



# Warming winters bring climatic opportunities and risks for winter crops in Northern Europe

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**Abstract.** Winter crops, crops sown in the autumn and harvested the following spring or summer, often provide higher yields and are more resilient to early-season climatic stress compared with spring crops. However, their yields depend on successful overwintering, and hence suitable temperature and snow conditions. It remains unclear whether warming will expand their cultivation opportunities by easing temperature limitations or rather increase exposure to harmful winter conditions across Northern Europe. We used a regional single-model initial-condition large ensemble (SMILE) based on the Canadian Regional Climate Model version 5 (CRCM5-LE) under the high-emission RCP8.5 scenario (1955–2099) to examine: (1) projected changes in winter climate conditions relevant to winter crops, (2) the timing at which climate change signals in these conditions emerge from natural climate variability, and (3) the influence of bias correction in robustness and detectability of these changes and their timing.

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20 Average winter temperature increases by the end of the century, expanding the climatic suitability for winter crops without compromising cold degree day requirements for crop acclimation or vernalization. However, freeze-thaw cycles and shallow snow become more frequent, raising risks of cold damage and premature cold deacclimation. Adverse winter conditions emerge as early as 2040 north of 60° N and around two decades earlier south of 60° N, indicating that, without adaptations, winter crop production can be challenged. After bias correction these conditions emerge earlier than in raw simulations,

25 calling for even earlier adaptation.

## 1 Introduction

Climate change is increasing temperatures and shifting the timing and amount of precipitation, as well as whether precipitation falls as rain or snow (IPCC, 2021). These changes disrupt seasonal cycles, with cascading effects on, among others, crop production (Lesk et al., 2022; Olesen et al., 2011; Ray et al., 2015). Our ability to reliably obtain sufficient food,

30 feed and fibre is increasingly compromised by the rising frequency of adverse climatic conditions (Zampieri et al., 2017; Zscheischler et al., 2017), ultimately making conditions locally less suitable for cultivation of certain crops (Bracho-Mujica



et al., 2024; Rezaei et al., 2023). To assess climate impacts on crops and inform adaptations, it is essential to understand how hydroclimatic conditions relevant to agriculture change under continued warming.

35 Winter crops, such as winter wheat and winter barley, are sown in autumn and resume growth in spring. They offer potential adaptation under climate change (Fang et al., 2017; Stewart et al., 2018), because they are already established in spring, and hence have easier access to soil water then, instead of solely relying on spring precipitation (Thorup-Kristense et al., 2009). They also reach maturity earlier, often before peak summer heat (Fang et al., 2017; He et al., 2020). However, their productivity depends on successful overwintering and suitable winter conditions. Extremely low temperatures can cause damage through intracellular ice formation and membrane disruption (Bokhorst et al., 2010; Salehi Sardoei and Fazeli-Nasab, 2025), against which snow cover provides protection through insulation (Chen et al., 2026). Freeze-thaw cycles can cause direct mechanical damage (Fowler et al., 2014) and have indirect effects through soil moisture dynamics influenced by snow accumulation and melt (Skinner et al., 2014). Cold acclimation, triggered by temperatures near freezing, enhances low temperature tolerance (Fowler et al., 2014; Fowler and Gusta, 1979). Sustained temperatures above freezing enable vernalization, ensuring subsequent flowering and hence grain formation (Weir et al., 1984). Despite their importance, key winter processes affecting winter crops, particularly snow dynamics and its interaction with temperature, are rarely included in climate change impact assessments (Hu et al., 2015; Rashid et al., 2019).

Future climate projections for estimating crop production rely on climate model outputs and are therefore affected by their biases and uncertainties. Bias refers to systematic model errors, such as temperature or precipitation relationships deviating from observations (Lehner, 2024; Tootoonchi et al., 2023). Even with bias correction, uncertainties remain. These stem from the difficulty in predicting future socioeconomic development and from the interactions between internal climate variability, arising from intrinsic atmospheric and oceanic processes, and externally forced climate change driven primarily by greenhouse gas emissions (Lehner and Deser, 2023). Together, they generate substantial uncertainty in regional climate projections on annual to multi-decadal scales (Dai and Bloecker, 2019; Hawkins and Sutton, 2009; Maher et al., 2021), limiting our ability to identify when climate change signals emerges from natural climate variability (François and Vrac, 2023; Hawkins and Sutton, 2012; Keller et al., 2014). This challenge is particularly pronounced for winter conditions relevant to crop overwintering, where detecting and interpreting spatial variations in the timing of emergence is complicated by interactions among multiple climatic variables and threshold-dependent processes, such as freeze-thaw cycles.

Single-Model Initial-condition Large Ensembles (SMILEs) consist of multiple simulations performed with the same climate model and external forcing but with slightly different initial atmospheric conditions. This design enables the separation of internally generated climate variability from the externally forced climate change signal (Deser et al., 2012; Maher et al., 2019) and thus facilitates assessing of the timing of climate change emergence (Deser et al., 2020). A number of coarse resolution SMILEs are available (e.g., Kay et al., 2015; Maher et al., 2019; Rodgers et al., 2021), while high resolution simulations remain relatively scarce. High resolution simulations are particularly valuable for impact studies that depend on an accurate representation of rare and adverse climatic conditions in local scales (Gutowski et al., 2020). Although SMILEs are increasingly used in climate impact research (Astagneau et al., 2025; Miller et al., 2024; Poschlod et al., 2020), their



application to cropping systems remains limited (Dietz et al., 2025; Jägermeyr et al., 2021), with no studies addressing the representation of crucial winter conditions for winter crops. Moreover, the role of bias correction in this context has received limited attention, with only a few studies addressing it (e.g., in Astagneau et al. 2025).

In northern Europe, low temperatures and short growing seasons currently limit cultivation at higher latitudes (Peltonen-Sainio et al., 2007). Warming can expand suitable conditions, enabling crop cultivation, including that of winter crops, in previously marginal regions. However, winter conditions such as snow depth and freeze-thaw cycles remain critical for overwintering crop survival (Chen et al., 2026). Despite this, and the potential advantages provided by winter crops in the face of more extreme summer conditions, we lack a targeted assessment of future winter variability relevant to cropping and the potential for expansion of overwintering cultivation in northern Europe.

