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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 extent 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 in spring in Eurasia. The findings show a good match with observations, though biases remain, particularly in boreal forest areas and some Arctic regions, where the model tends to overestimate spring melt. The production of this snow dataset is motivated by its use by the continental cryosphere community, and in particular by the collaboration between the French National Center for Meteorological Research (CNRM) and Environment and Climate Change Canada (ECCC), which has been involved in Arctic snow cover monitoring 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. This decline is particularly pronounced during the late summer and early autumn months, which leads in an increased heat storage capacity of the ocean, thereby delaying the formation of ice at the onset of the cold season. Simultaneously on land, near-surface permafrost temperatures have reached unprecedented levels, resulting in the formation of deeper active layers than previously observed with significant implications

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for soil stability, surface hydrology, and carbon emissions which in turn can contribute to climate warming. Finally, snow depth and overall snow cover duration is significantly impacted. For example, since the 1970s, snow cover has declined significantly in the northern hemisphere (Derksen and Mudryk, 2023; Mudryk et al., 2023).

The aforementioned evidence 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.

The motivation for the present study stems from the fact that, since 2017, the French National Center for Meteorological Research (CNRM) is 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 extent and mass each year (e.g. Mudryk et al., 2023). Unlike sea ice, terrestrial snow is entirely absent from the Arctic land surface during the summer months. The extent of Arctic snow is particularly sensitive to temperature variations, especially at the beginning of autumn and during the subsequent thaw in spring. Variations in snow have a profound effect on a number of key environmental processes, including the surface energy budget, permafrost stability, the timing of snowmelt contributions to streamflow, and the habitats of Arctic flora and fauna. Consequently, snow has become an important indicator of the impact of climate change in the Arctic, and is frequently included in global climate assessments (Derksen and Mudryk, 2023).

The CNRM contribution to the "Terrestrial Snow" ARC is to provide a daily snowpack product derived from the Crocus complex snow scheme (Brun et al., 1992, 1989) in order to take part of monitoring and improving of knowledge on the snow cover and mass of the North Hemisphere (NH). 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/). Until 2020, the model was driven by a meteorological forcing (temperature, precipitation, humidity, win s, etc.) derived from the ERA-Interim global atmospheric reanalysis (Dee et al., 2011, https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-interim) of the European Centre for Medium-Range Weather Forecasts (ECMWF). In Brun et al. (2013), this *Crocus-ERA-Interim* daily snow product was validated against local observations from over 1000 monitoring stations in northern Eurasia. Despite it uses 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) and can be freely downloaded at https://doi.org/10.5281/zenodo.14513040 (Decharme, 2024). Recently, our snow product has been updated using the

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same Crocus configuration but driven by the fifth generation of the ECMWF global atmospheric reanalysis (ERA5, Hersbach et al., 2020, https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5). This *Crocus-ERA5* product covers the entire Northern Hemisphere at 0.25° resolution over the 1950-07-01 to 2023-06-30 period. All snow characteristics are freely available on a daily basis at https://doi.org/10.5281/zenodo.14513248 (Decharme et al., 2024). 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 will be used in a number of studies on the evolution of the Arctic snow cover in the coming years. The Crocus-ERA5 product is a representation of the snowpack without forest, i.e. it concerns only the snowpack of open areas and only low vegetation is modelled as in Brun et al. (2013). 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. 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 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-ERA-Interim, 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

Warming and more frequent winter thaws are contributing to changes in snow pack structure with important implications for snow distribution. The performance of snowpack modelling in this context of climate change, can be summarized by the two main variables used as indicators of climate change because of their interactions and feedbacks with surface energy: the snow depth and the snow cover. Furthermore, 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. These two variables, strongly linked to each other, reflect the direct response of atmospheric forcing and provide 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-ERA-Interim 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.

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Snow depth is a critical variable for seasonal and long-term evolution of frozen ground and permafrost. Its changes have significant implications in atmospheric circulation and potentially may impact the weather in other parts of the world. For instance, large snow depths in western Russia have been associated with local cyclonic circulation as the northerly flow on west of the trough favour the advection of cold air into the regions, thereby preserving the mantle snowy. Locally, over regions at higher latitudes or altitudes the dynamics of snow depth may favour more prolonged periods of snow cover and thus be further modulated by local environmental conditions. For instance, extreme weather events such as blizzards, can lead to rapid changes in snow depth over short periods. The sensitivity of snow depth to atmospheric conditions and its interaction with them underline that this key variable plays an important role in the energy balance of the Earth's surface, the ground thermal regime and the water cycle. For these reasons, a major effort has been made over the years by various countries in the northern hemisphere to carry out extensive and consistent measurements of snow depth. 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. A series of daily observations were collated for over 2,000 stations spanning the period from 1950 to 2012. Given that a significant number of measurements are conducted at synoptic stations in accordance with the standards set forth by the World Meteorological Organization, the vast majority of the observations pertain to bare ground or open areas with regular grass cutting (e.g. Schellekens et al., 2017, https://doi.org/10.5194/essd-9-389-2017-supplement). This dataset is particularly valuable due to its extensive spatial and temporal coverage that offer robust insights into historical snow depth variability and trends. Decharme et al. (2019) described the processing to this dataset namely the difference between local and model elevation inferior to 100 m, a number of days with a non-zero measurement greater than 100 days over the whole period and, at least 8 snowy days per year. Furthermore snow depth is not obtained directly from satellite estimates but derived from satellite snow water equivalent if snow density is known or estimated. Therefore, there are still large uncertainties in satellite snow depth data, and we prefer to validate snow depth against this exceptional dataset of in-situ measurements. 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).

