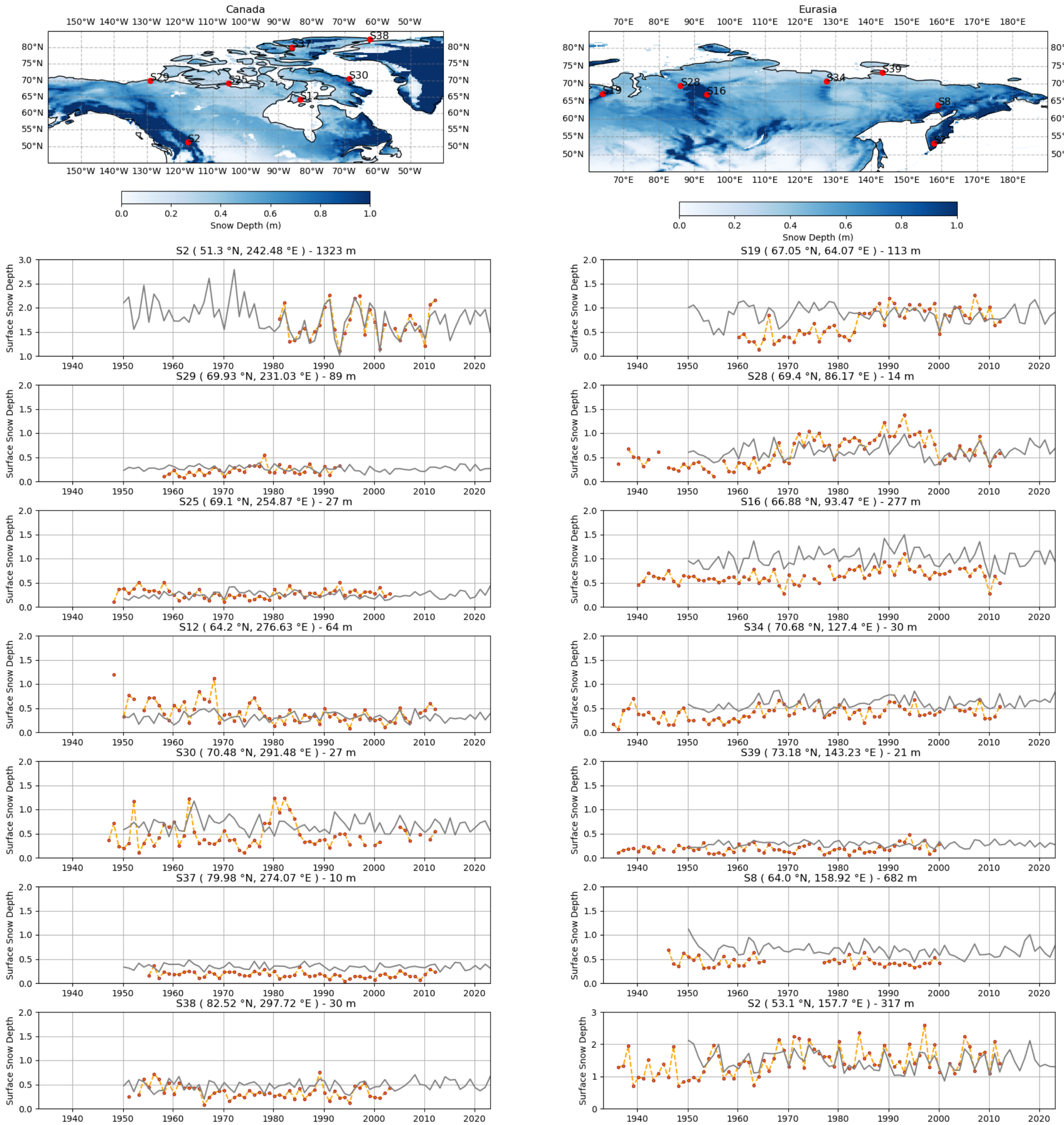

Figure 5. Location of stations on the spatial distribution of time-averaged snow depth in March for the period 1950-2022 and the two domains: Northern North America (stations on Canada only (top left)and Eurasia (top right) Below each domain (column) the time series of snow depth for each station is shown for both Crocus-ERA5 (grey lines) and observations (orange circle with dotted lines) on 10 March, early spring.