We examined the effects of climate change on winter climatic conditions, with a specific focus on variables relevant to winter crops in Northern Europe. Specifically, we quantified: 1) the projected changes in key winter climate conditions relevant for winter crop and 2) when winter climatic conditions show detectable changes from historical conditions (i.e., time of emergence), and whether bias correction influences the answer to these questions. To address these objectives, we used a regional high-resolution SMILE under a high emission scenario during 1955-2099.

## 2 Methods

We compare observational data (Sect 2.1) with historical climate simulations (Sect 2.2) to evaluate how well the simulations reproduce historical averages and trends of key winter climatic indicators for crops. We then apply bias correction (Sect 2.3) to these variables using observational datasets as reference. Based on the bias corrected variables, we calculate climatic indicators of relevance for winter crops (Sect 2.4) and analyze their average and trend. We then estimate the time of emergence of climate indicators (Sect 2.5).

In interpreting the results, we focus on regions where climatic conditions could become suitable for future crop cultivation. Although the Norwegian mountains are included in the analyses and maps, changes in these areas are not vastly discussed because topographic constraints limit their potential for cultivation even under future climate conditions.

### 2.1 Observations (reference dataset)

The study area comprises the Nordic Europe including Denmark, Finland, Norway, and Sweden (4 W to 32 E, 54 N to 64 N). This domain includes regions currently used for winter crop cultivation as well as northern snow-dominated areas where winter cropping is presently limited by prolonged cold conditions and frozen soils (Juhola et al., 2017; Wiréhn, 2018).

We use daily precipitation and temperature from the E-OBS v29 dataset at a spatial resolution of 0.11° (~12 km). E-OBS is a gridded dataset developed for climate analysis across Europe (Cornes et al., 2018), based on dense station observations. For snow depth, we use ERA5-Land daily data at a 0.1° (~9 km) resolution (Copernicus Climate Change Service, 2024; Muñoz-Sabater et al., 2021). ERA5-Land provides daily spatial resolution and long timespans while performing reasonably well in



representation of snow depth in high-latitude regions although regional snow depth biases exist in glaciers and Norwegian mountains (Räisänen, 2023; Muñoz Sabater et al., 2021). ERA5-Land directly provides snow depth instead of snow water equivalent, unlike observation-based products such as GlobSnow, making it suitable for deriving agriculturally relevant indicators (Sect 2.4). We retain all grid cells for precipitation and temperature analyses, excluding those covering glaciers in western Norway due to complex terrain-related artifacts (Hersbach et al., 2020).

We calculate three key climatic indicators, average precipitation ( $P_{\text{mean}}$ ), temperature ( $T_{\text{mean}}$ ) and snowdepth ( $SND_{\text{mean}}$ ) over a 50-year reference period (1956–2005). The long-term average and trend during this period serve as a baseline, with the average used to assess the mean state and the trend to assess whether climate simulations follow the same direction of change as the observations prior to bias correction (*Supplementary material, S1*). We focus on long-term averages and trends during December-February (DJF). This provides a consistent basis for comparing winter conditions across latitudes, with the selected period encompassing most of the snow season in regions where soil and topographic conditions permit winter crop cultivation and capturing the core winter conditions relevant to our analyses.

## 2.2 Climate model simulation using CRCM5-LE

We extract the daily DJF precipitation, temperature and snow depth from the 50-member Canadian Regional Climate Model version 5 (CRCM5) Single Model Initial-condition Large Ensemble (SMILE), hereafter CRCM5-LE, a dynamic downscaling of the global Canadian Earth System Model version 2 large ensemble (Kirchmeier-Young et al., 2017; Leduc et al., 2019; Šeparović et al., 2013). CRCM5-LE SMILE has high spatial resolution ( $0.11^\circ$ ) over Europe and has one of the largest ensemble size (50 members) at this resolution, allowing for robust assessments of trends and internal variability (Miller et al., 2024), for local scale impact studies.

The CRCM5-LE simulations span 1955–2099 after discarding the spin-up years (Leduc et al., 2019; Miller et al., 2024). The historical period (1950–2005) is driven by observed anthropogenic and natural forcings, while the future period (2006–2099) follows the high-emission scenario RCP8.5. The 50 ensemble members differ only by small random perturbations in their initial atmospheric conditions at the start of the simulations (Fyfe et al., 2017), allowing inter-member differences to be interpreted as internal (natural) climate variability (Hawkins and Sutton, 2009; Mittermeier et al., 2019). Compared with the CORDEX multi-model ensemble, the CRCM5-LE projects warmer and drier climate change signals over Northern Europe (von Trentini et al., 2019). Combined with the high-emissions RCP8.5 scenario, this produces a stronger forced climate signal, enabling robust detection of climate change with fewer ensemble members (Leduc et al., 2019) and providing a possible upper-bound estimate of the magnitude and timing of projected changes (Sarofim et al., 2024). This supports a precautionary approach by identifying the earliest plausible timing at which adaptation measures for winter crops may be required to reduce potential yield losses. At the same time, choosing earlier decades with radiative forcings aligned with lower emission scenarios allows for assessment of impacts under lower external forcing (Böhnisch et al., 2025).

Precipitation and temperature data are originally provided at sub-daily resolution. We aggregate them to daily averages. We then re-grid all three variables daily precipitation, temperature and snow depth from the original curvilinear grid to a regular



130 latitude-longitude grid with  $0.1^\circ$  resolution to match the observational dataset using the Climate Data Operators. We use the nearest-neighbour method for precipitation and snow depth and the bilinear interpolation for temperature.

### 2.3 Bias correction

To reduce systematic errors, we apply a univariate distribution-based bias correction approach to precipitation, temperature, and snow depth, accounting for changes in distributions between historical and future periods (Gudmundsson et al., 2012; 135 Poschlo et al., 2020). Gamma distributions are used for precipitation and snow depth, and a Gaussian distribution for temperature, as these minimally altered the original simulations (Teutschbein and Seibert, 2012). Precipitation is additionally corrected for drizzle days by correcting the probability of precipitation occurrence by applying a wet-day threshold  $> 1$  mm (Teutschbein and Seibert, 2012; Tootoonchi et al., 2022). We use a univariate approach because it performs comparably to multivariate methods in the Nordic region, while preserving temporal structure and avoiding high computational costs 140 (Tootoonchi et al., 2022, 2023), and because no strong inter-variable correlation exist among variables in this region (Astagneau et al., 2025).