Snow cover extent is an important proxy for climate change in the Northern Hemisphere. Its seasonal cycle drives a number of important energy and water cycle processes. The Arctic land surface is subject to many processes arising from seasonal snow cover dynamics that drive the seasonal thermal regime of the ground with implications for the carbon cycle, permafrost, and terrestrial and freshwater ecosystems. Namely, in spring when the observed snow cover extend decreases, it directly influence the extent of the climatic cooling, the timing and amount of river runoff, permafrost thawing, wildlife and fire rise. Across the boreal forest, early snow loss in late spring leads to greater carbon uptake in subsequent months, affecting gross primary carbon production. In general, the timing of snow onset and melt simulated by a large-scale model cannot be evaluated over a large regions with in situ observations, especially in southern regions where snow cover is sparse. Satellite estimates offer valuable data for assessing snow cover dynamics, helping to overcome limitations. Furthermore, over the years, significant

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advancements in snow cover extent analysis, particularly through multi-sensor approaches, have greatly improved mapping by reducing uncertainties from relying on sparse, single-sensor data. The ability of the Crocus-ERA5 to map snow cover extend is thus 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 resolution and accuracy have advanced due to the integration of various technologies and data sources, including NOAA AVHRR, MODIS, VIIRS, and Sentinel satellites, alongside in-situ observations and NCEP model data (Helfrich et al., 2007). It differentiates between snow and clouds using time-sequenced satellite images and has become a more efficient tool for validating snow cover over large areas like the Northern Hemisphere (Estilow et al., 2015). To get as close as possible to model resolution, snow cover from IMS is used here at a spatial resolution of 24 km for the period 2000-2022.

3 Crocus-ERA5 assessment

3.1 Comparison with the Crocus-ERA-Interim product

The latest global meteorological reanalysis ERA5 differs from its predecessor, ERA-Interim (hereafter referred to as ERAI), in terms of temporal coverage, spatial resolution and, in particular, it benefits from more than a decade of developments in model physics, core dynamics and data assimilation (Dee et al., 2011; Hersbach et al., 2020). ERAI data are available from 1979 to August 2019 whereas ERA5 cover the period from 1950 to the present, with continuous updates. The spatial resolution of ERA5 is approximately 0.25° latitude/longitude, whereas that of ERAI is of approximately 0.75° latitude/longitude. The ERA5 reanalysis includes an advanced land data assimilation system, which has been enhanced to include improvements in hydrological variables such as soil moisture and snow depth. This enhances the utility of ERA5 for the study of land surface processes and water cycle dynamics. The higher spatial resolution of ERA5 allows for a more detailed representation of topography and land cover compared to ERAI, which can influence the simulation of surface processes and atmospheric circulation patterns.

The variability of monthly snow depth is highlighted by the changes in its monthly anomalies over time, both 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. 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 correlated with the extent of snow cover, particularly in terms of its spatial distribution. The anomaly of snow cover varies considerably depending on the geographic location and local climate conditions. In the northernmost regions of North America and Eurasia where the largest tundra biome is found, the presence of snow cover

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during the winter months acts as an insulator for the underlying soil, limiting the flow of carbon from the northern permafrost. In particular, variations in snow cover in Eurasia can influence the thermal regime of permafrost, which may have consequences for the release of greenhouse gases. In the late spring (April to June), a decrease in snow thickness is observed as temperatures rise, leading to snow melt. Figure 2 shows the standardized anomalies in snow cover for land areas situated within the Arctic Circle (latitudes > 60° N) for the period of late spring, and for both the North American and Eurasian regions. Over these regions, the Crocus-ERA5 and the Crocus-ERAI snow cover products exhibit a closely similar variability, although the North American anomalies for Crocus-ERA5 in May and June seem to be less negative after the beginning of the 2000s. These results indicate that these products have equivalent deviations from the mean of their respective distributions.

The monthly standard deviation of snow depth from its mean on the land surface for the months of April and May on the period 1979-2018, highlight the main differences between both products. There is a more significant divergence for Eurasia than for North America (Figure 3). 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.

3.2 Snow depth

The annual cycle of snow depth is characterised by a gradual accumulation of continental snow from October to March, followed by a rapid ablation of the snowpack during the spring and summer months (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. In order 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.

The spatial distribution of the snow depth is generally well reproduced by Crocus-ERA5. 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. 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