Each time series panel corresponds to a station point on the map (top). The x-axis starts at the beginning of the longest available time series.

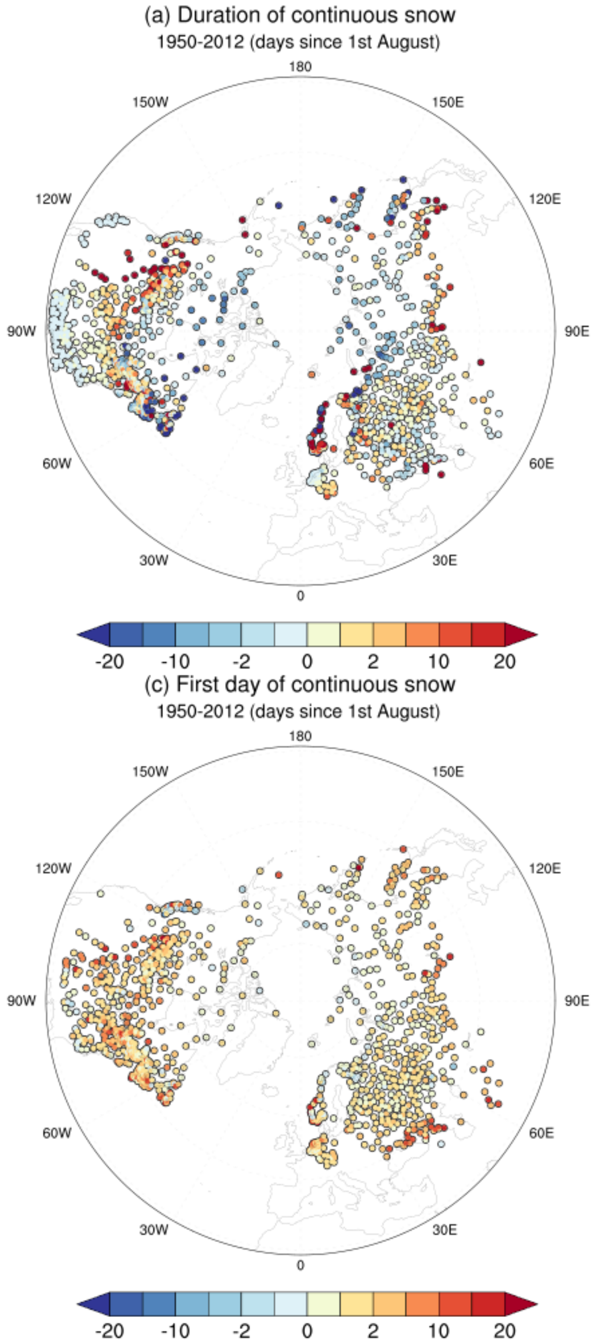

Figure 6. Bias between measurement stations and Crocus-ERA5 for 1950-2012 concerning their temporal phases: (a) Duration of continuous snow, (b) Maximum date of snowfall, (c) First day of continuous snow and (d) Last day of continuous snow.

Table 2. Statistics of biases between monitoring stations and Crocus-ERA5 for two levels of climatic normals: the period 1950-1980 related to the past climate and the period 1981-2012 related to the present climate.