Bias correction brings the ensemble mean closer to the observed mean and reduces the standard deviation across simulated trends over the historical period (not shown), motivating its application to reduce biases in the future period. As such, in Section 3.1 we show results only after bias correction. We evaluate the effect of bias correction by comparing bias-corrected 145 and raw simulations during the future period, focusing on differences in ensemble mean, ensemble trend, and time of emergence for selected relevant indicators for agriculture (Sect 3.2).

### 2.4 Winter climatic indicators

We consider two groups of climatic indicators (Table 1). The first describe general winter climate conditions ( $P_{\text{mean}}$ ,  $T_{\text{mean}}$ , and  $SND_{\text{mean}}$ ). The second comprise ecophysiologically informed indicators designed to capture winter conditions 150 relevant for winter crops. Here we parametrize these indicators using thresholds for winter wheat, a staple winter crop in the Nordic region, while providing a framework for assessing climatic suitability and winter stress relevant to winter crops more broadly.

To assess whether cold acclimation requirements are met, we use cold degree days (CDD), defined as the accumulation of low but non-lethal daily temperatures between  $-5^\circ\text{C}$  and  $10^\circ\text{C}$  for winter wheat (Fowler et al., 2014; Fowler and Gusta, 155 1979; Vaitkevičiūtė et al., 2022) required for crops to enter dormancy and develop freezing tolerance. In addition, we include three indicators for crop survival under adverse climatic conditions. The first is the number of freeze-thaw cycles, which increase the likelihood of mechanical damage through plant tissue injury and ice encasement (Fowler et al., 2014), reducing overall survival and potentially disrupting winter dormancy. The second indicator captures low-temperature damage in acclimated crops (Aase and Siddoway, 1979; Cox et al., 1986; Ejaz et al., 2023), defined as the occurrence of temperatures 160 below a critical threshold causing 50% mortality in acclimated crops ( $< -10^\circ\text{C}$  for winter wheat) when snow depth is insufficient for insulation to ensure a decoupling between air temperature and crop meristem temperature, at the soil surface



( < 10 cm) (Aase and Siddoway, 1979; Cox et al., 1986; Ejaz et al., 2023). The third indicator is the number of shallow snow days, defined as days with snow depth <5 cm. This indicator captures both freezing risk due to insufficient snow insulation (Zhu et al., 2022) and the reduced risk of snow molds, caused by phytopathogenic fungi that develops under persistent  
165 insulating snow cover in winter crops (Bruehl, 1982; Ponomareva et al., 2021), where temperatures remain near 0 °C and plants experience prolonged respiratory carbohydrate depletion (Bergjord et al., 2008; Byrns et al., 2020).  
We did not include a separate indicator for vernalization because the temperatures that promote vernalization largely overlap with those required for cold acclimation, although vernalization occurs over a broader temperature range (approximately 0–15 °C) and is effective at slightly warmer temperatures than those optimal for cold acclimation in winter crops (Eagles et al.,  
170 2010; Weir et al., 1984). Consequently, we use mean winter temperature as a proxy for the thermal conditions governing vernalization.



**Table 1: List of 8 indicators relevant for winter crops capturing (a) general winter climatic conditions and (b) specific aspects of development and survival. Thresholds refer to winter wheat.**

| Type             | Process captured             | explanation                                                                                                                                                     | Indicator                                                                                                                                                                                                                                                               | Reference                                                                 |
|------------------|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| (a) General      |                              | General description of climatic conditions                                                                                                                      | Mean of daily precipitation (Pmean)                                                                                                                                                                                                                                     |                                                                           |
|                  |                              |                                                                                                                                                                 | Mean of daily temperature (Tmean)                                                                                                                                                                                                                                       |                                                                           |
|                  |                              |                                                                                                                                                                 | Mean of daily snow depth (SNDmean)                                                                                                                                                                                                                                      |                                                                           |
| (b) Winter crops | Acclimation                  | Accumulation of specific low but non-lethal temperatures required for a crop to safely enter dormancy and gain hardiness                                        | <p>Cold Degree Days CDD = <math>\sum_{i=1}^n CDD_{day,i}</math></p> <p><math>CDD_{day} = \begin{cases} \max(0, 10 - T_d), &amp; -5 \leq T_d \leq 10 \\ 0, &amp; otherwise \end{cases}</math></p> <p>~300 CDD required for adequate cold acclimation in winter wheat</p> | (Fowler et al., 2014; Fowler and Gusta, 1979; Vaitkevičiūtė et al., 2022) |
|                  | Survival - mechanical damage | Increase the likelihood of mechanical damage through root tissue injury and ice encasement                                                                      | Number of freeze-thaw cycles, defined as at least one day with daily $T > 1^\circ\text{C}$ followed by $T < 1^\circ\text{C}$ or vice versa                                                                                                                              | (Fowler et al., 2014; Skinner et al., 2014; Willick et al., 2021)         |
|                  | Survival - low temp damage   | Temperatures below a critical threshold less than temperatures causing 50% mortality in acclimated crops and the damage increasing with insufficient snow cover | number of days where $SND < 10\text{ cm}$ & $T < -10^\circ\text{C}$                                                                                                                                                                                                     | (Aase and Siddoway, 1979; Cox et al., 1986; Ejaz et al., 2023)            |



|  |                                      |                                                                                                                                   |                                 |                                                                     |
|--|--------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------------------------------------------------|
|  | Survival – winter mold / cold damage | Tradeoff between Shallow snow increases the risk of damage due to low insulation, while deep snow increases the risk of snow mold | number of days with SND < 5 cm, | (Byrns et al., 2020; Gaudet and Laroche, 1997; Kosová et al., 2025) |
|--|--------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------------------------------------------------|

## 175 2.5 Time of emergence

For each variable, we estimate the time of emergence of trends, defined as the point at which the forced rate of change becomes distinguishable from internal climate variability (Bonan et al., 2021; Keller et al., 2014; Li et al., 2026; Rodgers et al., 2015). We compute linear trends for each member of the 50-member CRCM5-LE over expanding time windows beginning in 1956, with window lengths ranging from 50 years to the full period ending in 2099 (144 years). We select a  
 180 minimum window length of 50 years, rather than the 30-year normal period, to improve the robustness of the estimated climate change signal by reducing the influence of internal variability on trend calculations.