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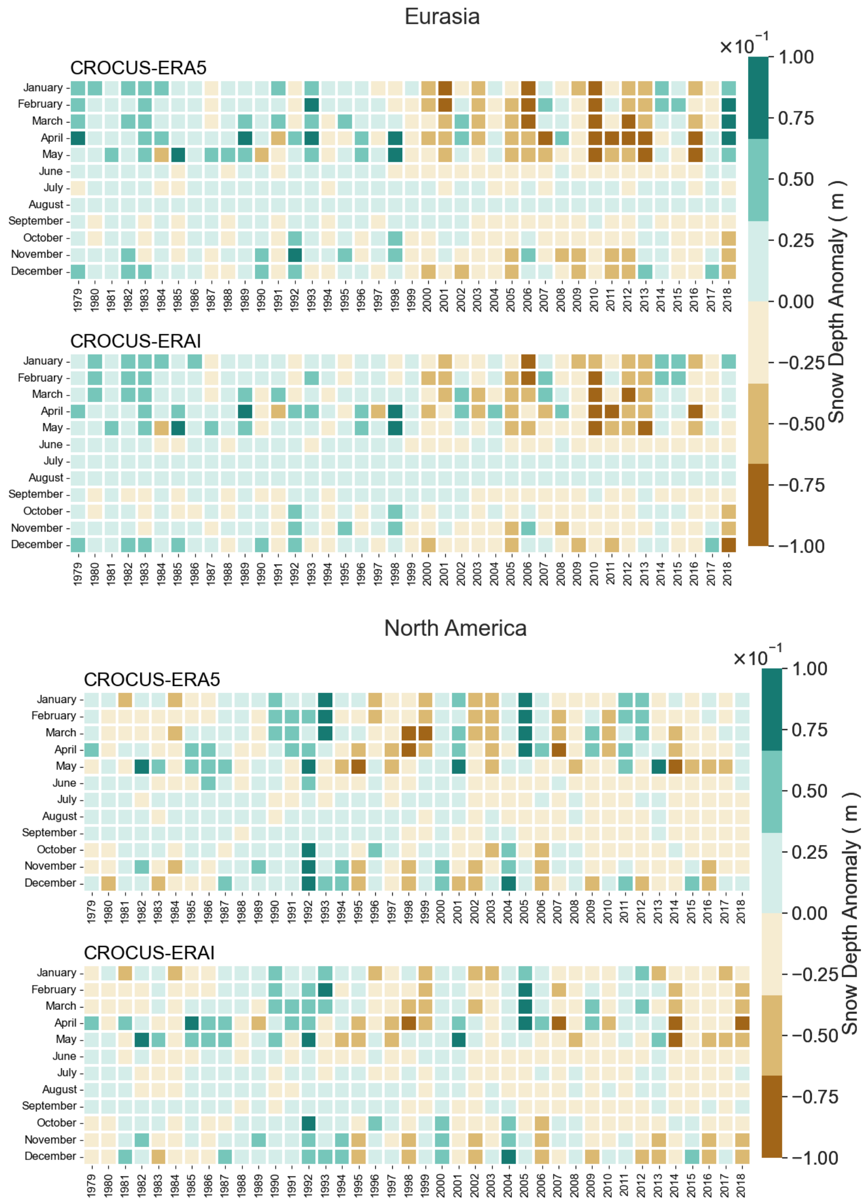

Figure 1. Time series of monthly snow depth anomalies from January 1979 to December 2018. Monthly snow depth anomalies are calculated relative to the mean snow depth for the period 1979-2018. Months with positive anomalies are shown in blue-green, while months with negative anomalies are shown in brown. Adapted from Figure 1 in Mudryk et al. (2020).

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

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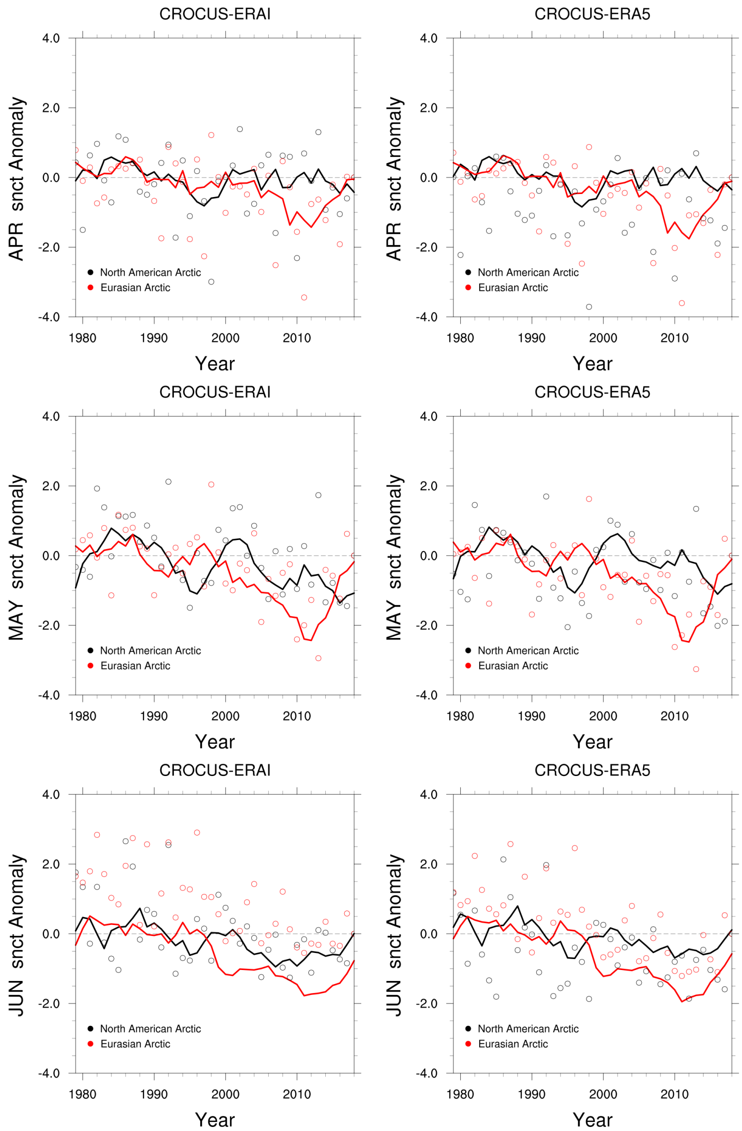