	1950-1980					1981-2012				
Dataset	Cocus	Obs				Cocus	Obs			
Variables	Mean	Mean	Bias	R	RMSE	Mean	Mean	Bias	R	RMSE
averaged snow depth (m)	0.07	0.07	0.01	0.82	0.06	0.07	0.08	-0.00	0.84	0.06
annual maximum snow depth (m)	0.29	0.30	-0.01	0.80	0.20	0.31	0.34	-0.02	0.84	0.19
date of maximum snow depth*	197.84	199.72	-1.88	0.55	35.24	198.34	200.25	-1.91	0.60	32.30
number of days with snow per year	85.97	86.54	-0.57	0.97	18.49	88.66	90.71	-2.06	0.98	17.17
first day of continuous snow*	112.69	104.85	7.84	0.86	20.12	109.90	101.70	8.20	0.84	20.21
last day of continuous snow*	238.70	249.95	-11.25	0.88	21.92	240.44	252.43	-11.98	0.88	21.36
duration of continuous snow	78.44	75.19	3.25	0.96	23.48	80.99	78.74	2.25	0.96	22.08

*number of days since 1st August

Table 2 shows the statistics of some Crocus-ERA5 variables related to the station measurements for the two periods 1950-1980 and 1981-2012. The lowest inter-annual correlations (R) are for the date of maximum snow depth with 0.55 and 0.60 for the periods 1950-1980 and 1981-2012 respectively, although this date remains quite close on average for both in situ observations and Crocus-ERA5, whatever the period. This point is relevant because of long-term trends in climate change may shift the maximum date of snowfall. Our results show that the climate has remained rather stable in the years leading up to 2012. All others variables exhibits significant correlations with R > 0.8. The strongest correlations (R>=0.96) are for the number of days with snow and the duration of continuous snow cover, reflecting the quality of both the Crocus snow model and the precipitation estimated by ERA5.

3.3 Snow Cover

The monthly SCE anomalies relative to the period 2000-2022 as its climatology were assessed in terms of their seasonality and inter-annual variability (Figure 7). Although the differences are striking with a high degree of inter-annual variability, three points stand out : (i) the good agreement from January to May, overlaps with the spring period (MAM), when SCE decreases sharply – the agreement in March is especially remarkable ; (ii) the disagreement in June when SCE anomalies is still significant in IMS ; and (iii) the broad agreement for the autumn (SON), with consistent inter-annual variability even there are some differences in magnitude.

Minor differences in small orders of magnitude, that lead to shifts between positive and negative values, can be seen here or there (e.g. April 2000, 2005, 2008 and 2015). Some zones of positive (green) and negative (brown) SCE anomalies can be detected as a ten-year alternation for both Crocus-ERA5 and IMS in autumn. In June, SCE anomalies are much more pronounced in the IMS indicating that snow remains longer on the land surface (Figure 7, left panel); this is even more evident