We first estimate the time of emergence by considering the forced signal as the ensemble mean of trends in the indicator and the noise defined as the standard deviation of trends across ensemble members. A single signal-to-noise ratio is calculated for each grid cell, and time of emergence is defined as the first year at which this ratio exceeds 1. Our definition of the signal  
 185 and of the noise for the ensemble mean case, as well as the choice to use a ratio of 1:1 for signal and noise, follow closely Rodgers et al. (2015). We then compare these times of emergence estimates with an alternative approach where the trend is estimated separately for each ensemble member and divided by the standard deviation of trends across ensemble members, resulting in a member-specific signal to noise ratio. Time of emergence is then determined independently for each ensemble member as the first year when its signal-to-noise ratio exceeds the same threshold of 1, and  
 190 the ensemble mean of the resulting member-specific time of emergence years is reported as the final estimate. Comparing these two approaches allow us to assess the sensitivity of time of emergence estimates to the representation of the forced signal (IPCC, 2021, Chapter 10.4.3.2), either as an ensemble-mean response or separate for individual ensemble members.

We present the results obtained using the first method in the Results section and those from the second method in the Supplementary material (S2). To evaluate the inconsistency between the two approaches, we compare the resulting time of  
 195 emergence spatial patterns visually and quantified their agreement using a pixel-wise correlation analysis.

Based on the time of emergence of trends under the high-emission RCP8.5 scenario for both beneficial and adverse crop-related indicators, we identify periods of opportunity and risk based on the relative timing of emergence across indicator types. Opportunity and risk periods are defined as intervals during which beneficial and adverse indicators, respectively, exhibited emerging favourable and unfavourable trends.



## 200 3 Results

### 3.1 Changes in and time of emergence of climatic indicators relevant for winter crops

Among the agriculturally relevant indicators calculated from the bias corrected simulations, cold degree days (CDD) range from approximately 200 to over 500 degree days during the historical period (1956-2005) excluding the Norwegian mountains, with higher values south of 60° N (Fig. 1a). In the future (2050-2099), CDD increase across most of the region, except in Denmark, where they decrease by up to 200 degree days. Freeze-thaw cycles are generally more frequent south of 60° N, reaching up to seven cycles within December-February during the historical period (Fig. 1b). In the future, they increase primarily north of 60° N, by up to three additional cycles, particularly in northern Sweden. Shallow snow days reach a maximum of around 70 days during the historical period (Fig. 1d) and increase to approximately 90 days in the future, particularly south of 60° N. Days with shallow snow (<5 cm) co-occurring with low temperatures (< - 10 °C) range from 0 to 12 days during the historical period (Fig. 1c). In the future period, changes are modest, with a slight decrease south of 60° N and an increase of approximately one day north of 60° N.

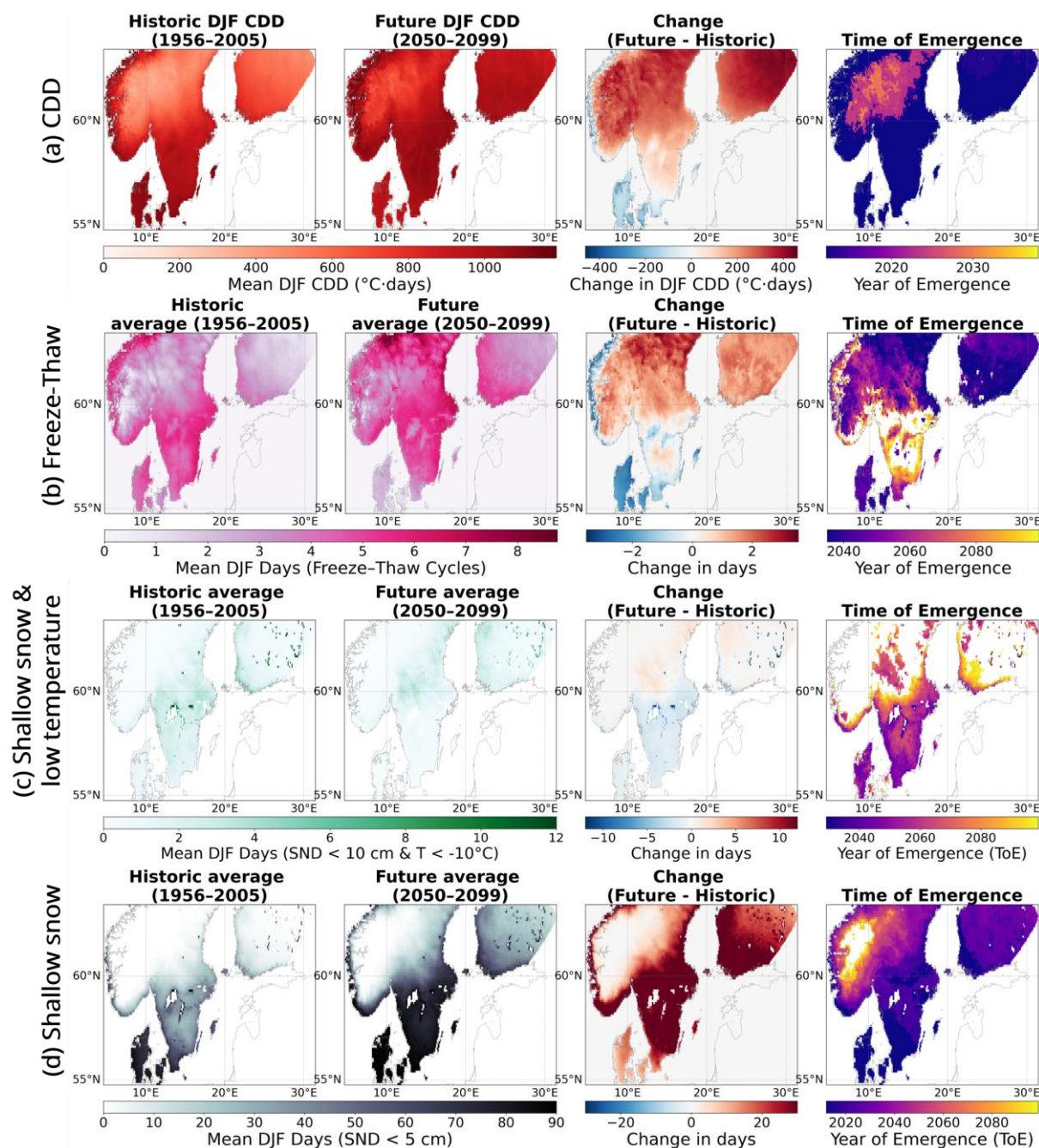


**Figure 1.** Ensemble historic averages (1956-2005), future averages (2050-2099), changes between future and historic period and the time of emergence of trends for the five agriculturally relevant climate conditions: (a) CDD, (b) number of days of freeze-thaw cycles, (c) number of days with temperature  $< -10^{\circ}\text{C}$  and SND  $< 10\text{ cm}$ , and (d) number of days with SND  $< 5\text{ cm}$ . All plots refer to indicators extracted from bias corrected variables.