Figure 2. Monthly time series of total areal snow cover fractions are shown as anomalies relative to the period 1979-2018. Land surface averages for North America and Eurasia refer to latitudes above 60° N. Filled circles are used to highlight anomalies relative to 2018. Adapted from Figure 1 in Mudryk et al. (2023).

represented. This performance has been already highlighted by Brun 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

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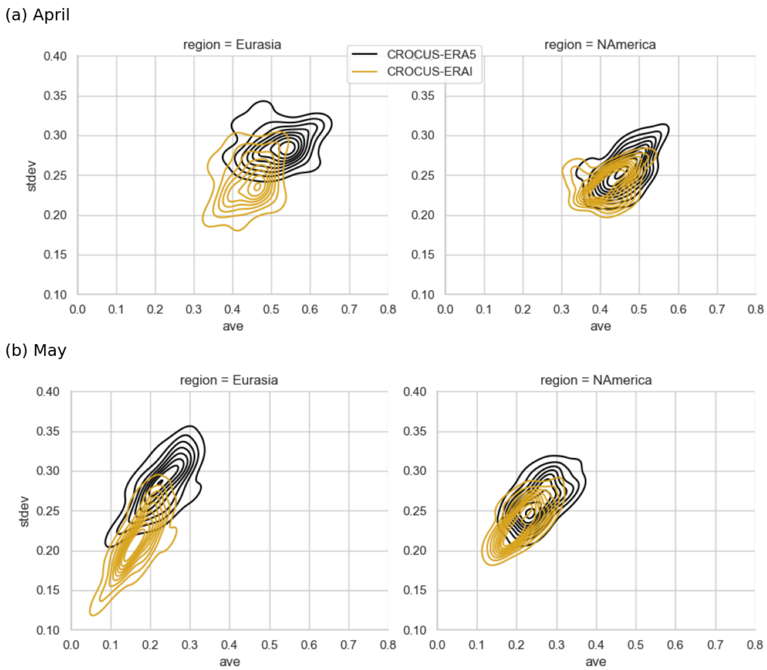

Figure 3. Monthly standard deviation of snow depth from its mean on the land surface for North America (left) and Eurasia (right) with respect to latitudes above 60° N. Representation of the months **(a)** April and **(b)** May.

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. 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). 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).

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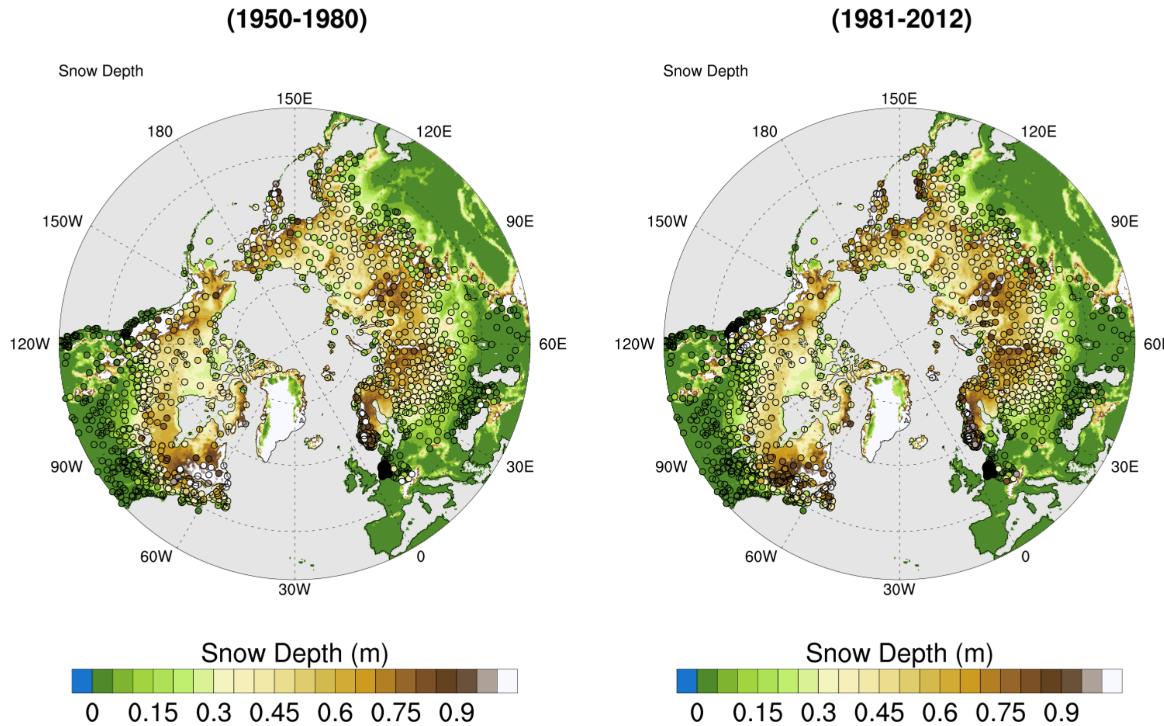

Figure 4. Time-averaged snow depth from Crocus-ERA5 (2D field) for the two climatological periods 1950-1980 and 1981-2012 on 10 March superimposed on the corresponding time-averaged observed snow depth (circles).

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.

