Tailored climate indices for climate-proofing operational forestry applications in Sweden and Finland

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ABSTRACT: In the light of the observed and projected regional warming trend in northern Europe, new recommendations are needed for climate-proofing the selection of forest trees seedlings and growth estimates. Drawing on recently developed climate data sets, both observations of the recent past, and scenarios for the future we present and analyse a set of climate indices tailored to be used for operational forestry applications.

Data covering Sweden and Finland include two high-resolution gridded observational data sets of daily mean temperature and daily total precipitation for the period 1961–2007, and an ensemble of regional climate model (RCM) projections based on forcing data from six global scenarios representing a medium high emission scenario. The observation-based data sets are used as reference in two ways: as reference for downscaling and bias-adjustment of daily data from the regional scenarios and to highlight recent observed climate changes and how these changes are represented in the RCM ensemble.

For seasonal temperature and related climate indices, there is a clear change towards warmer conditions between the two periods 1961–1990 and 1988–2007, most clearly seen in the observational data and less pronounced in the RCM ensemble. For the future period 2035–2065, ‘mid-century’, the medium high scenario ensemble used in this study shows substantial changes to several key indices relevant to forestry applications.

KEY WORDS: forest growth and adaptation; sustainable forests; Scandinavia; observed climate change; bias-correction; climate impacts

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1. Introduction

For Scots pine in northern Sweden, numerous studies have shown that growth and survival is related to the provenance origin at a given site in a predictable manner. As provenances originating from harsh locations are transferred towards milder climatic conditions, volume production per hectare is increased following a continuous climatic and photoperiodic gradient (e.g. Remröd, 1976; Eriksson et al., 1980; Persson, 1994a; Andersson et al., 2007). To model these effects, so-called transfer functions have been derived for growth and survival using latitude, altitude and temperature sum as explanatory variables (Persson and Ståhl, 1993; Persson, 1994b). Such transfer functions are essential when developing deployment recommendations of forest regeneration material (Berlin et al., 2014).

Current transfer functions have been derived from older climate data models (Odin et al., 1983; Morén and Perttu, 1994) that have some clear drawbacks in the light of present-day requirements and challenges. Some drawbacks are: (1) the time periods are from 1961 to 1976 (Odin et al., 1983) or from 1961 to 1990 (Morén and Perttu, 1994) and thus not necessarily good representations of the current climate; (2) the statistical models are coarse and very simplified compared to state-of-the-art climate models and data; (3) the climate data are not directly compatible to future climate projections; (4) few climate indices are available for analysis as independent variables; and (5) data are valid only within Sweden and it is not easy to extrapolate to other countries for a more comprehensive analysis. Consequently, there is a need to remedy the drawbacks described above by creating a new modelling structure from which a set of climate indices relevant for developing climate proof operational forestry applications can be derived. In particular, with the emerging need to take the ongoing climate change into account and to prepare for future climate change, data sets and relevant derived indices should support the use of climate projection data as input.

The overall aim of this article is threefold: (1) to introduce a methodology for linking gridded observational data sets to regional climate projections, (2) to present a set of climate indices tailored for climate-proofing new operational forestry applications, such as developing new.
transfer functions for Scots pine, and (3) to analyse how the recent observed, as well as future projected climate change influences these indices. This includes a comparison of the climate change signal during recent decades as represented by gridded reference data sets with the signal found in an ensemble of regional climate model (RCM) projections.

We combine two national gridded data sets of meteorological observations covering Sweden and Finland. This combined data set is then used as a reference in the bias-correction and downscaling of an ensemble of regional climate projections. Through this procedure the regional projections are mapped onto the same high-resolution grids that the two national reference datasets have.

In the last two decades, a wide range of climate indices have been developed to meet the growing interest to explore aspects of the climate that is not well described by traditional annual, seasonal and monthly mean statistics. Typically, such indices either focus on describing various aspects of climate extremes and how they may change over time (e.g. Zhang et al., 2011; Donat et al., 2013), or tailored for a specific application or context, (e.g. Persson et al., 2007). With our focus on operational forestry applications in Sweden and Finland, we concentrate on a set of climate indices that previous studies in the region have shown to be relevant. The key indices are based on temperature but we also include an initial analysis of three drought indices.