Precipitation changes are modest, with increases of approximately  $1\text{ mm day}^{-1}$  across most of the region, except for the Norwegian mountains (Fig. 2a). Winter temperatures increase by approximately  $4\text{--}5^{\circ}\text{C}$  throughout the study area, with the



largest warming occurring in the coldest northern regions (Fig. 2b). Average snow depth declines across the study region by  
 around 200 mm across most regions. The largest reductions occur in the Norwegian mountainous (Fig. 2c).

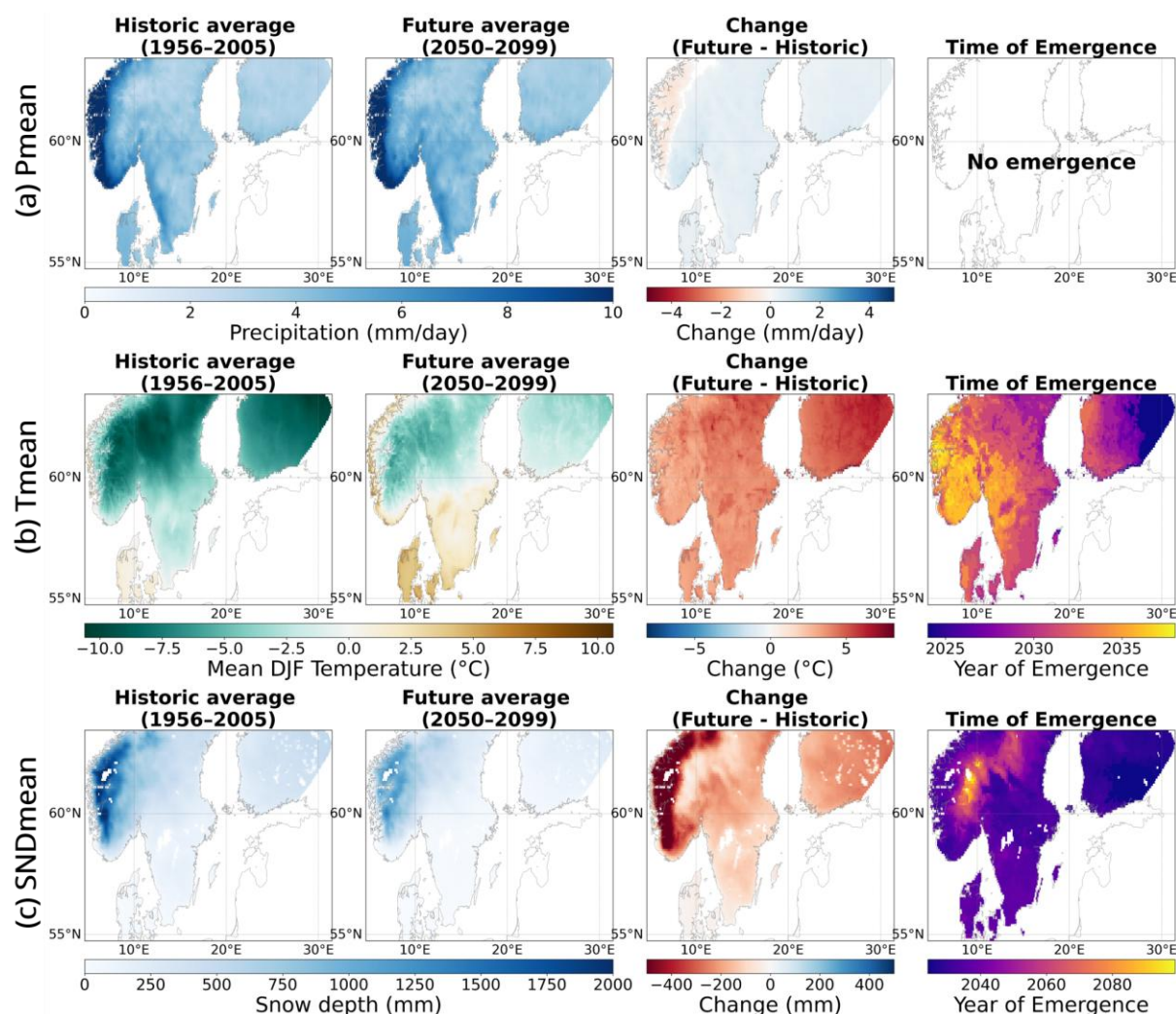


**Figure 2. Ensemble historic averages (1956-2005), future averages (2050-2099), changes between future and historic period and the time of emergence of trends for the three main variables Pmean, Tmean and SNDmean. Note that the color bar in Tmean is reversed relative to Pmean and SNDmean. All plots are for bias corrected indicators.**

When using the ensemble mean trend as the forced signal, the CDD trend becomes distinguishable from internal variability and emerges around 2015 across most of Scandinavia, except for inland regions north of 60° N, where time of emergence is delayed by approximately 10-20 years (Fig. 1a, far right). Freeze-thaw cycle trends emerge by mid-century in northern regions, while they appear later or not at all in southern areas (Fig. 1b, far right). Trends in combined cold and shallow snow depth days emerge mainly south of 60° N between 2050 and 2070 (Fig. 1d, far right). Shallow snow depth trends emerge as early as the 2020s in the southern regions but only toward the end of the century in northern areas (Fig. 1d). No trend



emergence in precipitation is detected (Fig. 2a, far right). Temperature-related trends emerge as early as the mid-2020s in eastern Finland and more broadly around 2040s across all regions (Fig. 2b, far right). Snow depth, trends emerge in most locations by the 2040s, whereas inland areas north of 60° N show no emergence, until the 2090s in some regions (Fig. 2c, far right). When the time of emergence is calculated separately for each ensemble member and then averaged, instead of from the ensemble-mean signal, the spatial patterns are similar for all indicators, but with earlier emergence, except freeze-thaw cycles and combination of shallow snow and cold stress having a distinctly different spatial pattern (Fig. S2). Agreement in the calculated time of emergence between the two methods varies, with Pearson correlation coefficients ranging from 0.1 for cold stress and shallow snow cover to 0.9 for shallow snow depth (Fig. S2).

