



# White Christmas in Germany? A High-Resolution Snow Climatology since 1950 (SNOWRAS v1.0)

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**Abstract.** Snow cover is highly sensitive to changes in temperature and precipitation, making it an important indicator of climate variability and climate change. It also strongly influences hydrological processes, for example, groundwater recharge, runoff formation, and flood risk during snowmelt. Long-term, spatially detailed information on snow depth and snow cover duration is therefore needed for climate monitoring, hydrological applications, and impact assessments. Here, we present

5 SNOWRAS, a new gridded snow depth dataset for Germany covering extended winter seasons from 1950/51 to 2025/26. The dataset is based on daily snow depth observations from the extensive monitoring network of the Deutscher Wetterdienst (DWD), complemented by measurements from partner networks in Germany and neighboring countries. After quality control and data cleaning, the station observations were interpolated to a regular  $1 \times 1$  km grid using an optimal interpolation scheme. Based on this dataset, we derived and analyzed several snow-climatological indicators, including seasonal mean and maximum

10 snow depth, the number of snow days, and the timing of the first and last days with seasonal snow cover. Across Germany, most indicators show a statistically significant decline over the past 75 years. The magnitude of these changes varies considerably with elevation: the largest decreases in snow depth and snow cover duration are found in lowland and mid-elevation regions, while these trends are generally weaker at higher elevations and are partly not statistically significant. SNOWRAS provides a spatially consistent, high-resolution dataset for monitoring snow conditions and investigating long-term changes

15 in Germany's snow climate. Together with complementary information, such as snow water equivalent, the dataset can also support hydrological modeling, assessments of water availability, and analyses of hydrological risks.

## 1 Introduction

Snow cover is an important part of the terrestrial cryosphere and has an impact on the hydrological water cycle as well as on the energy balance at the land surface (Barnett et al., 2005; Sturm et al., 2017). A fraction of winter precipitation is stored

20 temporarily as snow and enters the hydrological system delayed, during melt. This storage effect impacts several hydrological processes, including runoff timing as well as river discharge, groundwater recharge, and flood generation, particularly when snowmelt is accompanied by rainfall (e.g. Beniston et al., 2018; Musselman et al., 2017). The presence of snow also influences the radiative balance at the land surface. Snow-covered areas reflect considerably more shortwave radiation than snow-free



surfaces, and therefore changes in the extent of snow cover affect absorbed energy and the resulting surface temperatures as well as related regional feedbacks (Flanner et al., 2011). In turn, snow cover responds to changes in both temperature and precipitation and is therefore not only a hydrological variable but also an indicator of climatic conditions (Brown and Mote, 2009).

Across Europe, observational studies have found widespread decreases in snow cover variables such as extent, duration, and depth during recent decades, largely in response to increasing temperatures and changing precipitation regimes (Scherrer et al., 2004; Frei et al., 2018). This response of snow dynamics to climatic forcing is not spatially uniform. At higher elevations in some parts of the European Alps, snow-related trends may be weaker (Beniston et al., 2018), due to temperatures remaining sufficiently low for snow accumulation during much of the winter season. At lower and mid-elevation regions below approximately 1500 m, the decrease of snow cover and snow water equivalent is most evident (Hantel et al., 2012; Klein et al., 2016; Marty et al., 2017). Winter temperatures in these regions often lie close to that of the rain-snow transition, and even limited warming can have a large impact on the persistence of snow, making low-altitude snow regimes particularly sensitive to further climate change (Beniston et al., 2018).

Parts of Germany are situated within such an elevation-related rain-snow transition zone. Its snow regime is shaped by topography and the interaction of large-scale atmospheric circulation. This in turn impacts regional temperature and precipitation patterns and leads to large spatial differences in snow conditions over comparatively short distances. In the northern and western lowlands, snow cover is often intermittent and short-lived, while the central uplands and the Bavarian Alps in southern Germany experience more frequent and persistent winter snow cover (Matiu et al., 2021; Hantel et al., 2012). These contrasts make Germany a suitable region for studying elevation-dependent and regionally differentiated snow cover changes. Existing analyses indicate decreasing snow cover duration and earlier melt dates, in line with broader European developments (Frei et al., 2018). Yet previous studies have been limited in spatial extent, station density, or temporal coverage.

Satellite products, including those from the European Space Agency's Climate Change Initiative (ESA-CCI, Sun et al., 2025) and EUMETSAT's Satellite Application Facility on Climate Monitoring (CM SAF, Schulz et al., 2009), provide valuable information on snow cover, but their use for climatological assessments can be limited by spatial cloud cover, resolution, temporal coverage, or the lack of direct snow depth information (Gascoin et al., 2019). Station observations provide long records of snow depth but are irregularly distributed in space and often require careful quality control before they can be used for spatial analyses. Gridded datasets that combine long observational records with high spatial resolution are hence needed to characterize regional snow climatology, to detect trends and extremes, and to support applications in hydrology, climate monitoring, and impact assessment (Marty et al., 2017).

At the European scale, spatially continuous products such as ERA5 (Muñoz-Sabater et al., 2021), CERRA (Ridal et al., 2024), and the Mountain Tourism Meteorological and Snow Indicators (MTMSI Morin et al., 2021) dataset provide consistent long-term coverage. However, their comparatively coarse spatial resolution limits their ability to represent small-scale variability of snow depth, particularly in complex terrain where local topography strongly controls snow accumulation and melt (Monteiro and Morin, 2023; Varga and Breuer, 2023; Muñoz-Sabater et al., 2021).

At the national and regional scale, multi-decadal snow climatologies have been developed for several European countries,



including Switzerland, the Italian Alps, and Poland (Klein et al., 2016; Ranzi et al., 2024; Wibig and Jędruszkiewicz, 2023).

60 These studies consistently report decreases in snow cover duration, snow depth, and earlier melt dates, with particularly strong changes at lower and mid elevations. While they provide valuable insights into regional snow variability and trends, many are primarily based on point observations.

Gridded snow datasets have been developed for countries such as Austria and Switzerland by combining station observations with snow modeling approaches (Olefs et al., 2020; Marty et al., 2025). Despite the availability of European reanalysis prod-  
 65 ucts and regional snow climatologies for neighboring countries, Germany has lacked a spatially consistent, long-term, daily, observation-based snow depth dataset at kilometer-scale resolution.

In this study, we present SNOWRAS, a high-resolution gridded snow depth climatology covering all of Germany. The dataset has a spatial resolution of 1 x 1 km and covers the period from 1950/51 to the present (currently 2025/26). It is based on daily snow depth observations from the measurement network of the German Meteorological Service (Deutscher Wetterdi-  
 70 enst, DWD), supplemented by observations from partner networks within Germany and neighboring countries where available. From SNOWRAS, we derive key snow-climatological parameters, including mean seasonal snow depth, number of snow days, snow onset and melt dates, and maximum snow depth. The variables allow the analysis of spatial and elevation-dependent snow patterns, long-term changes, and extreme snow events across Germany. Potential applications include the validation of hydrological models, regional climate monitoring and climate services for winter tourism. SNOWRAS is made publicly avail-  
 75 able following FAIR principles (Wilkinson et al., 2016) and will be extended through annual updates and the integration of newly digitized historical observations.

## 2 Data and Methods

This section presents the data basis and quality-control procedures as well as the interpolation, analysis, and evaluation approach of SNOWRAS.

### 80 2.1 Data Basis

The compiled daily gridded snow depth dataset is based on a comprehensive set of snow depth observations from stations within the DWD measurement network in Germany and complemented by data from partner networks within Germany (available in the DWD database) and neighboring countries, including the Czech Republic, Poland, France, the Netherlands, Austria, and Switzerland (Tab. 1). Observations from neighboring countries were included to improve the spatial interpolation near  
 85 Germany's borders; the released dataset itself is restricted to the entire land area of Germany. All data were last downloaded on 11. June 2026. Accordingly, the dataset includes all observations that were publicly available up to that date. Most snow depth observations were obtained manually at 06:00 or 07:00 UTC. In more recent periods, automatic laser or ultrasonic measurement systems were used; for these records, the 06:00 UTC value was selected. If both manual and automatic measurements were available at a station, manual measurements were given priority. For this study we extracted data from 1st September 1950 to  
 90 31st May 2026. Observations were assigned to winter seasons, defined as the period from 1st September to 31st May of the



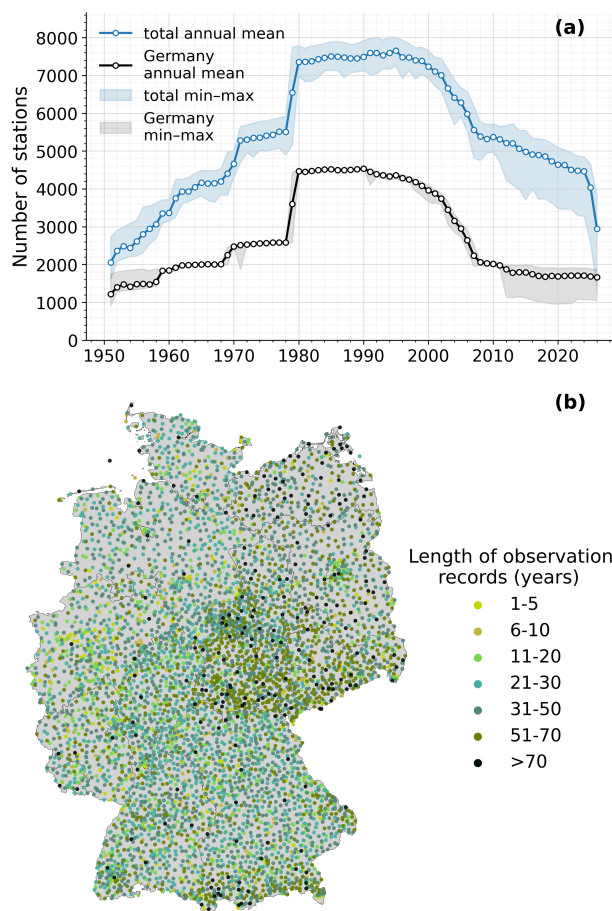
**Table 1.** European meteorological and hydrological open-data portals considered in this study.