In this article, we focus on climate change within two time-frames. The observational data sets cover a reasonably long period, 47 years, which allows us to begin analysing current observed trends of climate change and compare model results with observations. To explore future climate change effects on Scots pine production in the mid-21st century, we focus on the period 2035–2065, which is somewhere in the middle of the expected rotation period of seedlings planted today. This time-frame is far enough into the future to exhibit clear climate change signals but not too distant to make it abstract and intangible from a user perspective.

2. Data and methods

2.1. Climate data

Two kinds of climate data are used in this project, gridded observational data representing the last several decades, and regional climate projections representing the recent past and the future. The gridded observational data are combined from two national data sets, the PTHBV data set covering Sweden and its near surroundings, and the FINADAPT data set covering Finland. PTHBV contains daily precipitation and daily mean temperature for the period 1961–2007 at a spatial resolution of 4 x 4 km. It is generated from meteorological observations by an optimum interpolation procedure (Johansson, 2000; Johansson and Chen, 2003, 2005). The FINADAPT data set (Venäläinen et al., 2005) contains data for daily mean temperature and daily precipitation at a spatial resolution of 10 x 10 km for the period 1961–2007. This data set was produced using a Kriging interpolation method (see Venäläinen et al., 2005 and technical references therein), which is in principle similar to the optimum interpolation method used for the PTHBV data set. Preliminary analyses show that for daily mean temperature the difference between the two data sets at the common border in the north is small and hardly discernible (Figure 1), neither in the climatological average nor in the climate change signals between two periods. However, for daily precipitation, there is a strong systematic difference in the accumulated precipitation amounts between the two data sets (Table 3) because of a systematic underestimation of the interpolated precipitation amounts in the FINADAPT data set (P. Pirinen, 2015; pers. comm.). Preliminary investigations show that this difference between the two data sets affects only the precipitation amounts and not the wet/dry structure of the time series (P. Pirinen, 2015; pers. comm.). That is, the interpolation issue mainly affects how the precipitation is geographically distributed during rainy days and thus only causes marginal bias in the dryspell indices. We therefore choose to focus on the PTHBV data set when it comes to analyses of precipitation amounts.

These two national data sets are processed as one unit with a common period of 1961–2007, in the following denoted PTHBV/FINADAPT, where each one retains its original spatial resolution. This joined data set serves two purposes. First, it will be used for calculating tailored climate indices that are generally relevant for forestry applications, which also will serve as candidate explanatory variables in the development of Scots pine transfer functions. Second, it will be used as reference data for calibrating the regional climate projections.

To facilitate comparisons with widely available climate atlases, we choose to present index maps for the climatological normal period 1961–1990 defined by WMO whereas the indices for the full reference period 1961–2007 is used in the transfer functions because it enables us to make use of substantially more data from forest field experiments, in particular those established and assessed in the last two decades. With respect to analyses of observed recent climate change, the full period is not long enough to enable comparisons between two non-overlapping 30-year periods. In an endeavour to balance conflicting requirements, we make use of the following two periods: 1961–1990 is the reference period as presented above, and the recent 20-year period 1988–2007. The latter period covers only 20 years but we prefer this over having a substantial overlap that may cloud the comparison between two 30-year periods.

To account for projected climate change, we make use of an ensemble of six regional climate projections (Kjellström et al., 2011) forced by global climate models (GCMs) from the CMIP3 archive (Meehl et al., 2007, cf. Table 1). We choose to use future climate scenarios based on the socio-economic pathways and emission scenarios from the IPCC Special Report on Emission Scenarios (SRES; Nakicenovic and Swart, 2000). Although there is now a new generation of scenarios, representative
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Figure 1. Annual mean temperature, \( T_{\text{year}} [\degree C] \) and annual total precipitation, \( P_{\text{year}} [\text{mm year}^{-1}] \). Left column, (a) and (b), shows the climatology of the standard normal period 1961–1990. The right column, (c) and (d), shows the change from this normal period to the recent 20-year period 1988–2007. Precipitation is not shown for FINADAPT because of a systematic bias (see text). Spatial resolution in the PTHBV data set (covering Sweden and its near surroundings) is 4 × 4 km and in the FINADAPT data set (covering Finland) 10 × 10 km. Note that in all maps (including in the other figures), the individual gridcells are plotted, i.e. no spatial smoothing has been applied.