In summary, above 60° N, trends in beneficial (i.e. mean temperature and CDD) indicators emerge earlier than those in detrimental (e.g. freeze-thaw cycles and shallow snow conditions) indicators, whereas in the south, they have already emerged (Fig. 3). Trends in indicators of favourable thermal conditions, represented by increasing mean winter temperature and fulfilment of the CDD requirement, emerge north of 60° N by the 2030s (Fig. 3) and around 2020 south of 60° N. Adverse winter stress indicators, including freeze-thaw cycles and shallow snow conditions, emerge around the 2040s north of 60° N but around 2020 in southern regions. Days with both shallow snow and low temperatures emerge by the 2070s north of 60° N, compared with around the 2050s south of 60° N.

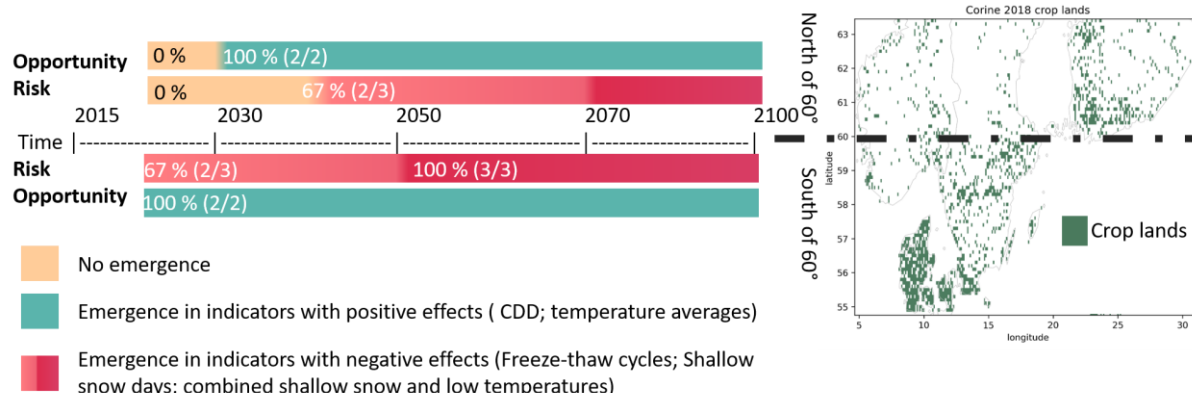


**Figure 3 Evolution of favourable and adverse winter conditions based on the mean time of emergence of agroclimatic indicators, separated for regions above and below 60°N. Favourable indicators include increasing winter temperature and enhancing cold degree days, whereas adverse indicators include increasing freeze–thaw cycles, shallow snow depth, and days with both insufficient snow cover and low temperatures. Percentages indicate the fraction of indicators that have emerged by a given year. For example, 67% corresponds to two of the three adverse indicators having emerged. The cropped area is based on CORINE landcover map relative to year 2018, where past conditions allowed for crop cultivation.**

### 3.2 Bias correction effects

Bias correction affects both the time of trend emergence and mean changes in the indicators. CDD trends north of 60° N emerge up to 40 years earlier (Fig. 4a), with freeze-thaw cycles showing a similar advancement after bias correction (Fig. 4b), in line with higher mean temperatures, stronger warming trends, and reduced trend variability in the bias-corrected simulations (not shown), which increase the signal-to-noise ratio. South of 60° N, freeze-thaw emergence is delayed by up to



around 30 years, as warmer temperatures reduce the frequency of crossings of the 0 °C threshold, weakening the trend signal. For days with shallow snow and cold stress (Fig. 4c), differences in means and trends are generally small, although emergence advances by up to 20 years south of 60° N in line with increase in the shallow snow days after bias correction. In addition to affecting time of emergence, bias correction increases CDD by up to 500 °C·day (from 300 to 800 °C·day; 2.7-fold) north of 60° N, particularly in inland Norway, while CDD trends south of 60° N strengthen by up to 3 °C·day·year<sup>-1</sup>. Freeze-thaw cycles increase by up to six events (from 5 to 10 events; 2-fold) in northern regions, with trends increasing by up to 0.04 events·year<sup>-1</sup>. Days with both shallow snow and low temperatures increase by up to five days (from 5 to 10 days; 2-fold) across most regions, while their projected trends change little.