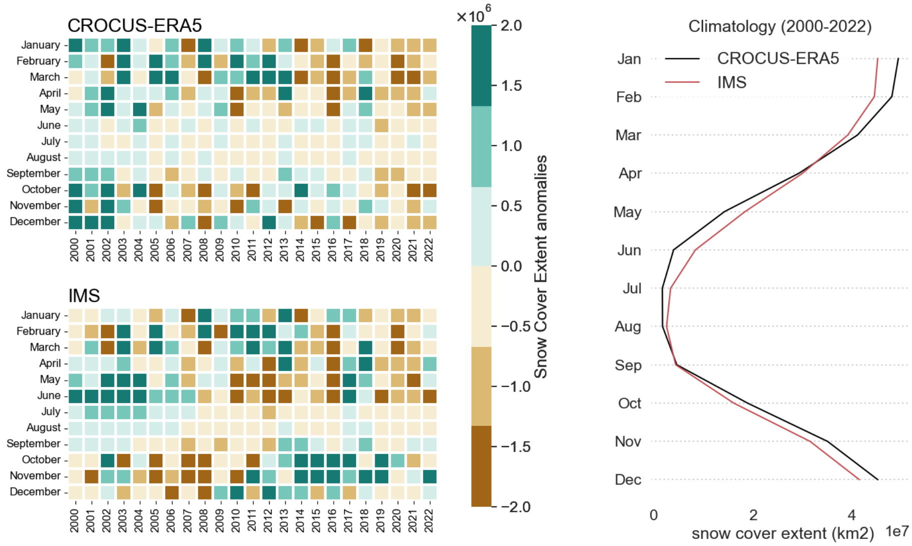

Figure 7. (Panels left)Time series of monthly snow cover extent (SCE) anomalies from January 2000 to December 2022, calculated relative to the mean snow depth for 2000-2022. Positive anomalies are shown in blue-green, while negative anomalies are shown in brown. (Panels right) Monthly climatology of SCE for Crocus-ERA5 (black line) and IMS (red line). The x-axis represents climatological values, while the y-axis lists months from January (top) to December (bottom).

in the climatology, where the Crocus-ERA5 SCE (black curve) drops sharply to near zero while the IMS curve (red) still shows significant snow cover (Figure 7, right panel).

SCE varies considerably with geographical location and local climatic conditions, particularly in the northernmost regions when vegetation emerges in early summer. However because Crocus-ERA5 does not take into account interactions with vegetation anomalies, it can significantly alter these dynamics in early summer - a limitation particularly evident in Figure 9, for spring (MAM). As a result, snowmelt in Crocus-ERA5 occurs more rapidly than in IMS over northern western Canada, southern eastern Canada and eastern Siberia. Furthermore, since Crocus-ERA5 only represents open areas with low vegetation, it may fail to accurately capture wind-driven snow redistribution, resulting in biases in snow depth and duration estimates in regions where blowing snow and drifting processes strongly influence snowpack evolution.

Figure 8 illustrates the evolution of the monthly anomalies of continental SCE across the Northern Hemisphere from Crocus-ERA5 and IMS for the period 2000-2022 . The correlation between the two datasets is 0.72, indicating they originate from the same distribution. Both time series show very similar seasonal variability, but there are differences in the magnitude of the peaks, which may explain the difference in trends. The long-term trend of SCE in the northern hemisphere from 2000 to 2022 is slightly downward in both time series although the Crocus-ERA5 exhibits a steeper decline compared to IMS with respectively a slope of -1.9×10^{-12} and -4.5×10^{-13}. In physical terms, these slopes suggest a gradual trend in snow cover anomalies over 2000–2022, evolving slowly over very large timescales. This highlights the progressive nature of changes.

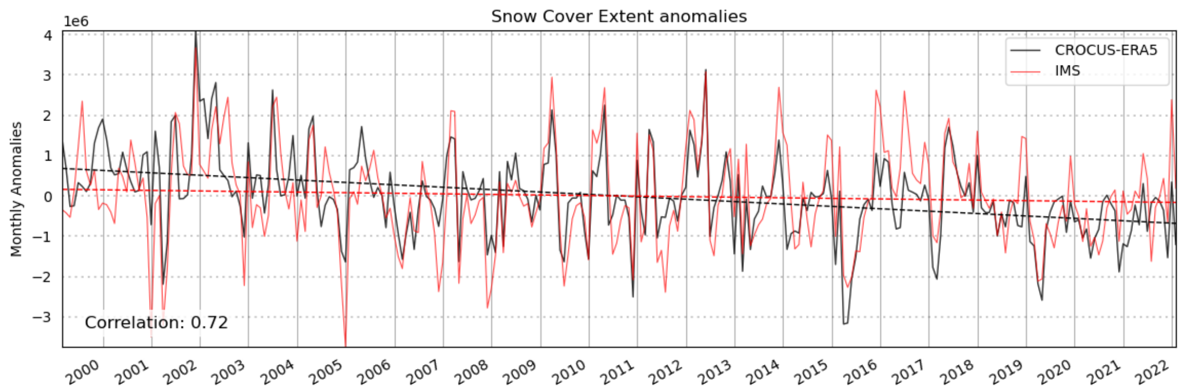

Figure 8. Time series from January 2000 to December 2022 of monthly SCE standardized anomalies presented as a continuous line graph to illustrate trends and variations over the specified period.