concentration pathways (RCPs) (Moss et al., 2010; van Vuuren et al., 2011), the SRES-based scenarios are well established and familiar to the Scandinavian forestry sector through numerous studies (e.g. Koca et al., 2006; Sonesson, 2006; Kellomäki et al., 2008; Bergh et al., 2010; Langvall, 2011; Jönsson et al., 2015) and high-level assessments (SOU, 2007), as well as systematic outreach activities by the Swedish Forest Agency. The SRES A1B scenario implies medium greenhouse gas emissions and hence intermediate projected climate changes compared to other SRES scenarios.

These regional scenarios were produced through dynamical downscaling using the Rossby Centre atmosphere regional model RCA3 (Samuelsson et al., 2011). The ‘raw’ regional climate projections cover the period 1961–2100 and cover the whole of Europe at a spatial resolution 0.44 × 0.44° rotated pole grid, which corresponds to approximately 50 × 50 km across the domain.

To achieve a smooth transition from present day climate condition to future conditions in operational applications, the regional scenario data have to be consistent (i.e. in terms of spatial resolution and representativity, as well as the absence of systematic differences) with the PTHBV/FINADAPT data set. Therefore, each individual ‘raw’ regional scenario has to be further downscaled to the same spatial resolution as the PTHBV/FINADAPT data set and bias-adjusted. The first step in calibrating the climate projections is a simple regridding of the RCM data to match the grids of PTHBV and FINADAPT. Next, the daily temperature scenario data are adjusted to account for the difference in altitude between the original 50 km scenario grid and the PTHBV/FINADAPT grids. This adjustment is based on the standard atmosphere temperature gradient of 0.0065 °C m⁻¹. This is a climatological ‘first-order’ altitude correction which is further refined in the bias correction step. For the purpose of this presentation, we take the term bias to cover both the proper model bias induced by the GCM and RCM and the bias introduced by using the climatological temperature gradient of the standard atmosphere instead of a more elaborate...
scheme in the altitude correction of the temperature. There exists no well-established method for altitudinal adjustment of precipitation data.

As additional reference and comparison data, we use seasonal data from 35 temperature stations spread across Sweden (http://www.smhi.se/klimatdata/meteorologi/temperatur/klimatindikator-temperatur-1.2430, accessed 12 August 2015). Data from these meteorological stations have been through a careful quality control procedure before being published at the SMHI web. Also we use the RCA3 regional downscaling of reanalysis data (Samuelsson et al., 2011). This is also known as an evaluation run of the RCM as the lateral boundary conditions are extracted from reanalysis data, in this case the ERA-40 (Uppala et al., 2005) and updates, which provide the best three-dimensional representation of the atmosphere throughout the period.

2.2. Procedure for bias adjustment
For bias-adjustment, we use the distribution-based scaling (DBS) method (Yang et al., 2010a, 2010b). The method is based on a quantile matching method (e.g. Déqué, 2007) that is applied to each grid cell time-series

$$y = F^{-1}_{\text{ref}}(F_{\text{scen}}(x))$$

(1)

where $x$ is the uncalibrated scenario data, $y$ is the calibrated (bias-adjusted) scenario data, $F_{\text{scen}}(\cdot)$ is a cumulative distribution function (cdf) representing the scenario data, and $F^{-1}_{\text{ref}}(\cdot)$ is the inverse cdf representing the calibration data set. In the DBS method, the reference data and the uncalibrated scenario time-series are used to estimate the parameters of suitable probability distribution functions (pdfs). From these pdfs, the corresponding (inverse) cdfs are determined. The reference period for estimating the cdfs is 1961–1990. First, we describe the method in some more detail in the following for the case of precipitation because the principle of the calibration procedure is simpler to describe compared to temperature.