| Country        | Provider                     | Portal name                | Type of data provided                                              | Access link                                                                 |
|----------------|------------------------------|----------------------------|--------------------------------------------------------------------|-----------------------------------------------------------------------------|
| Germany        | German Weather Service (DWD) | DWD Open Data Portal       | Meteorological and climatological station observations for Germany | <a href="https://opendata.dwd.de">opendata.dwd.de</a>                       |
| Czech Republic | CHMI                         | CHMI Open Data Portal      | Meteorological and climatological data                             | <a href="https://opendata.chmi.cz">opendata.chmi.cz</a>                     |
| Poland         | IMGW-PIB                     | IMGW Public Data Portal    | Meteorological and hydrological data                               | <a href="https://danepubliczne.imgw.pl">danepubliczne.imgw.pl</a>           |
| France         | Météo-France                 | Météo-France Data Portal   | Meteorological and climatological data                             | <a href="https://meteo.data.gouv.fr">meteo.data.gouv.fr</a>                 |
| Netherlands    | KNMI                         | KNMI Data Platform         | Meteorological, climatological, and observational data             | <a href="https://datapatform.knmi.nl">datapatform.knmi.nl</a>               |
| Austria        | Federal Ministry / eHYD      | eHYD                       | Hydrological data                                                  | <a href="https://ehyd.gv.at">ehyd.gv.at</a>                                 |
| Austria        | GeoSphere Austria            | GeoSphere Austria Data Hub | Meteorological, climatological, and geophysical data               | <a href="https://data.hub.geosphere.at">data.hub.geosphere.at</a>           |
| Switzerland    | MeteoSwiss                   | MeteoSwiss Open Data       | Meteorological and climatological data                             | <a href="https://opendatadocs.meteoswiss.ch">opendatadocs.meteoswiss.ch</a> |

following year.

We extracted data from the internal database, maintained by DWD, containing historical and current station observations for numerous meteorological variables from the DWD station network and from partnering networks (Kaspar et al., 2013). Some of the snow monitoring data prior to 1980 have not yet been digitized. Consequently, additional data coverage for the pre-1980 period is expected in future dataset updates. The number of available stations peaked in the 1980s and 1990s at approximately 4500, followed by a subsequent decline, as shown in Fig. 1a. Since 2011, the spread in the seasonal number of stations in Germany has increased, as measurement guidelines for some stations were adapted to cover only the period from October to April. Additional station observations from neighboring countries were obtained from publicly available web portals (Tab. 1) together with the corresponding metadata, including station coordinates and elevation above sea level. The number of additional stations from neighboring countries also peaked in the 1980s and 1990s at approximately 3500, resulting in a maximum total station count of nearly 8000 (Fig. 1a). The spatial availability of station observations across Germany varies considerably over the study period. On average, individual station time series cover approximately 35 years. Long-term stations with records spanning at least 70 years are mainly concentrated in eastern central Germany (Fig. 1b).





**Figure 1.** Station observations used for the interpolation procedure. (a) Seasonal mean number of observing stations available within Germany (black line) and across the full study domain, including neighboring countries (blue line). The shaded grey and light-blue envelopes indicate the minimum and maximum number of stations available per season for Germany and the full study domain, respectively. (b) Overview of station locations and length of the observation records (in years) for each station in Germany during the period 1950/51–2025/26. *Basemap* © *GeoBasis-DE/BKG* 2024.

## 105 2.2 Quality Control and Data Cleaning

Before interpolating, all observational and metadata records were checked and harmonized into a common format and processed using a unified workflow. This included consistency checks of station coordinates and temporal coverage, transformation into a common geographic reference system, and the verification of station elevations using a digital elevation model (DEM, Keydel et al., 2000). If the reported station elevation differed more than 50 meters from the DEM-derived elevation, the DEM-based elevation was used instead.

We then combined the existing DWD quality information with additional checks developed for this study. The aim was to



remove clearly implausible values, resolve duplicated records where possible, and identify observations that were inconsistent in time or space.

The snow depth observations from the DWD station network were first processed by the DWD-internal Qualimet system (Kaspar et al., 2013). Qualimet assigns quality information to each daily value using a set of automated checks, including range tests, temporal consistency checks, sensor-related flags, and station-specific climatological limits. All snow depth measurements from 1st September 1950 onwards were considered in this step. Values that failed the Qualimet checks were either corrected, where the error was obvious, or removed from the dataset. This included, for example, simple transcription or digit-order errors, as well as cases where snow observations were corrected to zero when snow cover was physically implausible under the prevailing conditions. A small part of the data remains unchecked at this stage, mainly because some records were digitized only recently or because quality information was not available for all data from neighboring countries (Kaspar et al., 2013). For the present study, we excluded all observations with suspicious or questionable data quality. The remaining observations were kept and used as input for the additional quality-control steps described below and for the subsequent interpolation. For periods before 2008, and especially for the earlier decades of the record, some snow depth observations extracted from the DWD database occurred more than once. These duplicates resulted from inconsistencies between different archival storage locations. In most cases, the duplicated values were identical. In a small fraction of the early data (approximately 1%), however, the duplicated entries differed. Because the original observation can no longer be reconstructed with certainty in these cases, we applied a simple and reproducible rule whenever neither of the duplicate records had a higher quality flag than the other. If one of the two values was missing or zero while the other was greater than zero, we retained the non-zero value; if one value was zero and the other was missing, we retained the zero value. If both values were present, greater than zero, and differed, we selected the value with the higher quality flag where available; otherwise, we used their arithmetic mean. This rule was chosen to avoid arbitrary selection of one of two conflicting records and to preserve the information that snow was observed. We used the same procedure for non-German stations where records from different data providers could be assigned to the same underlying station based on their location.

We also screened the station records for long periods of implausible zero values. Station seasons with more than 800 consecutive days reported as zero were excluded for the affected period. The threshold was selected conservatively to identify only exceptionally long zero-only sequences while minimizing the risk of removing genuinely snow-poor periods. Such sequences are unlikely to represent real snow conditions and more likely reflect reporting gaps, coding problems, or other data-handling issues. Only the identified zero-only sequence was excluded. When subsequent non-zero snow depth observations were available, these observations were retained, and the station record continued to be used.

Finally, we removed values that were physically implausible at all stations. Negative snow depths were discarded, as were snow depths greater than 999 cm. The upper threshold of 999 cm was selected as a conservative plausibility limit rather than as a physically optimized threshold. It exceeds the historical maximum observed in Germany and retains a margin for rare extreme snow depths, particularly at Alpine stations in Germany and neighboring countries. It was applied only to identify clearly implausible values or measurement errors and was not intended to exclude potentially realistic extremes.



### 2.3 Dixon-type screening

To ensure the quality and spatial consistency of the pre-cleaned daily snow depth observations, we applied a local Dixon-type outlier test to identify spatially inconsistent station values (Dixon, 1950). For each station and day, a local sample of surrounding stations was selected. The local sample size varied dynamically between 12 and 30 stations, depending on local station density. Before applying the Dixon tests, the local dependence of snow depth on elevation was removed by fitting a local linear regression of snow depth against station elevation. The tests were subsequently applied to the regression residuals rather than to the raw snow-depth values.

Let  $x_{(1)} \leq x_{(2)} \leq \dots \leq x_{(n)}$  denote the ordered residuals within a local sample. The quality control was performed in two stages. In the first stage, potentially suspicious low and high values were flagged using separate one-sided Dixon  $r_{22}$  tests:

$$r_{22,\min} = \frac{x_{(3)} - x_{(1)}}{\max(x_{(n-2)} - x_{(1)}, f_{\text{TolDix}})} \quad (1)$$

and

$$r_{22,\max} = \frac{x_{(n)} - x_{(n-2)}}{\max(x_{(n)} - x_{(3)}, f_{\text{TolDix}})}, \quad (2)$$

with TolDix as the Dixon tolerance parameter, set to  $f_{\text{TolDix}} = 20$  cm. A value was flagged as potentially suspicious when the respective statistics exceeded the tabulated  $r_{22}$  critical value for the local sample size at a nominal one-sided significance level of  $\alpha = 0.01$ . Flagged observations were retained at this stage.

In the second stage, flagged observations were re-tested using separate one-sided Dixon  $r_{10}$  tests:

$$r_{10,\min} = \frac{x_{(2)} - x_{(1)}}{\max(x_{(n)} - x_{(1)}, f_{\text{TolDix}})} \quad (3)$$

and

$$r_{10,\max} = \frac{x_{(n)} - x_{(n-1)}}{\max(x_{(n)} - x_{(1)}, f_{\text{TolDix}})}. \quad (4)$$

An observation was removed only if it remained the local minimum or maximum, its respective  $r_{10}$  statistics exceeded the tabulated critical value at a nominal one-sided significance level of  $\alpha = 0.005$ , and its absolute difference from the adjacent ordered residual exceeded  $2f_{\text{TolDix}}$ .

This procedure prevents unrealistically large test statistics in local samples with very small snow-depth variability and requires a minimum extreme-to-neighbor difference of 40 cm for final removal. For the local sample sizes used here, the implemented  $r_{10}$  critical values range from 0.522 for  $n = 12$  to 0.372 for  $n = 30$ . Stations above 800 m elevation were excluded from the final Dixon-based removal step because strong local elevation contrasts in mountainous terrain can produce physically plausible snow-depth differences over short distances. In total about 11000 observations (approximately 0.02%) were identified as outliers and excluded from the subsequent spatial interpolation.