The Northern hemisphere-wide snow cover fraction from Crocus-ERA5 is compared to that from the IMS long-term analysis to assess biases (Figure 9). During autumn (SON) and winter (DJF), above 60°N, there is strong agreement between Crocus-ERA5 and IMS, as most of continental North America and Eurasia is entirely covered with snow. However, below 60°N, in mountainous regions where snow cover is highly uneven, a positive bias is found between Crocus-ERA5 and IMS. This may be related to a poor representation of the topography at 0.25° resolution and thus to an overly simplistic relationship between simulated snow height and diagnosed snow cover used in Crocus in mountainous regions at this resolution. Snow extent seasonality is closely related to air surface temperature and radiative forcing, and in autumn and winter (low radiative forcing) is influenced by both temperature and precipitation. On the plains, and with accurate atmospheric forcing, Crocus-ERA5 shows excellent performance.

During spring (MAM), snow thickness decreases as temperatures (and radiative forcing) increase, leading to snow thinning and eventual melting. The spring thaw typically starts at lower latitudes and elevations and gradually moves northwards and to higher elevations as the season progresses. In Crocus-ERA5, snow melts more rapidly than in IMS over northern western Canada, southern eastern Canada and eastern Siberia. This bias is partly due to the model's lack of representation of boreal forests at high latitudes (below 60°N), which delay snowmelt by limiting incoming radiation at the snow surface (Decharme et al., 2019). The presence of the boreal forest prolongs the duration of snow cover in comparison to areas devoid of such vegetation. In Crocus-ERA5 the snowpack is simulated as an open-field surface so it does not take into account such process. Moreover, Crocus-ERA5 assumes a fixed herbaceous, so it cannot capture impact of tundra emergence above 60°N, which alter snowpack dynamics in early summer.

In summer (JJA), the negative effect of high altitude on the agreement between the two snow cover products is reduced by the absence of snow. There are negative biases in the northernmost part of the Arctic, excluding Greenland, which correspond to the largest region of the tundra biome, however the differences remain below 10%.