For precipitation, two gamma pdfs are joined together, one representing the bulk of the observations, and the other representing the upper tail,

$$X = f(x) = \begin{cases} \Gamma(x | \alpha_1, \beta_1), & x < P95 \\ \Gamma(x | \alpha_2, \beta_2), & x \geq P95 \end{cases}$$

(2)

where there are five parameters to estimate; $\alpha_1$ and $\alpha_2$ are location parameters and $\beta_1$ and $\beta_2$ are shape parameters of the gamma distribution, and $P95$ is the 95th percentile of precipitation amount taking only wet days into account. The approach to divide the pdf into two branches is similar to a method Gutjahr and Heinemann (2013) evaluated as favourably compared to several alternatives. As the gamma distribution cannot represent dry days, only days with precipitation above some (small) threshold are used in the estimation. In observational data sets of daily total precipitation, a threshold of 0.1 mm day$^{-1}$ is often used because of measurement limitations. In the Scandinavian region, RCA3 is too wet (Samuelsson et al., 2011), i.e. there are too many days having small precipitation amounts. A first step is therefore to find the threshold value, $x_0$, in the scenario time-series that make the proportion of wet days correspond to the same proportion in the reference data series. Once $x_0$ and $P95$ are determined from the data, the four gamma parameters are estimated using the maximum-likelihood method. This is independently repeated for the four seasons, December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). This procedure is done for each scenario grid cell time-series and corresponding reference grid cell. All in all, for each scenario and grid cell, there are eight of these ‘joined pdfs’; for each of the two data sets (ref and scen), there are four pdfs; one for each season. From these pdfs, the $F_{\text{scen}}(\cdot)$ and $F^{-1}_{\text{ref}}(\cdot)$ for each season are computed thus allowing the bias-adjusted time-series to be computed by means of Equation (1).

At the conceptual level, the DBS procedure for temperature is similar to that for precipitation. The overall goal is to find good approximations to $F_{\text{scen}}(\cdot)$ and $F^{-1}_{\text{ref}}(\cdot)$ of Equation (1). For temperature, the normal (Gaussian) distribution provides a suitable pdf, and there is no division into ‘normal’ and extreme temperatures as for precipitation. Instead of dividing the time-series into four separate seasons, as is the case for precipitation, the climatological seasonal cycle is estimated using harmonic decomposition and then removed before pdf estimation, and again added back to the final calibrated data. Moreover, the de-seasonalized temperature time series is stratified into dry and wet days before pdf estimation as there is a systematic difference in temperature between such days.

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Table 1. Key information on the GCM global scenarios used as lateral boundary conditions (forcing) for the regional climate projections.

| GCM version (shorthand name) | Variant | Institute | Country | Reference(s) |
|------------------------------|---------|-----------|---------|--------------|
| CCSM3 (CCSM3)                |         |           |         |              |
| HadCM3 (HadCM3-Q0)           | Q0      | Hadley Centre | UK       | Gordon et al. (2000), Collins et al. (2011) |
| ECHAM5/MIPI-OM (ECHAM5-r3)   | r3      | MPI-met   | Germany | Jungclaus et al. (2006); Roeckner et al. (2006) |
| BCCR-BCM2.0 (BCM)            |         | Bjerkenes Centre | Norway | Furevik et al. (2003) |
| IPSL-CM4 (IPSL)              |         | IPSL      | France  | Hourdin et al. (2006) |
| CNRM-CM3 (CNRM)              |         | CNRM      | France  | Voldoire et al. (2012) |

For two of the GCMs (HadCM3 and ECHAM5), alternative scenario variants were available. For technical details, see Kjellström et al. (2011) for an overview, or the individual references cited above.
Table 2. Overview of the climate indices used for development of the Scots pine transfer functions.