The Dixon-based quality control was applied conservatively, as snow depth can vary strongly over short spatial and temporal scales. More restrictive checks may therefore remove physically plausible observations and unnecessarily reduce the station



density used for interpolation. Accordingly, no additional temporal homogenization was applied, and the quality control focused on clear spatial inconsistencies prior to interpolation.

## 2.4 Interpolation Algorithm

Irregularly distributed station observations of snow depth were interpolated to the regular 1 x 1 km grid using a local statistical interpolation scheme. The method combines a deterministic background estimate with an optimal interpolation of station residuals. This approach accounts for both the spatial correlation structure of the observations and physiographic effects, in particular terrain elevation, which is a key control on snow depth variability.

### 2.4.1 Local Station Selection and Grid Representation

We chose a spatial 1 x 1 km grid with 910 cells in the  $y$  direction and 671 cells in the  $x$  direction, covering the whole of Germany. The grid is based on a polar stereographic projection with the North Pole as projection origin, a central meridian at 10°E, and a standard parallel at 60°N. A spherical Earth radius of 6370040 m is used.

Station measurements were not directly assigned to the grid cell containing the station location. Instead, the interpolated grid-cell value was used. This is important because elevation and snow depth can vary substantially within a 1 x 1 km grid cell. Consequently, the interpolated value of a grid cell may differ from the original point observation at a station located inside the same cell. The gridded product should therefore be interpreted as a grid-cell representative snow depth estimate rather than as a direct reproduction of point measurements.

For each target grid cell, stations were selected locally. The initial search radius was set to 40 km. If fewer than 12 stations were found within this radius, the search radius was increased until at least 12 stations were available. If more than 30 stations were available, the search radius was reduced until no more than 30 stations were retained. The upper limit of 30 stations was selected to limit computational cost and to preserve the local character of the interpolation procedure by avoiding the influence of more distant stations, which may experience substantially different snow conditions.

### 2.4.2 Background Field and Residual Calculation

The final interpolated snow depth field  $D(\mathbf{s})$  at a horizontal location  $\mathbf{s}$  was represented as the sum of a deterministic background field  $D_{\text{bg}}(\mathbf{s})$  and an interpolated residual component  $D_{\text{res}}(\mathbf{s})$ :

$$D(\mathbf{s}) = D_{\text{bg}}(\mathbf{s}) + D_{\text{res}}(\mathbf{s}). \quad (5)$$

For the background field we performed a deterministic background field estimation (e.g. Erickson et al., 2005):

$$D_{\text{bg}}(\mathbf{s}) = \beta_0 + \beta_x x(\mathbf{s}) + \beta_y y(\mathbf{s}) + \beta_H H(\mathbf{s}), \quad (6)$$

where  $x(\mathbf{s})$  and  $y(\mathbf{s})$  denote the horizontal coordinates,  $H(\mathbf{s})$  is the DEM-derived terrain elevation (Keydel et al., 2000), and  $\beta_0$ ,  $\beta_x$ ,  $\beta_y$ , and  $\beta_H$  are regression coefficients estimated separately for each target grid cell from the selected local station



205 sample.

Station residuals were computed as

$$d_{i,\text{res}} = D_{\text{obs}}(\mathbf{s}_i) - D_{\text{bg}}(\mathbf{s}_i), \quad (7)$$

where  $D_{\text{obs}}(\mathbf{s}_i)$  denotes the observed snow depth at station  $i$  and  $\mathbf{s}_i$  denotes the station location.

### 2.4.3 Correlation Model and Interpolation Weights

210 The residuals were interpolated using an optimal interpolation (OI) formulation following Gandin (Gandin, 1966). To derive the interpolation weights, a spatial correlation model was used. The correlations between stations and the target grid cell were described by

$$C(\text{dist}^2; p) = \frac{1}{1 + p \text{dist}^2}, \quad (8)$$

where  $\text{dist}$  denotes the effective separation distance (including horizontal separation and elevation difference) in km and  $p$  (in  
 215  $\text{km}^{-2}$ ) is the decorrelation parameter controlling the decrease of correlation with distance. Larger values of  $p$  correspond to a faster decrease of correlation with distance and therefore to a shorter effective correlation length. In the applied configuration,  $p$  was prescribed as  $p = 0.06 \text{ km}^{-2}$ . This value was adopted from the established configuration of the DWD SNOW4 interpolation system and should be interpreted as a prescribed configuration parameter rather than as a parameter newly optimized in this study.

220 The station–station correlations define the local correlation matrix  $R$ , while the station–grid correlations define the vector  $\mathbf{r}(\mathbf{s})$ . For numerical stabilization, a small diagonal nugget term  $\epsilon_{\text{nug}} = 0.01$  was included in the local station–station correlation matrix. Since the unregularized correlation of a station with itself is one, the diagonal entries of the regularized matrix used in the linear system are therefore

$$R_{ii} = 1 + \epsilon_{\text{nug}} = 1.01. \quad (9)$$

225 The interpolation weights were then obtained by solving

$$\mathbf{R}\mathbf{w}(\mathbf{s}) = \mathbf{r}(\mathbf{s}). \quad (10)$$

Here,  $R$  denotes the regularised local station–station correlation matrix,  $\mathbf{r}(\mathbf{s})$  the station–grid correlation vector, and  $\mathbf{w}(\mathbf{s})$  the corresponding weight vector. Its components are given by

$$\mathbf{w}(\mathbf{s}) = (w_1(\mathbf{s}), \dots, w_N(\mathbf{s}))^T, \quad (11)$$

230 where the interpolation weights are normalized such that their sum equals one. The residual estimate at the target grid cell was then computed as

$$D_{\text{res}}(\mathbf{s}) = \sum_{i=1}^N w_i(\mathbf{s}) d_{i,\text{res}}, \quad (12)$$



where  $N$  is the number of stations used in the local interpolation. The final interpolated snow depth field was constrained to the physically admissible range of 0–999 cm. The resulting product is a spatially complete, grid-cell representative snow  
 235 depth dataset that combines local station information, terrain-dependent background estimation, and statistical interpolation of residuals.

The final snow depth product is distributed as a CF-compliant NetCDF file on a 1 x 1 km polar stereographic grid over Germany. It covers the period from 1st September 1950 to 31st May 2026 and contains 20767 daily fields, each valid at 06:00 UTC. Snow depth itself is stored as *snow\_depth* with the dimensions *time*, *y*, and *x*. Values are given in centimeter and describe  
 240 the mean snow depth within each grid cell. Missing data are encoded by the fill value -9999. To make the file easier to use, it also contains two-dimensional latitude and longitude fields, coordinate bounds for *x* and *y*, and global metadata describing the source, version, license, temporal coverage, spatial resolution, and CF convention.

## 2.5 Snow-climatological Indicators

To examine how snow conditions have changed over time, we derived from the daily snow depth fields several seasonal  
 245 measures. This was done separately for each winter season from 1950/51 to 2025/26. In this study, the extended winter season runs from September to May. We used 1st September as the start of the season, so dates such as the first or last day with snow are expressed as the number of days since 1st September. A grid cell was counted as snow-covered when the interpolated snow depth was at least 1 cm.

For each winter season, we calculated:

- 250 – **First snow cover day:** the first day of the season with at least 1 cm of snow.
- **Last snow cover day:** the last day of the season with at least 1 cm of snow.
- **Snow cover period:** the inclusive number of days between the first and last snow cover day.
- **Number of snow days:** the total number of snow-covered days during the season.
- **Mean snow depth:** the mean snow depth on snow-covered days during the season, given in cm.
- 255 – **Maximum snow depth:** the highest snow depth during the season, given in cm.

These measures describe different parts of the seasonal snow regime. The first and last snow cover days show whether snow appears earlier or later in the season and whether it disappears earlier or later in spring. The snow cover period describes the full span from the first to the last occurrence of snow. The number of snow days, in contrast, counts only the days on which snow was actually present. This difference matters because a season can have an early snowfall and a late final snowfall, while  
 260 still having many snow-free days in between. Mean snow depth was calculated only for days with snow cover. We chose this definition because a mean over the full September–May season would also include all snow-free days and would therefore mainly reflect changes in snow duration. By restricting the calculation to snow-covered days, the mean snow depth provides a more direct measure of the intensity of snow conditions during periods when snow is present.



For each parameter, we then analyzed its temporal development over the full study period. Long-term changes were estimated using a linear trend, while a locally weighted regression (LOESS, Locally Estimated Scatterplot Smoothing) with a local linear fit and a 42-year smoothing window was used to estimate a smooth, non-parametric representation of non-linear variations and multi-decadal variability (De Valk, 2020). Finally, we quantified recent changes by comparing the LOESS-estimated value for the most recent season (2025/26) with the corresponding mean over the first 30 years of the study period. The statistical significance of the change between the first and last LOESS estimates was assessed using a two-sided z-test based on the corresponding 95% confidence intervals, with  $p < 0.05$  indicating statistical significance.

## 2.6 Evaluation Procedure

The evaluation combined two complementary approaches to assess the consistency of the SNOWRAS dataset and the performance of the interpolation procedure. Because no spatially continuous observational reference dataset of snow depth is available for Germany, the dataset was compared with the CERRA (Copernicus European Regional ReAnalysis) reanalysis (Ridal et al., 2024). The robustness of the interpolation scheme was additionally assessed using leave-one-out cross-validation against station observations.