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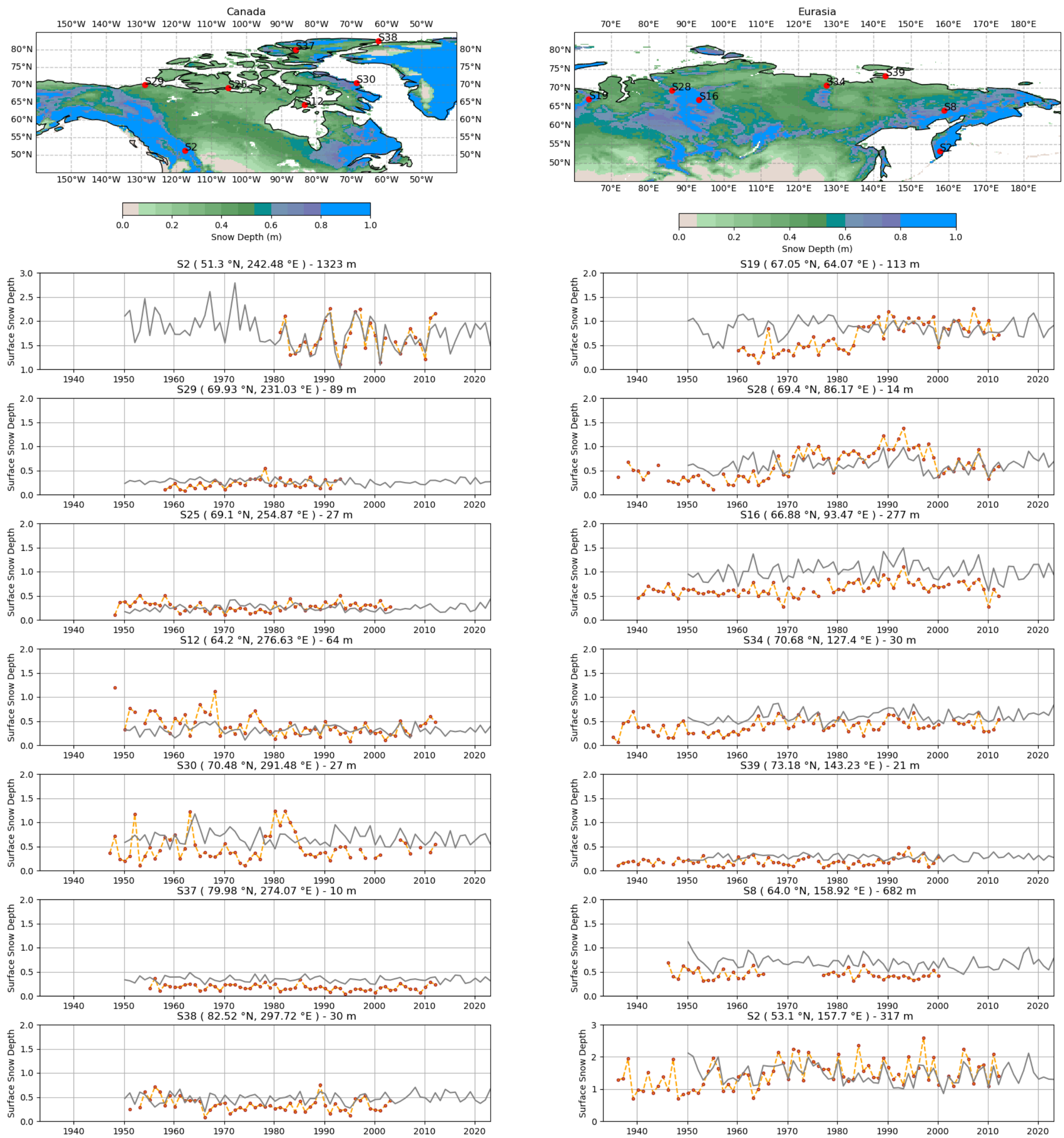

Figure 5. Location of stations on the spatial distribution of time-averaged snow depth in March for the period 1950-2022 and the two domains, Canada and Eurasia (top left and top right, respectively). Under each domain (column) the time series of snow depth for each station is shown for both Crocus-ERA5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