| Climate index                                      | Unit (change units) | Acronym | Input variable | Calculation period(s) |
|---------------------------------------------------|---------------------|---------|----------------|-----------------------|
| Mean temperature                                  | °C (°C)             | $T_{xxx}$ | Daily mean temperature | Year, DJF, MAM, JJA, SON, January, February, July |
| Beginning of vegetation period                    | Day number (number of days) | $G_{start}$ | Daily mean temperature | Year |
| End of vegetation period                          | Day number (number of days) | $G_{end}$ | Daily mean temperature | Year |
| Length of vegetation period                       | Number of days (number of days) | $G_{length}$ | Daily mean temperature | Year |
| Temperature sum                                    | Growing degree-days (GDD) | $T_S$ | Daily mean temperature | From $G_{start}$ to $G_{end}$ |
| Total precipitation                               | mm period$^{-1}$ (mm period$^{-1}$) | $P_{xxx}$ | Daily total precipitation | Year, DJF, MAM, JJA, SON, AMIJASO |
| Longest dry spell (<1 mm day$^{-1}$)              | Number of days (number of days) | $D_{S1_{ann}}$ | Daily total precipitation | Year |
| Longest dry spell (<2 mm day$^{-1}$)              | Number of days (number of days) | $D_{S2_{xxx}}$ | Daily total precipitation | AMJJ, ASO |

The abbreviation for calculation period indicates the first letter of the month (e.g. MAM = March–May), in the acronym this abbreviation replaces the ‘xxx’ (e.g. $D_{S2_{amjj}}$ is the longest dry spell below 2 mm day$^{-1}$ during the period April–July).

2.3. Tailored climate indices

The daily data in the reference data set and the bias-corrected scenario data sets are used to calculate a set of climate indices. These climate indices were designed to capture various aspects of the climate known to be relevant to the survival of young pine seedlings and influence the biomass production at a later stage (e.g. Morén and Perntu, 1994; Persson, 1994a, 1994b; Persson and Beuker, 1997; Andersson et al., 2007). In addition, for estimation of Scots pine transfer functions and deployment recommendations, we opted for well-established indices that were easy to interpret biologically and communicate to a wide user-base. Furthermore, the data available in the PTHBV/FINADAPT data set also set some restrictions in developing indices. Annual, seasonal mean temperatures were included as basic standard indices. Monthly mean temperature for January, February and July was included to enable calculation of the classic continentality index based on the annual temperature amplitude (Gorzynski, 1920). Moreover, the beginning ($G_{start}$) and end ($G_{end}$) of the growing season were calculated, as well as its length ($G_{length}$). We follow the definitions presented by Persson et al. (2007) on the basis of extensive interaction with stakeholder expert groups working under the Swedish Government Commission on Climate and Vulnerability (SOU, 2007). The growing season is defined to begin at the fourth day in the first four-day period with a daily mean temperature of above +5°C. Similarly, the growing season ends at the last day of the last four-day period with a daily mean temperature above +5°C. Finally, the temperature sum ($T_S$) above the threshold +5°C was calculated for the growing season. These definitions are similar to previous studies (Odin et al., 1983; Morén and Perntu, 1994).

To explore the influence of dry spells, we designed three simple indices that are based on finding the longest spell of dry days within the year or season, where a dry day is defined to have precipitation less than a small threshold. One index that has been widely used in previous work (e.g. SOU, 2007, and operational work since then) captures the longest dry spell on an annual basis (using a threshold of 1 mm day$^{-1}$), abbreviated $D_{S1_{ann}}$. The two other dry spell indices focus on the spring-summer season (April–July), $D_{S2_{amjj}}$, and the late summer-autumn season (August–October), $D_{S2_{aso}}$. For these two indices, the threshold was set to 2 mm day$^{-1}$ based on a preliminary analysis of wet/dry spell temporal structure in RCA3 drawing on the methodology developed by Bärring et al. (2006). The final set of candidate indices is listed in Table 2.

The climate indices were calculated for each of the six individual members of the regional climate projections ensemble and then averaged to arrive at the ensemble average that is the focus of this study. One value per year was calculated for each climate index for each grid cell time-series. In this way, climatological averages can be calculated for any desired period.