### 2.6.1 Comparison with CERRA Reanalysis Data

We compared the SNOWRAS dataset with the CERRA reanalysis dataset over Germany (Ridal et al., 2024). CERRA provides European wide, sub-daily data for multiple surface and atmospheric variables and is available from 1984 to present (March 2026). In this study, daily snow depth (variable "sde") at 06:00 UTC (instantaneous values) was analyzed to match the observation time of the station measurements on which our dataset is based. The analysis covered the months from September to May for the period 1984–2026, representing the extended winter season and encompassing the majority of snow occurrences in Germany. To ensure spatial comparability, the 1 x 1 km SNOWRAS dataset was remapped to the 5.5 x 5.5 km CERRA grid using the Climate Data Operators (CDO 2.0.5, Schulzweida). In the grid-cell-based comparison only grid cells with snow depth > 0 cm in both datasets were considered because the inclusion of snow-free grid cells would strongly bias the comparison towards the large number of zero values and could mask differences under actual snow conditions.

### 2.6.2 Leave-one-out Cross-validation

We applied a leave-one-out (LOO) cross-validation using the in-situ snow depth observations to evaluate how well the interpolation reproduces independent station measurements and how sensitive the results are to individual stations. For selected years, the interpolation was repeated several times, each time excluding one station from the input dataset. Snow depth in the grid cell where the excluded station is located was then estimated from the remaining surrounding stations only. The interpolated value for the corresponding grid cell was subsequently compared with the observed snow depth at the excluded station.

To obtain a set of stations for the LOO that is spatially and topographically representative, stations were selected using a structured sampling approach based on the DEM with a spatial resolution of 1 x 1 km. Stations were grouped into 200 m





295 elevation classes based on DEM derived elevations to ensure a spatially and topographically representative validation network. If more than one station was available in a grid cell, then one of these stations was selected randomly. A minimum distance criterion, depending on the number of stations, between selected stations was additionally applied to ensure a balanced spatial distribution. The final validation network was generated using a two-stage random sampling strategy: Stations were selected to ensure representation across all elevation classes. Additional stations were then added while maintaining the spatial distance  
 300 criterion until the target number of stations was reached. We selected 80 stations as a compromise between computational cost and spatial representativeness.

The method was applied to the winter seasons 1978/79, 1990/91 and 2010/11 using the corresponding station metadata. These years were selected because they represent winters with relatively high mean snow depths across Germany. Despite variations in station availability, the average distance between the selected stations remained virtually constant, ranging from 59 to 63  
 305 km with a standard deviation of 5.4–7.6 km, resulting in a comparable spatial distribution of the validation network across the three seasons. Stations with significant gaps in the time series were subsequently removed. A total of 76, 73 and 71 stations were selected for the winter seasons 1978/79, 1990/91 and 2010/11, respectively (Supplementary Figure S1).

### 2.6.3 Evaluation Metrics

310 The performance of the SNOWRAS dataset was evaluated using several standard statistical metrics. Systematic deviations were quantified by using the bias, defined as

$$\frac{1}{n} \sum_{i=1}^n (M_i - O_i). \quad (13)$$

The magnitude of deviations was assessed using the root mean square error (RMSE)

$$\sqrt{\frac{1}{n} \sum_{i=1}^n (M_i - O_i)^2}, \quad (14)$$

315 while the linear relationship between the datasets was quantified using the Pearson correlation coefficient ( $r$ ),

$$\frac{\sum_{i=1}^n (M_i - \bar{M})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^n (M_i - \bar{M})^2} \sqrt{\sum_{i=1}^n (O_i - \bar{O})^2}}. \quad (15)$$

Here  $M_i$  and  $O_i$  denote the paired snow depth values of the reference dataset and SNOWRAS, respectively,  $\bar{M}$  and  $\bar{O}$  are their corresponding mean values, and  $n$  is the total number of paired observations.

## 3 Results

320 We first assess the quality and consistency of the SNOWRAS dataset. We then present the main results of the snow-climatological analysis, focusing on spatial patterns, temporal variability, and long-term changes in snow depth and snow cover characteristics across Germany.



### 3.1 Comparison with CERRA Reanalysis

The comparison of the SNOWRAS dataset and CERRA reveals generally consistent large-scale snow depth patterns while also highlighting systematic regional differences in bias (Fig. 2a) and RMSE (Fig. 2b), particularly in areas with complex terrain. Both datasets identify the winters 1984/85, 1986/87, 2009/10, and 2010/11 as those with the highest mean snow depths on snow-covered days since 1984/85 in Germany (not shown).

The spatial distribution of the bias shows that the largest deviations between SNOWRAS and CERRA occur in the German low mountain ranges and the Alpine region (Fig. 2a). In most low mountain ranges, including the Harz, the Thuringian Forest, the Westerwald, the Vogelsberg, the Ore Mountains, and the Bavarian Forest, bias is predominantly positive, suggesting a tendency towards higher snow depth by CERRA in these regions compared with SNOWRAS. In contrast, negative bias values dominate in the Black Forest and the Alps, suggesting an underestimation by CERRA, with the exception of the Chiemgau Alps, where positive bias values are observed (Fig. 2a). Highest RMSE values are observed in the Harz, the Bavarian Forest, the Black Forest, and in the Alpine region (Fig. 2b). These regions largely coincide with the areas where the strongest absolute bias values occur (Figs. 2a and b). At low snow depths, there is good agreement between the two datasets. The spread of the data points increases with increasing snow depth. The area-averaged bias is small (0.4 cm) and the mean RMSE is 3.8 cm. The 95th percentile reaches 2.7 cm for the absolute bias and 7.6 cm for the RMSE (Fig. 2c).

Overall, the differences are concentrated around 0 cm, with their frequency decreasing as the absolute error increases. Large absolute deviations exceeding 4 cm occur for only 24 % of all values > 0 cm. A slight positive skew suggests that positive differences occur slightly more frequently than negative ones (Fig. 2d).

### 3.2 Validation against Station Observations

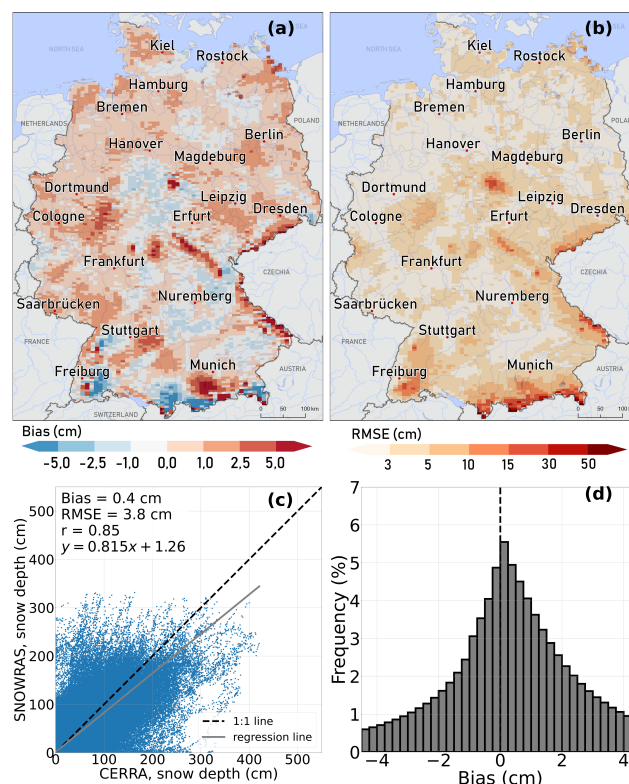
The interpolation performance was assessed using two complementary approaches for the winter seasons 1978/79, 1990/91, and 2010/11: 1. omitting certain stations from the interpolation process and predicting their values from the remaining data (leave-one-out, LOO) and 2. a direct comparison between the final interpolated fields and the corresponding station observations to evaluate the internal consistency of the gridded dataset at station locations.

The distribution of station-wise mean errors from the LOO validation is clearly centered around 0 cm, with 83 % of the stations showing a mean error within  $\pm 1$  cm (Fig. 3a).

The station observations, the LOO interpolation, and the SNOWRAS dataset show an almost identical seasonal cycle in monthly mean snow depth. Only the seasonal maximum is slightly lower for the LOO interpolation than for the SNOWRAS dataset and the station observations (Fig. 3b).

Comparison of the leave-one-out (LOO) interpolation with the selected station observations (see 2.6.2) shows good overall agreement ( $r=0.89$ ). The mean bias is  $-0.1$  cm and the RMSE is 5.0 cm. Low snow depths are reproduced well, whereas the spread of paired values increases with snow depth, indicating larger deviations under deeper-snow conditions (Fig. 3c).

Comparison of the interpolated snow depths with the corresponding station observations shows excellent agreement ( $r=0.99$ ;

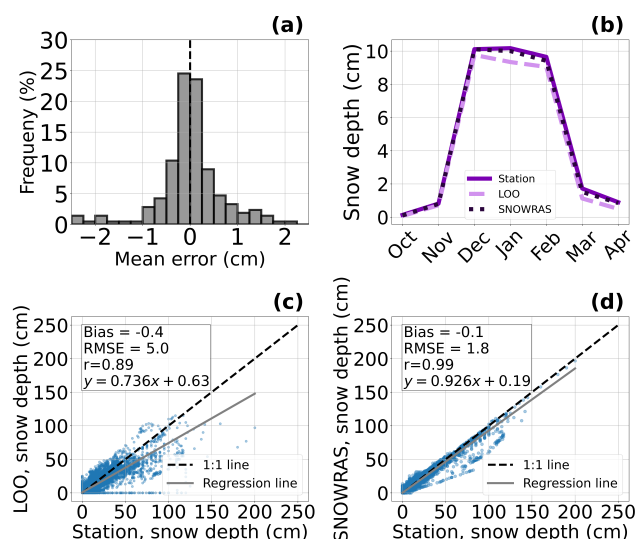


**Figure 2.** Snow depth error statistics based on daily snow depth values for the period 1984–2026. Bias is defined as CERRA minus SNOWRAS. (a) Mean bias. (b) Mean RMSE. (c) Scatter plot of daily snow depth values from both datasets. (d) Histogram of the bias. Basemap © GeoBasis-DE/BKG 2024.