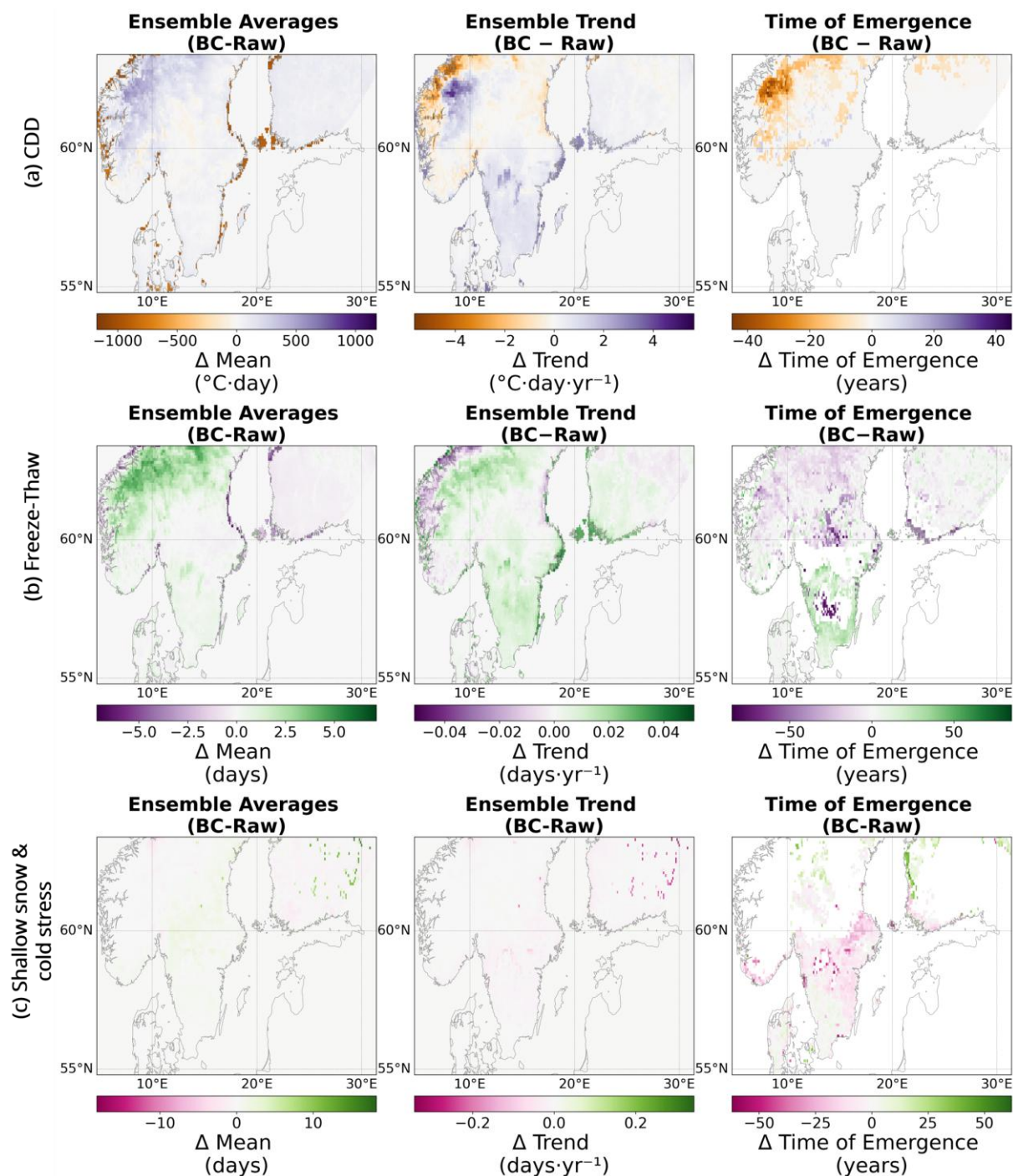


**Figure 4.** Differences between the raw and bias-corrected 50-member simulations in future (2006–2099) ensemble averages, ensemble trends, and time of emergence for (a) CDD, (b) freeze-thaw cycles, and (c) number of days with  $T < -10^\circ\text{C}$  and  $\text{SND} < 10\text{ cm}$ .



## 4 Discussion

### 4.1 Changes in climatic indicators relevant for overwintering in crops

By the 2030s, northern regions (north of 60° N) experience increasingly favourable thermal conditions, including warmer winters and enhanced cold degree-day accumulation, reducing thermal constraints on winter crop cultivation (Fig. 4).  
275 Despite this warming, winter temperatures remain within the range required for cold acclimation (approximately −5 to 10 °C; Fig. 1a) and adequate to fulfil the vernalization requirement, which occurs over a broader and slightly warmer temperature range than cold acclimation (Fowler et al., 1996; Jylhä et al., 2008; Porter and Gawith, 1999). These results suggest that warmer winters are likely to improve thermal suitability for winter crops without compromising these key physiological requirements. The projected changes could enable a northward expansion of winter crop cultivation (Wiréhn,  
280 2018) beyond its current concentration in southern Nordic regions, particularly Scania in southern Sweden and much of Denmark (Fig. 4; Sjulgård et al., 2023; Tootoonchi et al., 2026).

The emergence of beneficial conditions from warmer temperatures are accompanied by emerging risks from the 2040s onward north of 60° N, including more frequent freeze-thaw cycles and reduced snow cover, which increase exposure to frost damage and soil disturbance, followed by the combination of shallow snow cover and cold events (Fig. 1b-d, 4). These  
285 changes can reduce the protective role of snow, increasing the exposure of winter crops to temperature fluctuations during winter. In particular, premature dehardening during mild periods in late winter (i.e. in February) can increase susceptibility to subsequent frost damage and reduce winter survival (Fogelfors et al., 2009; Fowler et al., 2014; Pagter and Arora, 2013; Shimoda et al., 2024; Strandberg et al., 2026). This can be particularly important because the onset of the vegetative period is regulated by photoperiod (Kiss et al., 2017), potentially constraining the extent to which warmer temperatures can advance  
290 vegetative development under future climates. A shorter snow season could nevertheless reduce the risk of snow mold development (Gaudet and Laroche, 1997; Pagter and Arora, 2013; Ponomareva et al., 2021). These changes are consistent with other EURO-CORDEX climate projections and observations across the Nordic region, where a decrease in snow cover, duration and depth was observed and projected for future (Dyrddal et al., 2020; Migala et al., 2025; Teutschbein et al., 2023). Consequently, even in the north, warmer winters do not necessarily improve overwintering conditions, highlighting the need  
295 for adaptation through, for example, breeding winter crop varieties with greater tolerance to freeze-thaw cycles and waterlogging associated with general higher, but uncertain average winter precipitation in future (Fig. 2a) under higher temperatures (Fig. 2b, Hakala et al., 2012; Olesen et al., 2012).

Our results indicate that southern regions have already experienced favourable thermal conditions for winter crop cultivation (Fig. 1a, 2b, 4), while also facing an increase in adverse winter conditions (Fig. 1b-d, 4). These findings are consistent with  
300 the observed expansion of winter crop cultivation and associated yield gains (SCB, 2024; Tootoonchi et al., 2026), as well as with recent observations of reduced snow depth and more frequent snow droughts (Canedo Rosso et al., 2025; Fontrodona Bach et al., 2018; Teutschbein et al., 2022). Together, these results suggest that the benefits of warmer winters become increasingly constrained under future climates south of 60° N, with intensifying adverse winter conditions reflected in the



earlier emergence of shallow-snow and cold stress. In addition, conditions during the main growing season, for example  
 305 higher temperatures and reduced water availability, which are already observed across the Nordic region (Beillouin et al.,  
 2020; Tootoonchi et al., 2026; Westra et al., 2014), can further limit crop production and require adaptation measures such as  
 irrigation (Grusson et al., 2021). Further warming in winter temperatures can facilitate a shift from spring to winter wheat,  
 which generally has higher yield potential (Asplund et al., 2013; Trnka et al., 2011; Wiréhn, 2018), although decreasing  
 CDD in Denmark and Scania can constrain this potential if further warming prevent cold degree day requirements to be met.  
 310 The distinct latitudinal transition around 60° N was evident in the spatial distribution of time of emergence, separating  
 earlier-emerging signals in southern regions from later emergence in northern regions. This transition broadly corresponds to  
 differences in climatic regimes, including the shift from milder, precipitation-dominated southern conditions to colder, snow-  
 dominated northern environments with greater topographic complexity (Beck et al., 2018). Similar relationships between  
 climate zones and emergence timing have been reported globally, where the emergence of temperature and precipitation  
 315 extremes varies systematically among climate regions (Zhang and Gao, 2023)