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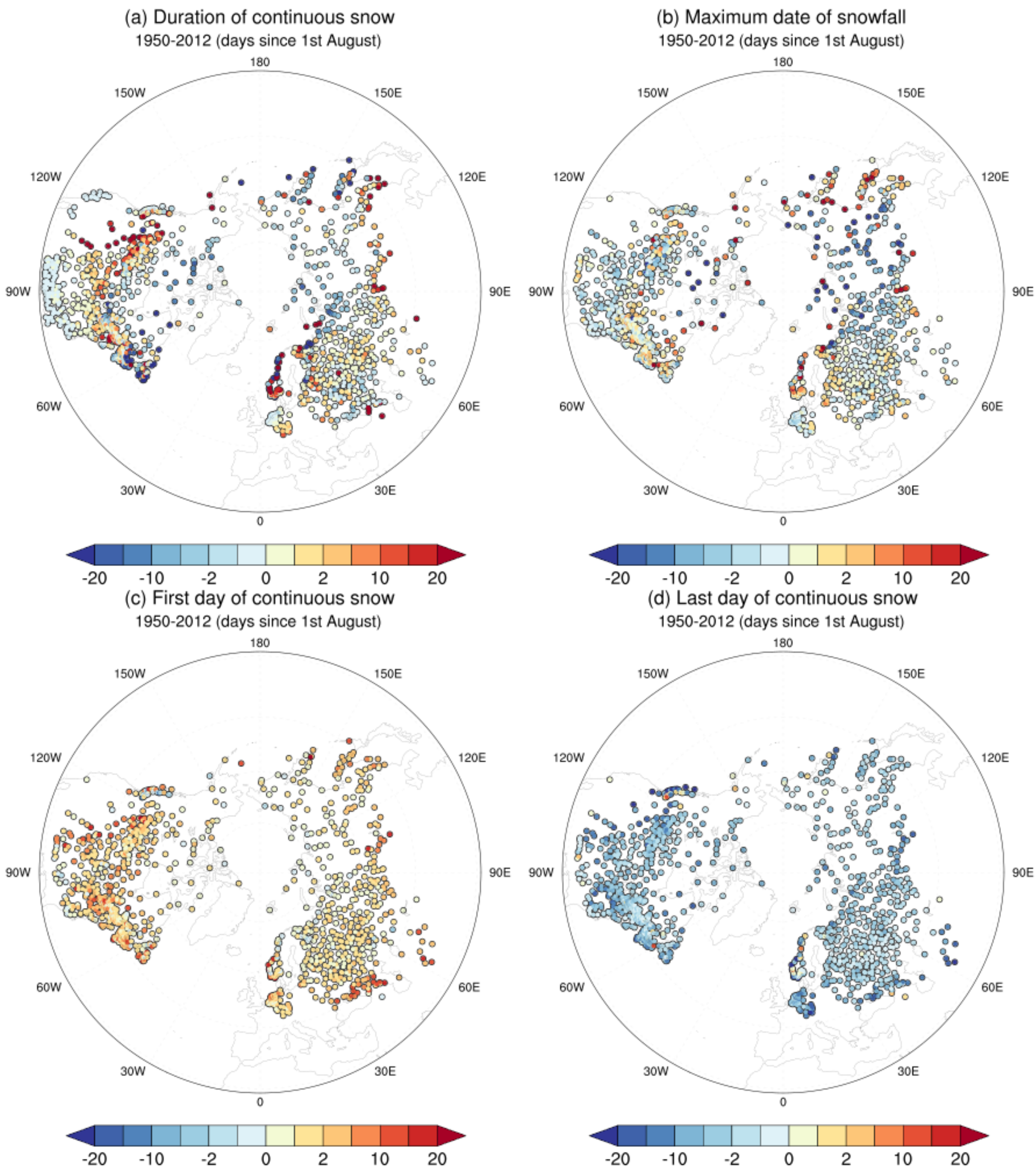

Figure 6. Bias between measurement stations and Crocus-ERA5 for 1950-2012 concerning their temporal phases: (a) Duration of continuours snow, (b) Maximum date of snowfall, (c) First day of continuous snow and (d) Last day of continuous snow.

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Figure 6 compares the Crocus-ERA5 and observations for the period 1950-2012 in terms of average duration, maximum, 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 1), allowing accurate estimation and forecasting of changes in snow cover.

Table 1 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 extent

The monthly snow cover anomalies relative to the climatology for the period 2000-2022 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 2007 for the months of January to May, overlapping with the spring period (MAM) when the strong decrease in snow extent occurs ; (ii) the disagreement for the month of June when the snow cover continues to decrease in IMS ; and (iii) the good agreement for the autumn (SON), although there are some differences in magnitude. In spring, the seasonal cycle of snow cover is well reproduced, with only minor differences in small orders of magnitude that can lead to shifts between positive and negative values. Note that the years 2001, 2002 and 2006 show significant positive snow cover anomalies in Crocus-ERA5, but the signal remains consistent with IMS. The El Niño event of 2006-2007, which affects atmospheric circulation and contributes to global warming, favours typical weather patterns. These patterns have been accurately reproduced by the atmospheric forcing, which may result in Crocus-ERA5 snow cover anomalies closely matching those of IMS. In autumn, as in spring, the early 2000s show more significant positive snow cover

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Table 1. 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

anomalies in Crocus-ERA5 than in IMS. Note that in October a decadal shift between decreases and increases in snow cover is well phased. However, in June the snow cover anomalies are positive and more pronounced in the IMS dataset for most of the climatological period indicating that snow remains longer on the land surface. Snow cover varies considerably with geographical location and local climatic conditions, particularly in the northernmost regions when vegetation emerges in early summer. 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), so it does not take into account interactions with vegetation anomalies, which can significantly alter these dynamics in early summer when vegetation emerges.

The evolution of the monthly anomalies of continental snow cover in the Northern Hemisphere from CROCUS-ERA5 and IMS for the period 2000-2022 is shown in Figure 8. The correlation is 0.73 with a p-value of 0.87, indicating that the two curves come 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 snow cover 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 -2.2×10^{-19} and -6.6×10^{-20}. However, the Mean Absolute Error (MAE) between the two curves is of 0.066 showing that the average absolute difference between the two series is relatively small. In physical terms, these slopes suggest a gradual trend in snow cover anomalies over the time period 2000-2022 that is slowly evolving on very large timescales. It might make sense as a highlight of these minimal changes.