RMSE = 1.8 cm). As expected, the agreement is higher than in the LOO validation because the corresponding station observations are included in the interpolation (Fig. 3d). It should be noted that a perfect agreement between interpolated snow depths and station observations is not expected. The interpolated values of a grid cell represent the mean value of the grid cell, while the observed values relate to point measurements. Nevertheless, these results indicate that the interpolation procedure provides a reliable representation of observed snow depth variability at the validation stations (Supplementary Figure S2).

### 3.3 Long-term Snow Cover Characteristics in Germany

The analysis of Germany-wide mean snow indicators for 1950/51–2025/26 reveals clear changes in several snow-related variables. Most indicators show a decline over the study period, although the magnitude and statistical significance of the trends differ between variables and regions. Here, we present a selection of analyses that illustrate the potential of SNOWRAS. We focus on Germany-wide means and averages over longer time periods; selected additional analyses, including for several mountainous regions, are provided in the Supplement (Supplementary Figures S3–S5).



**Figure 3.** Results of the leave-one-out (LOO) validation and the comparison with station observations for the winter seasons 1978/79, 1990/91, and 2010/11. (a) Histogram of the mean error between LOO-interpolated and observed snow depth across the evaluated stations. (b) Monthly mean snow depth averaged across station observations, the LOO interpolation, and the SNOWRAS dataset. (c) Scatter plot comparing LOO interpolated snow depths with station observations. (d) Scatter plot comparing SNOWRAS data with the corresponding station observations used for the interpolation.

### 3.3.1 Spatial Climatology

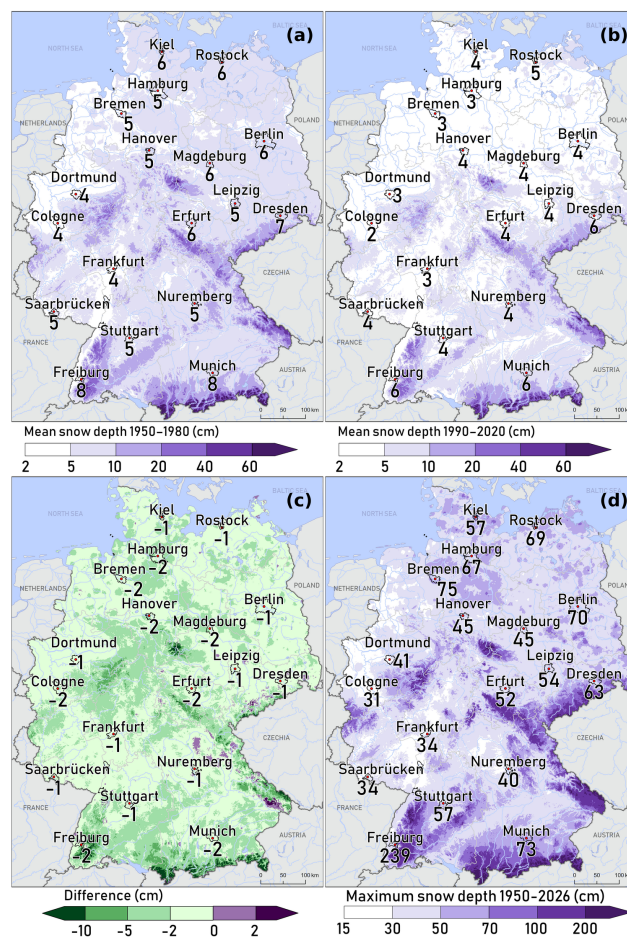
Mean and maximum snow depth in Germany are strongly controlled by elevation (Fig. 4). Low-elevation areas typically show mean snow depths of about 3–6 cm, whereas mountainous regions reach substantially higher values. Mean snow depth ranges between approximately 20 and 40 cm in lower mountain ranges, such as the Harz, and exceeds 60 cm in Alpine regions. The lowest mean snow depth in Germany can be found in the flatter parts of northern-western Germany.

A widespread reduction in mean snow depth is visible when comparing 1950/51–1980/81 (Fig. 4a) with 1990/91–2019/20 (Fig. 4b). Only relatively small areas, for example, parts of the Bavarian Forest, show an increase between the two periods (Fig. 4c). In most regions, the reduction is up to about 5 cm, with larger changes mainly occurring in high-elevation areas.

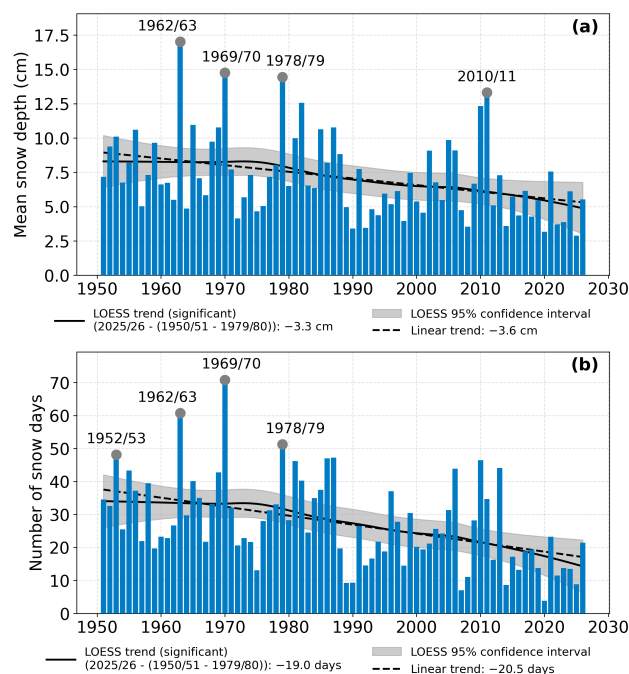
The maximum daily snow depth (here displayed over the full period 1950/51–2025/26) shows a spatial pattern similar to that of mean snow depth but with values roughly one order of magnitude higher (Fig. 4d). Even low-elevation cities, such as Berlin, where mean snow depth is about 4–6 cm, reached maximum snow depths of around 70 cm. In mountainous areas, maximum snow depths exceeded 200 cm.

### 3.3.2 Long-term Trends

Seasonal mean snow depth and the number of snow days over Germany decreased significantly during the 76-year period (Fig. 5). The LOESS trend indicates a similar decline, with the most recent winter season (2025/26) showing a mean snow



**Figure 4.** Spatial distribution of snow depth statistics over Germany. (a) Mean snow depth for the first three full decades of the dataset (1950/51–1979/80). (b) Mean snow depth for the last three full decades of the dataset (1990/91–2019/20). (c) Difference in mean snow depth between 1990/91–2019/20 and 1950/51–1979/80, calculated as 1990/91–2019/20 minus 1950/51–1979/80; green colors indicate lower mean snow depth in 1990/91–2019/20 than in 1950/51–1979/80. (d) Maximum snow depth during 1950/51–2025/26. Basemap © GeoBasis-DE/BKG 2024.



**Figure 5.** (a) Seasonal mean snow depth and (b) seasonal number of snow days from 1950/51–2025/26 as a spatial mean over all Germany, including linear and LOESS trend estimates with a 95 % LOESS confidence interval. The respective four maximum years are marked. Both variables show a significant decline over the study period.

depth 3.3 cm lower and 19 fewer snow days than the reference period (1950/51—1979/80) .

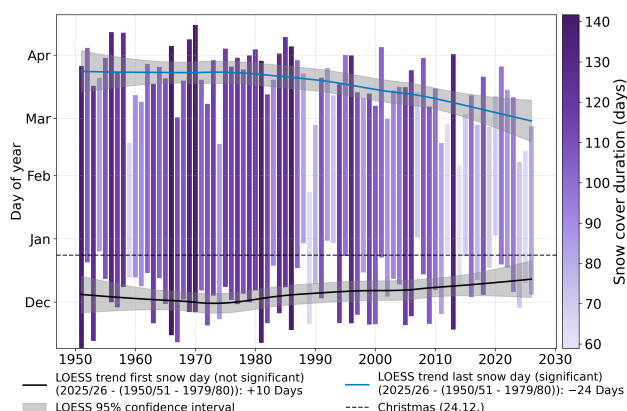
In the 1950s, mean snow depth in Germany was around 7.5 cm, with seasonal values ranging from about 5 to 10 cm. The mean number of snow days was around 35, ranging from approximately 20 to nearly 50 days. In recent years, following the  
 385 snow-rich winters of 2009–2011, mean snow depth has been around 5 cm, with values ranging from approximately 3 to 7 cm. The number of snow days has decreased to about 15, ranging from only around 3 days in 2019/20 to approximately 20 days in other recent seasons (Fig. 5).

The highest Germany-wide mean snow depths occurred in 1962/63, 1969/70, 1978/79, and 2010/11. The seasons with the highest number of snow days all occurred before 1980, namely 1952/53, 1962/63, 1969/70, and 1978/79. Regional trends  
 390 and the years of maximum snow depth or maximum number of snow days may differ substantially from these Germany-wide results (for example Supplementary Figure S5).

### 3.3.3 Seasonal Timing

In parallel with the decline in the number of snow days, the timing of seasonal snow cover also changed. The first day with snow cover of the season shifted towards later occurrence, while the last day with snow cover shifted towards earlier occurrence (Fig.  
 395 6). Consequently, the duration of the snow cover season (snow cover period), defined as the number of days between the first





**Figure 6.** Germany-wide mean timing of the first and last day with snow cover, together with the resulting length of the snow cover period, for each snow season from 1950/51–2025/26. The timing of the first and last day of snow cover is shown by the start and end of the bars, with LOESS trends shown in black and blue, respectively. The length of each bar, as well as the color, indicates the length of the snow cover period, defined as the interval between the first and the last day of snow cover.