## 4.2 Influence of time of emergence calculation method and bias correction

Mean temperature, cold degree days, and shallow snow depth, exhibited early emergence of trends, often by the 2030s (Fig.  
 1a,d, Fig. 2b), while trends in precipitation-related indicator could not be distinguished from internal variability in the region  
 before the end of the century (Fig. 2a). These findings are consistent with previous SMILE explorations, showing earlier and  
 320 more robust emergence of temperature-related indicators compared to precipitation-related indicators, reflecting the stronger  
 and more spatially coherent forced response of temperature, whereas precipitation is more strongly influenced by internal  
 variability, large-scale circulations, and local-scale processes (Gampe et al., 2024; Schuhen et al., 2026; Zhang and Gao,  
 2023). Changes in threshold dependent (i.e. freeze-thaw cycles) and compound indicators (i.e. co-occurrence of low  
 temperatures and shallow snow) emerged later, typically from mid-century, and showed greater spatial variability and  
 325 uncertainty (Fig. 1b,c).

The method used to estimate time of emergence influenced the representation of uncertainty (Fig. S2). Continuous single-  
 variable indicators (CDD and shallow snow days) showed similar emergence times across the two methods. In contrast,  
 discrete and threshold-dependent indicator (freeze-thaw cycles), and the multivariate indicator (combination of shallow snow  
 and cold stress) showed different emergence estimates. The ensemble-mean approach (Method 1) generally produced  
 330 smoother and later emergence patterns by averaging across runs and thereby reducing member-to-member variability. In  
 contrast, the member-specific approach (Method 2) retained internal variability and produced more heterogeneous, but  
 generally earlier, emergence estimates. For freeze-thaw cycles, which vary over a narrow range and in discrete steps, small  
 year-to-year changes produced statistically detectable trends despite limited changes in the overall magnitude of the  
 indicator. Averaging across runs in Method 1 therefore smoothened or canceled these step changes, whereas estimating  
 335 emergence separately for each run in Method 2 allowed individual changes to directly influence the emergence time. For the  
 multivariate indicator combining shallow snow and cold stress, the Method 2 emergence pattern largely followed that of



shallow snow, suggesting that the snow component dominated the timing of emergence across individual runs. Overall, these results highlight the importance of considering both indicator characteristics and the treatment of ensemble members when interpreting time of emergence, particularly for discrete or threshold-dependent indicators with narrow ranges, where statistical emergence might not necessarily be consistent with what is experienced in the one realization that will materialize in reality (Lehner et al., 2017).

The time of emergence showed advancement of up to several decades across variables after bias correction compared with the emergence extracted by the raw outputs, indicating an influence of this step on the detected climate change signal (Fig. 4). These findings are consistent with results from Switzerland using the same CRCM5-LE SMILE for precipitation (Astagneau et al., 2025). Bias correction improved agreement between historical simulations and observations, with agriculturally relevant temperature-based indicators such as cold degree days showing larger adjustments, whereas more complex indices, such as the co-occurrence of low snow and low temperature, adjusted less. This likely mirrors stronger inter-member consensus in direct temperature-driven variables in CRCM5-LE and their clearer response to bias correction, whereas multivariate indicators are influenced by multiple drivers.

Our results are based on the CRCM5-LE ensemble under the high-emissions RCP8.5 scenario and therefore represent a high-impact climate trajectory rather than an intermediate estimate (i.e., RCP4.5) of future conditions. This scenario is useful for precautionary risk assessment in climate-sensitive sectors such as agriculture (Bevacqua et al., 2026), while also allowing assessment of conditions under lower-emissions pathways by considering earlier future periods, such as mid-century rather than late-century (Böhnisch et al., 2025). Lower-emission pathways generally delay time of emergence, although the spatial patterns of emergence remain largely similar across emission scenarios (Jägermeyr et al., 2021; Rojas et al., 2019; Zhang and Gao, 2023). Such spatial patterns can inform adaptation by identifying regions where climate conditions are likely to change earlier than elsewhere, supporting the prioritization and timing of adaptation measures.

## 5 Conclusions

We used a 50-member ensemble of high-resolution climate model simulations over Northern Europe under the RCP8.5 scenario (1955–2099), to assess differences between future and historical conditions relevant for winter crops and determine the time of emergence of trends in key variables. Changes in climatic conditions imply both opportunities and risks for overwintering of winter crops, with opportunities predominant north of 60° N and in the first half of the century and detrimental conditions dominating elsewhere and later this century. Specifically, while winters become warmer, cold degree day requirement for successful acclimation of winter crops are still met, even at lower latitudes north of 60° N. This, together with higher temperatures, will open cultivation opportunities beyond current areas. At the same time, the frequency of potentially damaging conditions, such as shallow snow and freeze–thaw cycles increase, emerges earlier south of 60° N and in the second half of the century in northern regions, highlighting the need for adaptation. The exact timing of emergence depends on the emissions scenario, bias correction, and method to estimate time of emergence in agriculturally relevant conditions, suggesting that there is large uncertainty in the exact time at which adaptation practices need to be implemented.



## 370 Code and data availability

All runs and analysis were performed with the Python coding language and Climate Data Operators (CDO) and are available upon request. CRCM5-LE simulations can be found in the ClimEx project (<https://www.climex-project.org>). Climatic data and land cover data are publicly available from E-Obs dataset (Cornes et al., 2018) and Corine land cover maps (<https://doi.org/10.2909/08560441-2fd5-4eb9-bf4c-9ef16725726a>, European Environment Agency, 2020). Further  
375 information can be found in Sect. 2.

## Author contributions

FT: Conceptualization, data curation, formal analysis, investigation, methodology, visualization, software, writing and editing. GV, GM and AD: Review and editing. FL: Conceptualization, methodology, review and editing.

## Competing interests

380 None of the authors have any competing interests.

## Acknowledgements

We thank Magdalena Mittermeier and Raul Wood for providing us with the CRCM5-LE simulations from the ClimEx project (<https://www.climex-project.org>). This research was supported by the Swedish Research Council (VR 2023-06545 and 2022-06599). FT thanks Yashar Imanlou for valuable suggestions on working with Linux and supercomputers, which  
385 enabled her to implement the methods, as well as the computational resources provided by NCAR supercomputing facility.

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