The overall Northern hemisphere-wide area covered by snow from Crocus-ERA5 is compared to those from the IMS long-term analysis (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

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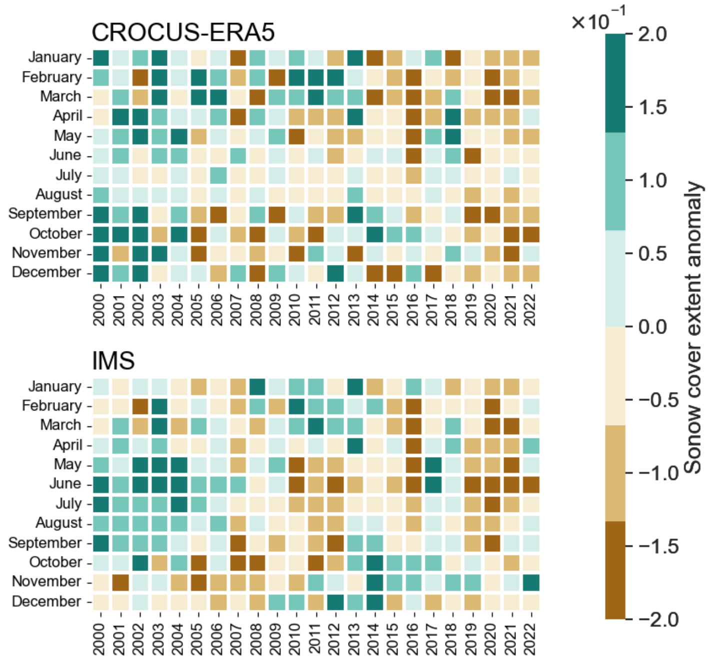

Figure 7. Time series of monthly snow cover extent anomalies from January 2000 to December 2022. Monthly snow cover extent anomalies are calculated with respect to the mean snow depth for the period 2000-2022. Months with positive anomalies are shown in blue-green, while months with negative anomalies are shown in brown.

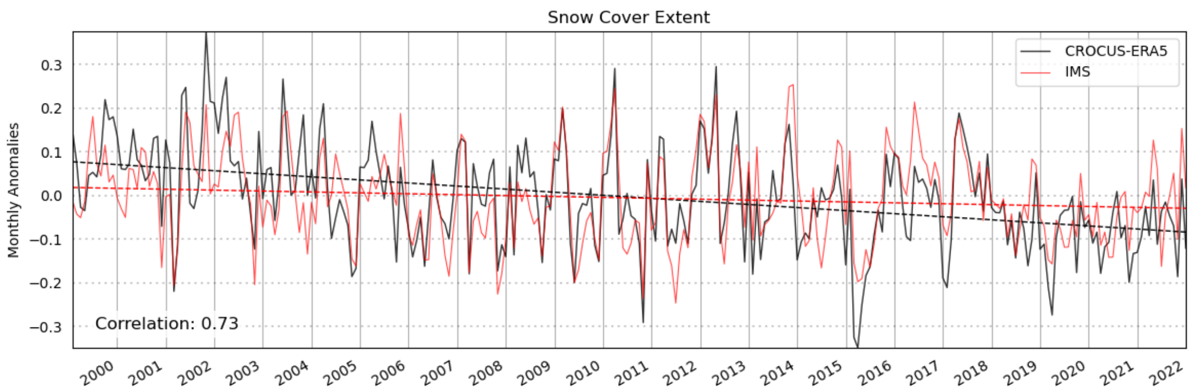

Figure 8. Monthly time series from January 2000 to December 2022. Monthly snow cover extent is presented as a continuous line graph to illustrate trends and variations over the specified period.

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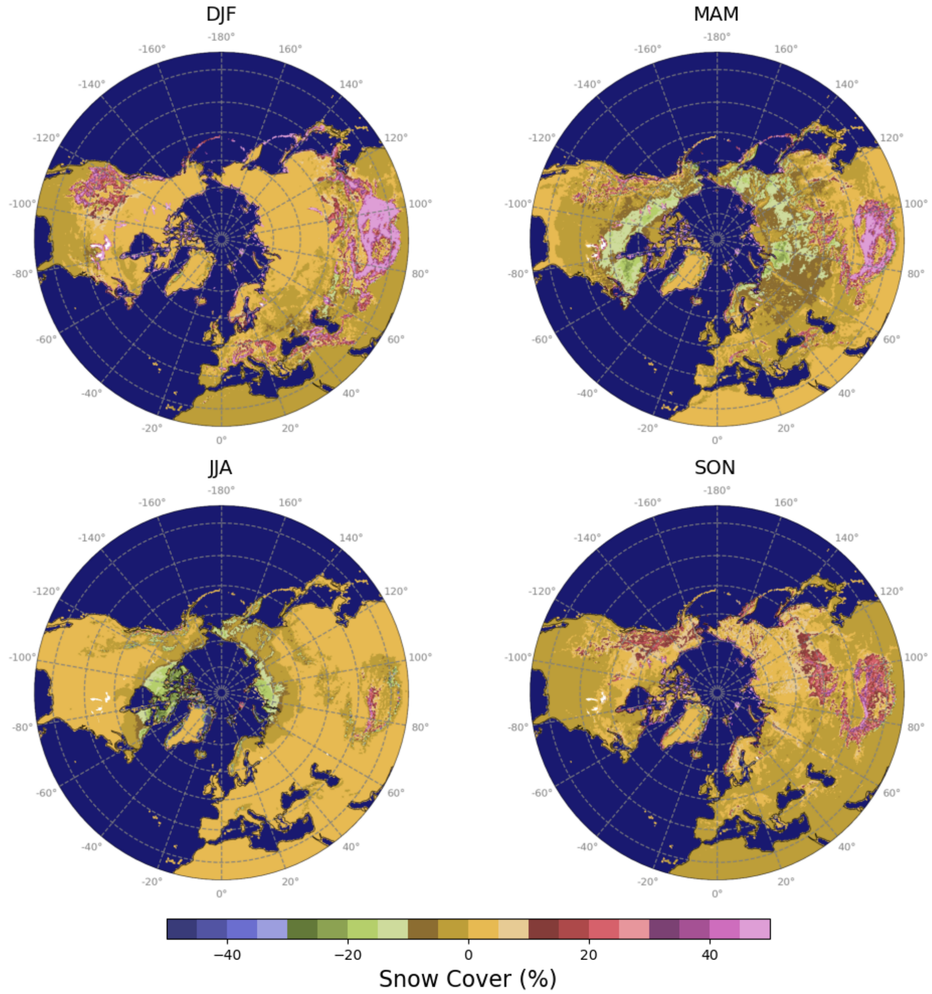