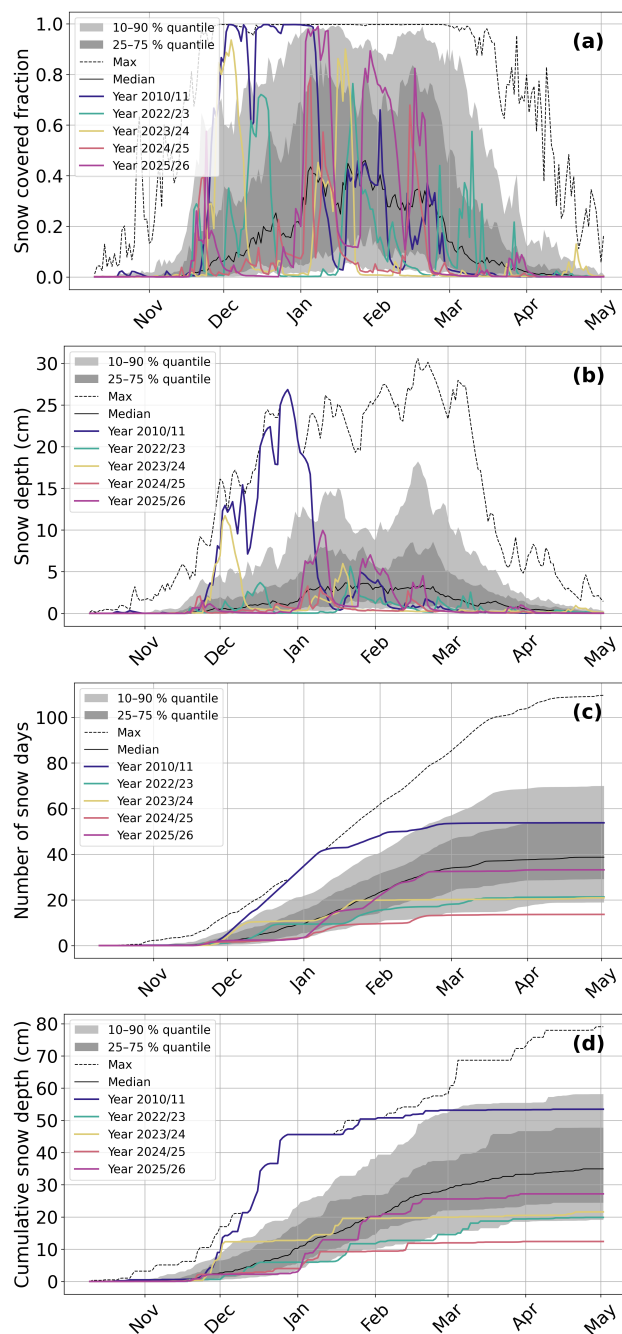
and last day with snow cover, decreased over time. The LOESS trend for the first snow day indicates a non-significant delay of 10 days in 2025/26 relative to the reference period 1950/51–1979/80, shifting the onset of snow cover from the beginning of December towards mid December. In contrast, the LOESS trend for the last day with snow cover shows a significant advance of 24 days, shifting from end of March towards end of February. The larger and statistically significant shift in the last snow day, compared with the non-significant shift in the first snow day, shows that changes in spring snow cover termination dominate the change in seasonal duration.

### 3.3.4 Seasonal Evolution and Interannual Variability

Figure 7 shows the seasonal evolution of four snow cover variables between October and May for selected winter seasons, compared with the full period (1950/51–2025/26). The variables include the snow-covered fraction of Germany, mean snow depth, the cumulative number of snow days, and the mean cumulative increase of snow depth. The latter is calculated by summing only positive day-to-day changes in mean snow depth. The selected winters illustrate the large range of conditions observed within the record. In addition, the 10–90 % and 25–75 % quantile ranges, as well as the median and maximum values for each day of the season, are shown.

Overall, snow coverage was strongest between December and March. During this period, mean snow depth increased to values of up to 30 cm, and the snow-covered fraction often reached 1, indicating snow cover across all of Germany. While the previous paragraph highlighted the variability between different years, Fig. 7 illustrates the strong intra-seasonal variability. Snow coverage can peak between late November and early April, often with a few days to weeks of pronounced snow coverage within a season and weak snow coverage during the remaining days. As these values represent spatial means over Germany, snow cover can be more persistent throughout the snow season in higher-elevation regions.





**Figure 7.** Seasonal overview of snow cover data for the period 1950/51–2025/26 as a mean over all grid cells in Germany, including selected years, maximum and median values, as well as 10–90 % and 25–75 % quantiles. (a) Fraction of the total area covered by snow. (b) Mean snow depth. (c) Mean number of days with snow cover. (d) Mean cumulative increase of snow depth.



415 The 2010/11 snow season was characterized by exceptionally high snow depths from early winter until mid-January. Mean snow depth increased strongly during December and reached values above 25 cm, clearly exceeding the long-term 90 % quantile of approximately 5–8 cm for this time of year (Fig. 7b). The snow-covered fraction also remained close to 1 throughout December (Fig. 7a). The cumulative variables reached values near the maximum of the time series in December and partly in January. Towards the end of the season, snow depth and snow-covered fraction decreased, and the cumulative number of snow  
 420 days fell within the 90 % quantile range, resulting in a total value of about 55 days.

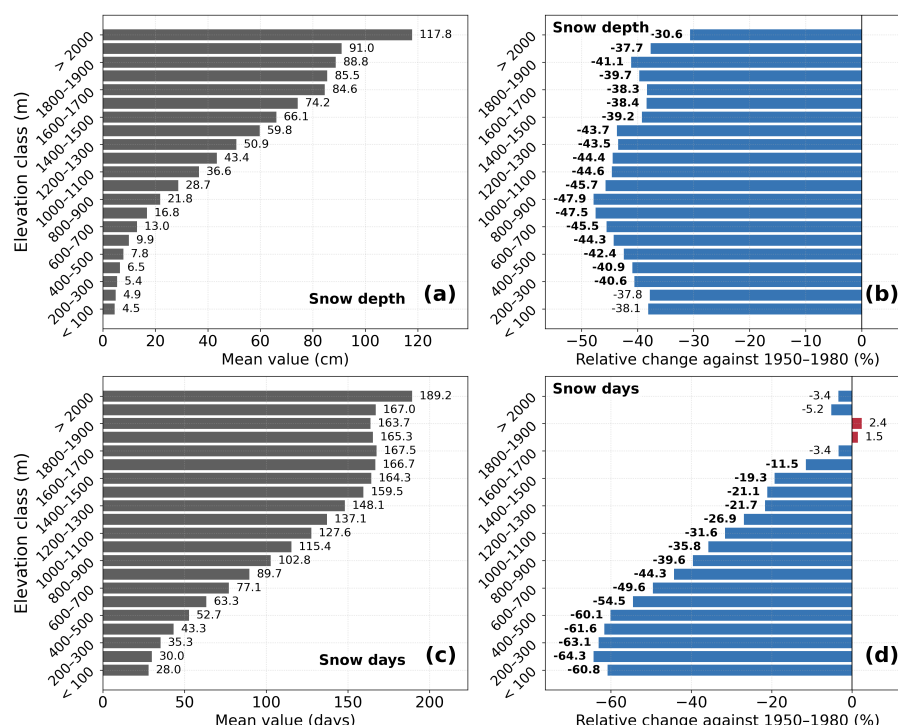
The last four snow seasons were generally characterized by relatively low snow coverage. Only in early December 2023 did mean snow depth exceed the 90% quantile; during most of the remaining days of these four seasons, values were close to or below the median. Also, the length of the snow period was relatively short. The cumulative variables showed final values well below the median in all four seasons (Figs. 7c and d). The 2024/25 season was particularly snow poor, with the number of snow  
 425 days falling within the lowest 10 % of all snow seasons and below in early spring. Mean snow depth exceeded the median only for a few days in late November and never exceeded 3 cm as a Germany-wide mean.

### 3.4 Elevation Dependence of Snow Cover in Germany

Snow depth and the number of snow days varied strongly with elevation over the entire study period. Both variables increased markedly from lowland to mountain regions (Figs. 8a and c). Below 100 m, the mean snow depth during 1950/51–2025/26 was  
 430 only 4.5 cm, whereas it reached 117.8 cm above 2000 m. The average number of snow days increased accordingly, from 28.0 days in grid cells below 100 m to 189.2 days in grid cells above 2000 m. The strongest increase with elevation occurred below approximately 600 m. Between about 600 and 1500 m, snow depth and the number of snow days continued to increase, but more gradually and approximately linearly. At higher elevations, both variables tended to level off. Although the values above 2000 m were considerably higher than at lower elevations, this altitude class comprises only a small proportion of Germany's  
 435 grid cells. Mean values for this class should therefore be interpreted with some caution. The long-term changes also differed between elevation bands (Figs. 8b and d). The number of snow days declined particularly strongly at low elevations. In the 100–200 m band, for example, the LOESS-smoothed value for 2025/26 was 64.3 % lower than the 1950/51–1979/80 reference-period mean. The decline became much weaker at higher elevations. In the 1700–1900 m range, the smoothed change was even slightly positive: snow-day numbers increased (statistically not significant) by 1.5 % in the 1700–1800 m band and by 2.4 % in  
 440 the 1800–1900 m band (Fig. 8d). In contrast, changes in mean snow depth showed no equally clear relationship with elevation (Fig. 8b). The LOESS-smoothed change was -38.1 % below 100 m and reached its largest decline of -47.9 % in the 800–900 m band. Towards higher elevations, the relative decline became smaller again, amounting to -30.6 % above 2000 m. Nevertheless, mean snow depth in 2025/26 was at least than 30 % lower than in the reference period in all elevation bands.