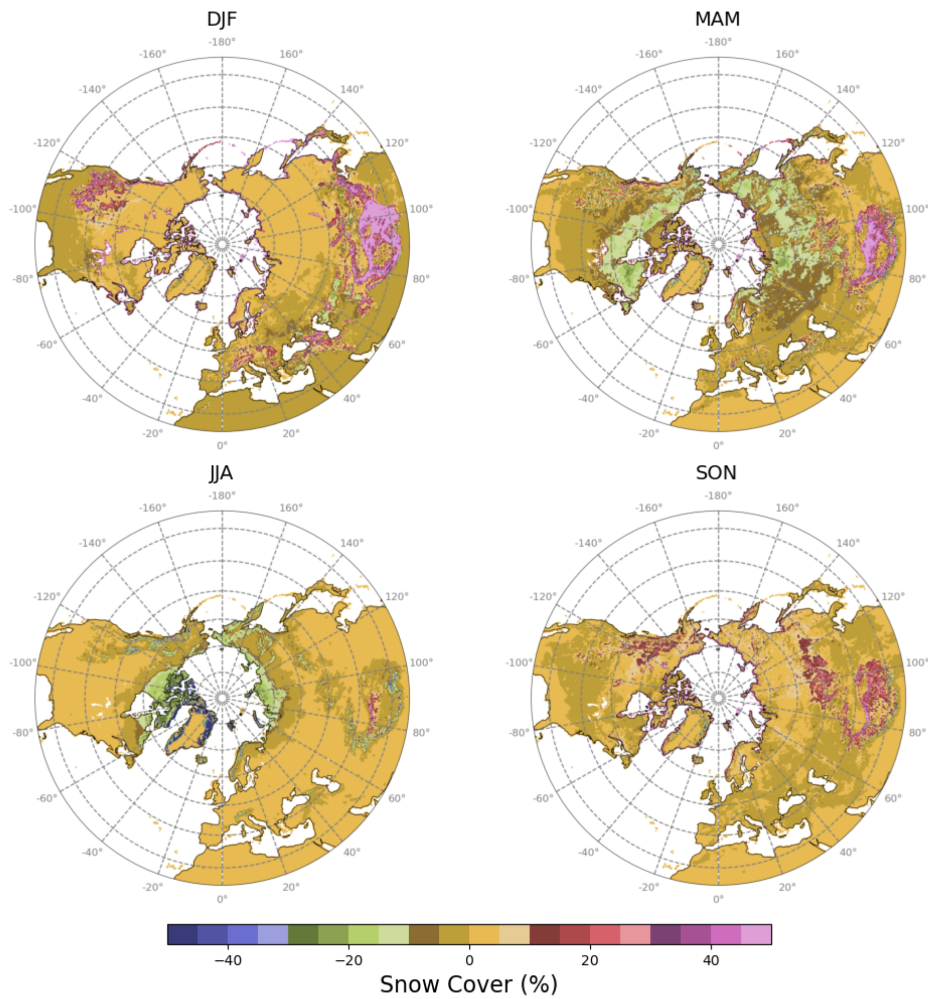

Figure 9. Northern hemisphere distributions of mean seasonal snow fraction biases of Crocus-ERA5 compared to IMS estimates in winter (DJF), spring (MAM), summer (JJA) and autumn (SON) over the period 2000-2022.

In autumn (SON), the emergence of continental snow cover shows significant bias only over mountains range as Yablonoi and Rocky Mountains.

4 Conclusions and Perspectives

This paper is based on the two variables most representative of snow characteristics and commonly used to monitor snow, snow depth and snow cover. The challenge was to validate model simulations against independent data in order to minimize the uncertainty attributed to the interdependence between explained and independent variables. The strengths of this study include direct comparisons of Crocus-ERA5 with homogeneous long-term time series from in situ snow depth observations and gridded satellite multi-sensor analyses of snow cover fraction. Comparisons reveal a strong overall performance of Crocus-ERA5 in capturing snow dynamics in the Northern Hemisphere.

Sensitivity to atmospheric forcing was assessed by comparing Crocus-ERA5 with Crocus-ERA-Interim (Crocus-ERAI), for the common period 1979 to 2018. The ERA5 forcing uses an advanced land data assimilation system. Its higher spatial resolution of 0.25° provides more detailed representations of topography and land cover than ERAI, which has a resolution of 0.75°. This led to snow depth increase and snow cover decrease in Crocus-ERA5 compared to Crocus-ERAI. Regarding snow depth, Crocus-ERA5 is in agreement with Crocus-ERAI in terms of inter-annual variability and seasonal cycles in Eurasia and North America. It is noteworthy that Crocus-ERA5 tends to produce stronger anomalies, which are consistent with improvements in the atmospheric forcing. A persistent negative trend in snow depth over Eurasia is evident since 2000, while North America shows greater inter-annual variability. The statistics (mean and standard deviation) show a shift in the CROCUS-ERA5 distribution toward higher values. The standard deviation varies similarly around the mean for both Crocus-ERAI and Crocus-ERA5 distributions, in both regions, Eurasia and to a lesser extent, North America. Crocus-ERA5 shows generally higher snow depth than Crocus-ERAI in spring, especially in Eurasia.