Figure 9. Northern hemisphere distributions of mean seasonal snow extent biases of Crocus-ERA5 compared to IMS estimates in winter (DJF), spring (MAM), summer (JJA) and autumn (SON) over the period 2000-2022.

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, the snow melting seems to occur more rapidly than in IMS over northern western Canada, southern eastern Canada and eastern Siberia. This weakness is

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well known for models that do not take into account the influence of the boreal forest on the timing of snowmelt (Decharme et al., 2019). By limiting incident radiations at the snow surface, 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. 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, due to the lack of snow cover over the melt zone in Crocus-ERA5. nally and widely, differences during the melt seasons remain inferior to 10%. In autumn, the emergence of continental snow cover shows significant bias only over mountains range as Yablonoi and Rocky Mountains.

4 Conclusions and Perspectives

This paper proposes a synthetic assessment of current Crocus-ERA5 snowpack over land, based on the two variables most 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.

Sensitivity to atmospheric forcing was assessed by comparing the Crocus-ERA5 product with its predecessor, Crocus-ERA-Interim, for the common period from 1979 to 2018. The ERA5 forcing includes an advanced land data assimilation system, and its higher spatial resolution of 0.25° in latitude/longitude offers more detailed representations of topography and land cover compared to ERA-Interim, which has a resolution of 0.75°. These improvements translate to increased snow depth and snow cover extent, particularly concerning spatial distribution. The Crocus-ERA5 shows generally higher values than Crocus-ERA-Interim in spring, especially in Eurasia. The distributions of snow depth highlight differences between both simulations for April and May, with a more significant difference observed in Eurasia than in North America. This comparison between the two products is important for the community that has been using Crocus-ERA-Interim (e.g. Mudryk et al., 2015; Mortimer et al., 2020; Kouki et al., 2023) and is in the process of migrating to Crocus-ERA5 (e.g. Mudryk et al., 2023; Derksen and Mudryk, 2023; Mudryk et al., 2024).

The analysis of the climatological periods within 1950-2022 reveals notable agreements in snow depth between Crocus-ERA5 and independent in-situ data. The snow cover extent in the Northern Hemisphere is characterized by high inter-annual variability linked to the snow depth that indicates how much snow has fallen and compacted. The ability of Crocus-ERA5 to represent daily snow depth (or mass, related to depth by density) is assessed against long-term snow depth on 10 March for various in-situ stations covering different geographical regions in both Canada and Eurasia. South of 70°N in North America, the long-term snow depth estimates from Crocus-ERA5 align remarkably well with in-situ observations. The most significant differences in periodicity and/or magnitude are found in the Arctic Circle, likely due to the challenges of achieving accuracy in reanalysis when using incomplete or sparse observational data in the region. In Eurasia, the results are more mixed and

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not directly linked to latitude variations. Despite this, Crocus-ERA5 generally captures inter-annual variability well, providing valuable insights into snow depth patterns and trends.

An important limitation of the Crocus-ERA product was highlighted by comparing the simulated snow cover with estimates from the IMS multi-sensor product. Crocus-ERA5 simulates the Northern Hemisphere snow cover on an "open field" surface, neglecting the boreal forest. This hypothesis leads to a significant bias during spring melt, which occurs too quickly in Crcocus-ERA5 where the boreal forest is present. This underscores that Crocus-ERA5 should not be used to quantify the absolute value of spring snow cover in areas where forests dominate. However, using this product to quantify the evolution of interannual variability in snow cover or its long-term evolution seems quite acceptable.

To effectively assess water resources and forecast spring runoff, it is essential to measure the total water volume stored in snowpack, with the Snow Water Equivalent (SWE) being a key indicator. SWE is more accurate than snow depth and/or cover, as it accounts for snow density and compaction. Furthermore, SWE has a profound impact on Arctic amplification and climate change that is altering the timing and extent of snowmelt. Under this conditions, a spatially comprehensive and temporally continuous monitoring system is essential for tracking the total amount of water stored in solid form within the snowpack, particularly in regions with limited in situ data. There are major differences in time and spatial resolution between existing SWE products Mudryk et al. (2024) which significantly restrain their usefulness in cryosphere and climate change studies. The long-term time series of SWE obtained through climate models or derived directly from remote sensing has a 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 and their changes, 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 (Snow Water Equivalent) 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 developed datasets. It should be noted, however, that recently Mudryk et al. (2024) showed that Crocus-ERA5 was one of the most effective products 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.

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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 pre-processed observational data, developed the analytic calculations, performed the analysis and write 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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