### 3.5 White Christmas in Germany since 1950

445 A White Christmas is commonly understood as the presence of snow cover during the Christmas period. In this analysis, it is defined more specifically as measurable snow cover of at least 1 cm snow depth on at least one of the days between 24 and 26 December. This definition allows a consistent assessment of White Christmas conditions in Germany since 1950. The term

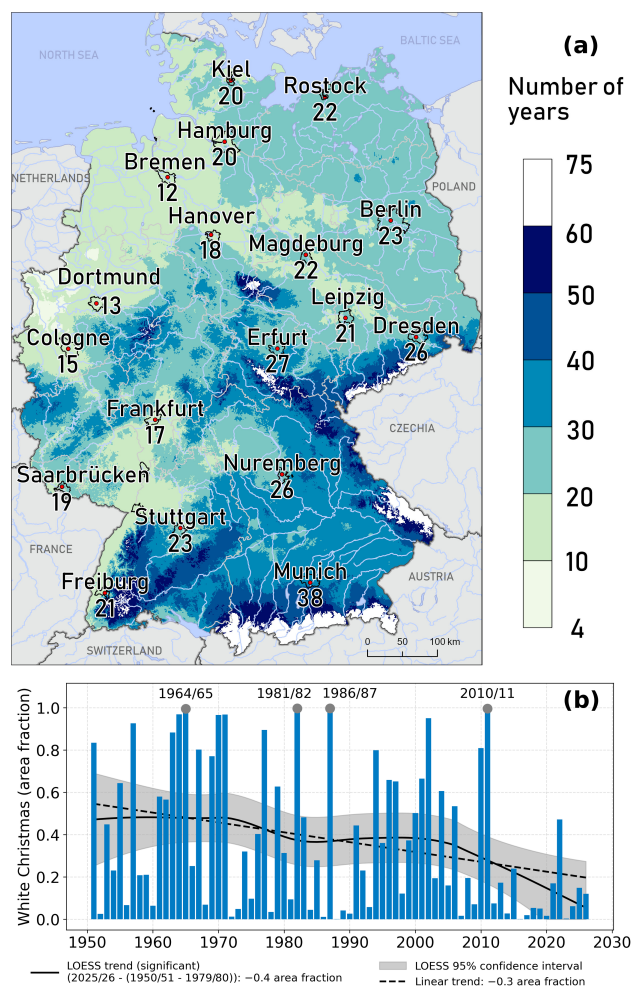


**Figure 8.** Elevation-dependent snow-cover characteristics in Germany during the period 1950/51–2025/26, calculated as the mean over all grid cells within the respective elevation band. Statistics are shown for 100 m elevation bands. (a) Mean seasonal snow depth. (b) Relative change in mean snow depth between the 2025/26 season and the 1950/51–1980/81 reference period, based on LOESS-smoothed time series. (c) Mean seasonal number of snow-cover days. (d) Relative change in the seasonal number of snow-cover days between the 2025/26 season and the 1950/51–1980/81 reference period, based on LOESS-smoothed time series. Significant LOESS trends are indicated in bold.

“probability” for a White Christmas is here used in a spatial context and expressed as the relative snow-covered area fraction over Germany.

450 The probability of a White Christmas in Germany varies strongly with elevation and region. Snow cover around Christmas is relatively frequent in Alpine and highland areas, whereas lowland regions in northern and western Germany experience such conditions only irregularly (Fig. 9a). Cities in eastern Germany mostly recorded between 20 and 30 White Christmas years since 1950; for example, Berlin with 23 years, Magdeburg with 22 years, and Dresden with 26 years. This corresponds to roughly every third year. In northwestern Germany, the occurrence was lower, with only 10–20 years in many cities, for  
 455 example, Bremen with 12 years, Hannover with 18 years, and Dortmund with 13 years. Southern Germany showed a much higher probability of White Christmas conditions, for example, Munich with 38 years, while Alpine regions recorded more than 60 years.

The fraction of Germany experiencing White Christmas conditions varied strongly between years (Fig. 9b). In 1964, 1981, 1986, and 2010, White Christmas conditions occurred across all of Germany. In contrast, White Christmas conditions were



**Figure 9.** White Christmas in Germany. (a) Number of years per grid cell in which at least one of the Christmas days, 24–26 December, had snow cover greater than 1 cm. City values are means within the respective administrative city boundaries. (b) Fraction of Germany with White Christmas conditions in each year, defined as snow cover greater than 1 cm on at least one of the Christmas days, 24–26 December. Basemap © GeoBasis-DE/BKG 2024.

460 nearly absent across Germany in several years, such as 1971, 1987, and 2015.

The LOESS-filtered time series shows a relatively stable White Christmas probability from 1950 to around 2005. During this period, the LOESS trend indicates an area fraction of approximately 0.5 until 1975 and approximately 0.4 until 2005. More recently, following the snow-rich winter of 2010/11, the area fraction of White Christmas conditions decreased strongly. The statistically significant LOESS trend for 2025 relative to 1950–1979 shows a decrease of 0.4 in area fraction, resulting in an

465 area fraction of only about 0.05. Except for Christmas 2021, all recent values were below an area fraction of 0.2.



## 4 Discussion

### 4.1 Snow Cover Trends in Germany in a Changing Climate

In this study, we present SNOWRAS, a newly developed gridded snow depth dataset based on daily station observations. The dataset enables the analysis of snow conditions in Germany at a 1 x 1 km resolution since 1950. A leave-one-out validation  
 470 shows that the interpolation procedure is internally consistent. Compared to the CERRA reanalysis, SNOWRAS shows comparable results with slightly higher snow depth in highly elevated terrain (such as the Alps), reflecting a potential limitation in CERRA arising from the coarser and smoother representation of topography.

The results from the analysis of SNOWRAS reveal a pronounced decline in mean snow depth, from approximately 7.5 cm in the early 1950s to about 5 cm in recent years on a Germany-wide average. The mean number of snow days likewise decreased  
 475 by about 20 days over the full period, and the snow season shortened by approximately 34 days on average across Germany, mainly because of an earlier last day of snow cover. At the Germany-wide scale, 2010/11 was among the most snow-rich winters in the record and marked the last prominent peak in the area-mean series.

A marked recent decline is also evident for White Christmas conditions in Germany. The multi-year mean probability remained relatively stable until around 2005, but the LOESS-smoothed trend of the White Christmas area fraction then declined from  
 480 approximately 0.4 – 0.5 to below 0.1. This strong decrease is consistent with the broader snow cover trends and shows that White Christmas conditions have become markedly less frequent in many lowland regions. Although White Christmas is not a physically based indicator of snow conditions, it is an easily understood proxy for winter conditions.

The observed decline in snow depth and snow cover duration is consistent with a warming trend, which is especially pronounced over land areas such as Germany. Since pre-industrial times, the mean temperature in Germany has increased by  
 485 about 2.5 °C (Friedrich et al., 2025) and mean winter temperatures in Germany have increased by approximately 1.7°C since the late nineteenth century, with recent decades showing an accelerated warming (Kaspar and Mächel, 2023). As a result, a larger fraction of winter precipitation falls as rain rather than snow, reducing snow occurrence. Higher temperatures also promote earlier snowmelt where snow cover persists through a substantial part of the season. However, this study did not formally assess climate attribution, so no definitive causal conclusion can be drawn from the present analysis alone. Other studies have  
 490 nevertheless reported a clear influence of rising temperatures on snow occurrence in Germany (e.g. Schröter et al., 2026).

Snow depth and snow-day trends both increase strongly with elevation, but the trend in snow days over the study period differs markedly by altitude. The LOESS-smoothed series indicates a decline of more than 60 % relative to the reference period in low-land areas below approximately 500 m, indicating a shift towards snow-poor winters in which strong snow coverage becomes increasingly rare. Highly elevated regions, such as the German Alps, show a much weaker trend, with slightly positive values  
 495 between 1700 and 1900 m. This elevation-dependent pattern is consistent with the weaker snow depth trends reported at higher elevations by Beniston et al. (2018). Because snow occurrence depends strongly on whether temperatures are above or below freezing, it does not respond linearly to gradual temperature changes. If temperatures remain below 0 °C, snow can accumulate and persist. Increasing winter precipitation in recent years (Brasseur et al., 2023) may partly offset temperature-driven snow losses at high elevations; this mechanism was not tested explicitly here. The positive LOESS-smoothed changes between 1700



500 and 1900 m should nevertheless be interpreted with caution, because these elevation bands represent only a small fraction of Germany, and the corresponding trends may be strongly affected by local variability.

Snow depth still decreases substantially at higher elevations, by approximately 45 % around 1000 m and 30 % at 2000 m, indicating that increasing temperatures also may affect Alpine regions. The strongest decline occurs around 1000 m, suggesting that snow-rain transition zones between lowlands and mountainous regions are particularly sensitive to warming and the  
505 associated reduction in snowfall.

Although the long-term trends in Germany-wide snow depth and number of snow days are mostly statistically significant and strongly negative, the record also shows substantial interannual and intraseasonal variability. Snow-rich winters such as 2009/10 and 2010/11 demonstrate that high-snow seasons remain possible, even though their probability has decreased substantially in recent decades. The winter of 2010/11 was among the seasons with the most pronounced snow conditions in the record.  
510 More recently, a relatively strong snow event affected northern Germany in January 2026 (Schröter et al., 2026). Although this event did not stand out in the historical record since 1950, it attracted considerable public attention and caused several infrastructure-related impacts. Such events now occur against a background of decreasing mean snow depth, fewer snow days, and shorter snow cover duration.