3. Results

3.1. Observational data

In this section, we will first concentrate on the reference period climate (1961–1990), as well as observed changes to the recent period (1988–2007) as represented by the PTHBV/FINADAPT data set (Table 3, Figures 1–3). The annual and seasonal temperature for the reference period follow established climatological reference atlases (e.g. Alalammi and Arvola, 1988; Raab and Vedin, 2004; Tveito et al., 2001; and http://www.smhi.se/klimatdata/meteorologi/temperatur, accessed 12 August 2015). With the exception of the summer season (JJA), the geographically averaged mean temperatures are higher in the PTHBV data set than those in the FINADAPT data set. This is an effect of several contributing factors. Finland
### Table 3. Overall climatological summaries for the two national gridded observational data sets for PTHBV (Sweden and near surroundings) and FINADAPT (Finland).

|                | PTHBV | FINADAPT |
|----------------|-------|----------|
|                | Mean  | St.dev.  | P25   | P75   | Mean  | St.dev.  | P25   | P75   |
| $T_{\text{year}}$ (°C) | 1961–2007 | 2.7 | 3.2 | 0.2 | 5.9 | 2.0 | 2.2 | 0.1 | 3.7 |
| $T_{\text{djf}}$ (°C) | 1961–2007 | −7.1 | 4.5 | −10.6 | −2.8 | −9.2 | 3.1 | −12.0 | −7.1 |
| $T_{\text{mam}}$ (°C) | 1961–1990 | −7.9 | 4.6 | −11.5 | −3.4 | −10.0 | 3.2 | −12.8 | −7.9 |
| $T_{\text{jja}}$ (°C) | 1961–2007 | 13.0 | 2.3 | 11.5 | 15.1 | 13.8 | 1.6 | 12.9 | 15.0 |
| $T_{\text{son}}$ (°C) | 1961–2007 | 12.8 | 2.3 | 11.4 | 14.8 | 13.6 | 1.5 | 12.6 | 14.7 |
| $G_{\text{start}}$ (day number) | 1961–1990 | 161 | 40 | 133 | 196 | 152 | 22 | 134 | 170 |
| $G_{\text{end}}$ (day number) | 1961–2007 | 163 | 41 | 134 | 200 | 154 | 23 | 136 | 173 |
| $G_{\text{length}}$ (number of days) | 1961–1990 | 161 | 40 | 133 | 196 | 152 | 22 | 134 | 170 |
| $P_{\text{year}}$ (mm) | 1961–1990 | 745 | 198 | 619 | 806 | 494 | 59 | 452 | 537 |
| $P_{\text{djf}}$ (mm) | 1961–1990 | 727 | 195 | 602 | 790 | 472 | 64 | 426 | 520 |
| $P_{\text{mam}}$ (mm) | 1961–1990 | 166 | 76 | 122 | 175 | 88 | 17 | 77 | 98 |
| $P_{\text{jja}}$ (mm) | 1961–1990 | 161 | 70 | 120 | 168 | 78 | 17 | 67 | 89 |
| $P_{\text{son}}$ (mm) | 1961–1990 | 22 | 26 | 4 | 30 | 28 | 10 | 22 | 34 |
| $P_{\text{amjjas}}$ (mm) | 1961–1990 | 134 | 35 | 110 | 149 | 82 | 12 | 75 | 91 |
| $D_{S1\text{-year}}$ (number of days) | 1961–2007 | 20 | 3 | 20 | 22 | 22 | 2 | 21 | 23 |
| $D_{S2\text{-amj}}$ (number of days) | 1961–2007 | 20 | 3 | 19 | 22 | 22 | 2 | 21 | 24 |
| $D_{S2\text{-son}}$ (number of days) | 1961–1990 | 16 | 2 | 15 | 17 | 16 | 1 | 15 | 17 |

The following statistics are shown: arithmetic mean (‘Mean’), standard deviation (St.dev.), 25th percentile (P25) and 75th percentile (P75). For each index, the statistics are shown for two periods, the standard 30-year normal period 1961–1990, and the full data period 1961–2007. Note that the ‘Change’ is calculated as the difference between the (slightly) overlapping periods: 1988–2007 minus 1961–1990.
has a more continental climate compared to Sweden, hence the larger seasonal span. PTHBV extends further to the south, which contributes to a higher annual mean temperature, despite the high-altitude cold climate in the northwest part. The spread, both standard deviation and inter-quartile range ($P_{75} - P_{25}$), is higher in PTHBV. In addition to the larger latitudinal extent, this is a result of the higher altitudinal range in the Scandinavian mountain range, as well as an effect of the spatial resolution that allows better representation of local altitudinal variations in the complex terrain.