The climatological periods 1950–1980 and 1981–2012 reveals strong agreement in snow depth between Crocus-ERA5 and in-situ data. The ability of Crocus-ERA5 to represent daily snow depth (or mass, related to depth by density) is assessed relative to long-term snow depth on 10 March for various in-situ stations covering different geographic regions in Canada and Eurasia. The long-term Crocus-ERA5 snow depth aligns remarkably well with in-situ observations, demonstrating its ability to capture inter-annual variability. In Canada, the simulation performs well across a range of environments, including complex regions as mountains, hills and glacier-carved lakes. In Eurasia, although there is a slight overestimation of snow depth in earlier decades, Crocus-ERA5 shows good phase and amplitude agreement in snow occurrence, particularly from the 1990s onward.

Compared to the IMS multi-sensor product, Crocus-ERA5 performs less effectively in early summer due to its idealized herbaceous surface with fixed climatological properties and its omission of forest-snow interactions. This simplification introduces a bias , causing snow disappear too early in regions where vegetation is evolving. For example, Crocus-ERA5 fails to capture the impact of tundra emergence at higher latitudes (above 60°N). As a result, CROCUS-ERA5 proves to be a reliable tool for simulating snow dynamics in all seasons and regions, exepted during June especially in Arctic circle. From early autumn to late winter, the snow cover fraction in Crocus-ERA5 shows a positive bias compared to the IMS dataset in mountainous regions below 60°N, likely due to coarse topographic representation.

To effectively assess water resources and forecast spring runoff, it is essential to measure the total water stored in snowpack using Snow Water Equivalent (SWE) as a key indicator. SWE reflects snow density and compactionand plays a critical role in Arctic amplification and climate change by influencing snowmelt timing and extent. There are major differences in time and spatial resolution between existing SWE products (Mudryk et al., 2024), which significantly limits their usefulness in studies of the cryosphere and climate change . Long-term time series from climate models or remote sensing data have spatial accuracy often limited, especially in areas where snow processes, such as melting and compaction, are not well-represented. Winkler et al. (2021) proposed a method to estimate SWE using only snow depths, which outperforms models relying on empirical regressions. Fontrodona-Bach et al. (2023) regionalized this method to create the NH-SWE dataset for the Northern

Hemisphere. Shao et al. (2022) developed a high-precision SWE product by integrating various existing SWE data sources into a Ridge Regression Model (RRM), which uses machine learning. The temporal resolution of the RRM SWE product is daily, and the spatial resolution is 10 km. The study demonstrated that this method is effective for creating SWE products on a global scale, offering seamless spatial and temporal coverage. The RRM SWE product minimizes dependence on a single SWE dataset, optimally utilizing multiple SWE sources and considering altitude. While this paper focuses on direct spatio-temporal validation of the Crocus-ERA5 snow product using independent data, an interesting future direction would be to evaluate SWE from Crocus-ERA5 against these newly datasets. It should be noted, however, that recently Mudryk et al. (2024) showed that Crocus-ERA5 was one of the most effective product for reproducing SWE in the Northern Hemisphere, at least in plain areas.

5 Data availability

The new ***Crocus-Era5*** dataset is free to access and available at https://doi.org/10.5281/zenodo.14513248 (Decharme et al., 2024). The dataset is provided over the period 1950-2023 in netcdf format and contains modelled daily snow depth, snow water equivalent, liquid water content in the snowpack, snow albedo, snow surface temperature, snowpack internal temperature, and snow cover fraction. The previous ***Crocus-Era-Interim*** dataset is free to access and available at https://doi.org/10.5281/zenodo.14513040 (Decharme, 2024). The dataset is provided over the period 1979-2019 in netcdf format and contains modelled daily snow depth and snow water equivalent, as well as monthly snow surface temperature, snowpack internal temperature, and snow cover fraction.

Author contributions. BD defined the scientific framework, performed the numerical simulations and supervised the findings. SRB defined the methodology and selected the relevant datasets, pre-processed the observational data, developed the analytic calculations, performed the analysis and wrote the manuscript. AB and LF performed the ERA5 and the ERA-Interim atmospheric forcing, respectively.

Competing interests. The authors declare that they have no competing interests.

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