## 4.2 Hydrological Implications of Declining Snow Cover

515 Globally, more than one-sixth of the population depends at least partly on glaciers and seasonal snowpacks for freshwater supply (Barnett et al., 2005), highlighting the broader relevance of changes in seasonal snow storage for water security. In Germany, the winters 2019/20 and 2024/25 were exceptionally poor in snow. Snow depths were low, snow cover lasted only for a short time, and the seasonal snow amount was strongly reduced. Such winters are not isolated anomalies but part of the observed long-term trend and show how the role of snow in the seasonal water cycle can change. Their strong decline compared  
520 to conditions in the first decades of the SNOWRAS dataset supports the interpretation of a broader shift towards shorter and more variable snow seasons.

Because winter precipitation in Germany has shown a modest overall increase since the mid-twentieth century (Kaspar et al., 2023), atmospheric water supply is not reduced, and the decline in snow cover parameters seems to be more closely associated with rising winter temperatures and a shift from snowfall towards rainfall. In mild winters, less precipitation is stored as snow,  
525 and snow cover often melts earlier. In 2025/26, the mean last day of snow cover in Germany occurred approximately 24 days earlier than during 1950–1980 (see Fig. 6). This shift is expected to favor an earlier release of snowmelt-related water during winter and early spring (Stewart, 2008). Because seasonal snow storage normally delays runoff until spring, an earlier disappearance of snow cover may reduce the contribution of snowmelt to streamflow, soil-moisture replenishment, and groundwater recharge at the beginning of the warm season, when water demand from agriculture and ecosystems is often higher (Blöschl  
530 et al., 2017). This effect is particularly pronounced in regions that rely heavily on snow and glacier melt and cannot store increased winter flows for later use (Barnett et al., 2005). While most lowland areas in Germany are less dependent on snowmelt, upland and Alpine regions are more affected. Catchments in these areas often show a pluvio-nival runoff regime, with discharge controlled by both rainfall and seasonal snowmelt. Higher runoff during winter months, where soils are saturated or frozen,





could increase the potential for flooding. Furthermore, reduced snow insulation can increase frost stress for soils and vegetation and impact winter habitat conditions for mountain ecosystems (Zhao et al., 2026). Concurrent climate-change effects could amplify the impacts of declining snow cover on the water cycle: Rising temperatures also outside the snow cover period could lead to higher evapotranspiration and more frequent and stronger dry periods, which can further reduce water availability during already sensitive seasons (Samaniego et al., 2018).

In German upland and Alpine catchments, improved water management, supported by better seasonal runoff forecasts and reliable snow monitoring, can help adapt to this shift. Possible measures include adjusting reservoir operations, improving water-retention measures, implementing managed aquifer recharge, and adapting seasonal water demand. SNOWRAS can support such actions by providing a spatially consistent observational basis for analyzing long-term changes, interannual variability, and snow-poor or snow-rich seasons across Germany. Our analysis emphasizes that declining snow cover is not only a visible sign of climate change in the cryosphere but also a relevant factor for future water-resource management.

### 4.3 Limitations and Possible Ways Forward

The interpolation approach used for SNOWRAS allows us to analyze long-term changes in snow cover across Germany on a common spatial and temporal basis. However, the resulting fields are only as well constrained as the observations on which they are based. The station network is not evenly distributed across the country, and its density also changes over time. Observations are generally more abundant in densely populated and accessible regions, whereas remote, high-elevation, and topographically complex areas are less well represented. This uneven station distribution may introduce spatially varying interpolation uncertainties, particularly in regions where snow conditions are strongly controlled by local terrain effects (López-Moreno and Nogués-Bravo, 2006).

Additional uncertainties are associated with the long temporal coverage of the study period from 1950 to 2026. Within such a long time period, changes in measurement practices, instrumentation, station exposure, reporting routines, and station relocation are unavoidable. Although extensive quality control was applied to remove implausible observations, residual temporal and spatial inhomogeneities may remain and affect the consistency of the dataset (Kaspar et al., 2013). Furthermore, SNOWRAS begins only in the 1950s due to historical data availability. Between 1950 and 1980, the available number of stations was relatively low, as much of the data was not yet digitized. The station observations then peaked in the 1990s before decreasing again after the year 2000. These limitations in the temporal coverage are important for trend analyses as temporal inhomogeneities can affect long-term trends. With the absence of earlier observations the derived trends may not fully represent multi-decadal variability prior to the 1950s.

The representation of snow variability in mountainous areas is limited as snow depth is highly sensitive to elevation, slope, wind exposure, and small-scale precipitation differences. These processes are especially important in southern Germany, where Alpine and pre-Alpine topography creates pronounced spatial variability over short distances. While the  $1 \times 1$  km grid resolution represents a substantial improvement over coarser gridded products, it cannot fully resolve local-scale snow accumulation and redistribution processes (Grünewald et al., 2013). Additionally, snow does not accumulate in mountainous areas as evenly as in flatter terrain. Some of the above-mentioned reasons can cause large differences over short distances, with snow being





enhanced in some places and removed or redistributed in others (Mott et al., 2023). As these processes are difficult to represent fully in interpolation methods and reanalysis products, the uncertainty of the interpolated snow fields is expected to be larger in mountainous regions than in lowland areas.

Moreover, uncertainty propagation through the whole described workflow remains methodologically challenging. Measurement errors, residual quality-control uncertainties, and interpolation errors are carried forward into derived snow indicators such as the first and last day of snow cover, snow cover duration, and seasonal aggregates. Although our evaluation provides an assessment of interpolation performance, a complete quantification of cumulative uncertainty is difficult. Independent validation is constrained by the need to retain sufficient observations for interpolation, while repeated validation experiments, as described in Section 2.6.2, are computationally demanding.

The integration of complementary data sources could further improve the quality of the dataset. For example, remote sensing observations from optical and microwave sensors offer valuable information on snow cover extent and, in some cases, snow water equivalent (Takala et al., 2011). Such data could help constrain snow estimates in regions with sparse station coverage and complex terrain. However, satellite-based snow products are only available for the more recent decades and therefore cannot provide a fully consistent basis for the entire 1950–2026 study period. Their greatest potential may therefore lie in supporting validation, bias assessment, and methodological refinement for the satellite era.

Advanced statistical and machine-learning approaches also provide promising opportunities for improving snow depth interpolation (e.g. Hengl et al., 2018). Methods capable of representing non-linear relationships between snow depth, atmospheric conditions, and terrain characteristics could enhance the depiction of spatial variability, particularly in regions where traditional interpolation approaches are limited. Deep learning and hybrid statistical–physical methods could be especially useful for capturing complex spatio-temporal dependencies and local-scale topographic effects (Reichstein et al., 2019). However, such approaches require careful validation, transparent uncertainty assessment, and safeguards against overfitting, particularly when applied to long-term climate analyses. The implementation of physically informed correction factors into the interpolation procedure could further improve the interpolation scheme. Processes such as orographic precipitation enhancement, wind redistribution, preferential snow accumulation, and melt-related elevation gradients exert a strong influence on observed snow patterns. Accounting for these processes more explicitly could improve the realism of interpolated snow fields, especially in mountainous and exposed regions.

Finally, extending the analysis from snow depth and snow cover duration to snow water equivalent (SWE) would substantially increase the hydrological relevance of the dataset. SWE provides a more direct measure of the amount of water stored in the seasonal snowpack and is therefore highly relevant for runoff generation, water-resource management, and climate-impact assessments (Barnett et al., 2005). However, long-term in situ SWE observations are scarce in Germany. Deriving SWE from snow depth fields would require robust approaches for estimating snow density and its temporal and spatial variability. Developing and validating such methods represents an important step towards a more comprehensive assessment of changes in Germany’s snow regime and their hydrological consequences.



## 5 Conclusions

In this study, we presented SNOWRAS, a novel long-term dataset of daily gridded snow depth for Germany at a spatial resolution of 1 x 1 km, covering the period from 1950 onwards. We derived key snow-cover indices, including seasonal mean snow depth and the number of snow days, which show mostly pronounced decreasing trends over the past 75 years. The decline is weaker in high-elevation regions, where winter temperatures more often remain below freezing temperatures despite continued warming. In contrast, lowland areas show a pronounced decrease of approximately 40% in mean seasonal snow depth and, in some areas, declines of more than 60% in the number of snow days. The probability of a White Christmas has declined markedly since around 2005, falling to approximately 0.05 after remaining relatively stable at around 0.4 during previous decades. Despite the observed long-term decline in snow-related parameters, snow-rich winters and notable snow events remain possible, as illustrated by the relatively recent winter of 2010/11. Declining snow cover in Germany may shift the timing of snowmelt-related water availability, particularly in snow-influenced upland and Alpine catchments. Reduced snow cover can also have implications for infrastructure, winter tourism, and snow-related hazard assessment. SNOWRAS provides a consistent spatial framework for analyzing changes in snow depth across Germany and can support assessments of water availability, hydrological modeling, and snow monitoring.

**Data availability.** The exact version of the SNOWRAS v1.0 dataset described in this paper is permanently archived on Zenodo at <https://doi.org/10.5281/zenodo.22249666>. Updated versions of the SNOWRAS dataset are made available through the DWD Open Data portal: [https://opendata.dwd.de/climate\\_environment/CDC/grids\\_germany/daily/snowras\\_de/](https://opendata.dwd.de/climate_environment/CDC/grids_germany/daily/snowras_de/).

**Author contributions.** MD conceived the study, developed the final dataset, performed the data processing, and analysis, and wrote most of the original manuscript draft. AK prepared the input data for the final dataset and substantially contributed to data processing, analysis and manuscript writing. GMS, IH and FC supported the preparation of the input data. UB, GS, FC and BW contributed to developing an earlier version of the dataset. GMS and AF created individual figures. UB, MR and TD reviewed the manuscript. All authors provided feedback, and approved the final version.

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Their contributions substantially enhanced the spatial coverage of SNOWRAS, particularly in regions close to Germany’s borders.



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