The observed temperature changes between the reference and the recent period climate showed a consistent direction towards warmer conditions. The changes were very similar in the two national data sets, i.e. it was not possible to distinguish any boundary effect along the common national border. The change showed a marked seasonal variation with the strongest signal in the winter and little change during the autumn. During winter, the change was somewhat smaller in the south of Sweden but this was offset in the spring, thus making the annual change about +1 °C in both countries.

The mean annual and seasonal temperature conditions, and changes thereof, were generally consistently reflected in the climatic indices (Table 3, Figure 3). It is, however, worth noting the distinct advance in $G_{start}$ (Figure 3(e)) of about 20–30 days in southernmost Sweden, along the Swedish west coast and extending into the interior towards the major lakes in southern Sweden (Lake Vänern and Lake Vättern). This was an effect of nonlinearity of the index induced by the threshold of 5 °C. This signal

![Figure 2](image.png)

Figure 2. Seasonal mean temperatures derived from the PTHBV/FINADAPT observation-based data set. Mean for the normal period 1961–1990 (note the different colour scales): (a) winter, DJF; (b) spring, MAM; (c) summer, JJA; (d) autumn, SON. Panels (e)-(h), next page, show the observed climate change from the 1961–1990 period to the recent 1988–2007 period (same colour scales): (e) winter, DJF; (f) spring, MAM; (g) summer, JJA; (h) autumn, SON. All units are °C.
carries over to a similar pattern of change in \textit{Glength} but was not seen as clearly in \textit{TS}. The explanation is that even though the growing season shows a marked advancement in spring the temperature reaches just above the threshold of 5°C, hence does not add much to the temperature sum.

For annual and seasonal precipitation in PTHBV, the observed change between the two periods (Figure 1(d)) was mostly concentrated to the western part of the South Swedish plateau and the Scandinavian mountain range, and to a lesser extent in a larger part of northern Sweden. An exception is a conspicuous local anomaly of a negative (drying) change in the northern mountain range. This is the result of an inhomogeneity of the precipitation data from one station. Interestingly, in the autumn there seems to be a decrease in precipitation. Closer inspection of the underlying data shows that this decrease was largely confined to the westernmost part of the Scandinavian mountain range, i.e. towards the western fringe of the PTHBV domain. For other parts of the PTHBV data set, very little change is seen in the autumn. In the FINADAPT data set (Table 3), the increase seems to have been more evenly distributed across the domain. These changes to the seasonal precipitation totals did not carry over to any substantial changes in the dry spell indices, which were virtually constant between the two periods. The reason for this is that the precipitation during wet days increased whereas the basic proportion or temporal structure of wet and dry days remained constant.

For the total period, 1961–2007, the climate change signal was integrated into the average. Consequently, temperature averages were somewhat higher than the averages for the reference period 1961–1990.

3.2. Bias-adjusted performance

Next we focus on the bias adjustment of the regional climate projection ensemble. Bias-corrected data are compared to ‘raw’ model output in Table 4. For the annual and seasonal mean temperature, almost all of the bias is removed; the remaining bias is within ±0.1°C. For an example, the map describing a typical geographical pattern of the remaining bias is shown in Figure 4(b).
Similarly, for annual and seasonal precipitation, the bias is substantially reduced (Table 4). For Sweden, the remaining bias is within ±8 mm. For the climate indices, the bias adjustment of the underlying daily data resulted in substantial improvements, although not as dramatic as for seasonal mean temperatures and precipitation totals, because the indices include thresholds that introduce non-linear responses. The bias adjustment was carried out independently for each grid cell, which means that not only the overall mean bias across the domain was reduced but also the bias standard deviation across the domains was reduced. Typically, the largest biases as well as the largest variability between adjacent grid cells were found in the complex terrains of the Scandinavian mountain range. For the climate indices related to growing season, the overall biases across the two national data sets were already small, but the bias adjustment still improves the data as there were substantial reductions in the standard deviations across the domain. This is clearly illustrated for mean annual temperature in Figure 4, where the mountainous region exhibits both strong positive and negative biases that were removed by the adjustment procedure. Finally, from similar statistics (not shown) as in Table 4, it is evident that the bias-adjustment only resulted in marginal alterations of the climate change signal.

3.3. Model-based climate projections

Now we turn to the projected changes. First we note that the ensemble mean of the projected changes during the recent past, 1988–2007 minus 1961–1990 (Table 5) are smaller than the observed change (Table 3). For the future period 2035–2065, Table 5 shows that the projected average temperature change for the SRES A1B emission scenario varies seasonally, between 3.0 °C in winter and 1.7 °C in the summer for Sweden. In Finland, the corresponding change is slightly larger, 3.6 °C in winter and 2.0 °C in summer. In the following presentation of the results, we will focus on the ensemble average and, if not

Figure 3. Climate indices derived from the PTHBV/FINADAPT observation-based data set. Mean for the normal period 1961–1990: (a) start of the growing season, $G_{\text{start}}$ [day number]; (b) end of the growing season, $G_{\text{end}}$ [day number]; (c) length of the growing season, $G_{\text{length}}$ [number of days]; (d) temperature sum during the growing season, $TS$ [GDDs]. Panels (e)–(h), next page, show the climate change from the 1961–1990 period to the recent 1988–2007 period for the corresponding index.
specifically mentioned, put the ensemble minimum and maximum in square brackets. Like the ensemble mean, the ensemble minimum and maximum is calculated for each grid cell separately.

The spatial variation of the change of annual mean temperature (Figure 5) is smooth and mainly shows a large-scale spatial gradient from about 1.5 to 2 °C warming in the south of Sweden to about 3.5–4 °C warming in the northernmost Finland. The ensemble minimum shows a similar spatial gradient, but about 0.5 °C colder, and similarly the ensemble maximum is about 0.5 °C warmer. This spatial gradient in the warming is stronger in winter (not shown), where the 1–1.5 °C warming is confined only to the very southernmost tip of Sweden, and then it gradually increases to about 6 °C in the very northern end of Finland. In the summer (not shown), the spatial gradient of the warming trend goes from 1 to 4 °C.

These warming trends carry over to changes to the temperature indices. In Finland, the growing season (Figure 6(a)–(c)) is on average projected to start about 10 days earlier compared to the reference period, with only small differences across the country. The same goes for large parts of the northern and central Sweden. Only south of about 60°N, the change is projected to be more pronounced, up to about 30 days, but also geographically more variable. The local influence of the major lakes and proximity to the sea is evident, as is the influence of the elevated interior plains in south Sweden. This southern region coincides with the regions where the average temperature during the reference period is in the range 2–6 °C (Figure 2(b)). For the ensemble minimum, any discernible change (>10 days) is seen only in the coastal zone of southern Sweden and near the major lakes. For the ensemble maximum, most of Finland and Sweden north of about 60°N is projected to experience 10–20 days earlier start of the growing season, with the same geographical pattern of the amplification in southern Sweden and locally at coastal locations the advancement of the start of growing season exceeds 50 days.

The picture that emerges for projected changes when the growing season ends (Figure 6(d)–(f)) is rather different.
In the autumn, the growing season is on average prolonged by about 10–20 days throughout the region, with little geographical variation. For the ensemble minimum the extension of the growing season reaches above 10 days mainly in broad zone along the northern Baltic Sea and Bay of Bothnia. For the most of the region, the prolongation of the ensemble maximum is projected to reach 20–30 days, with the exception of the interior north of both countries that has a more continental climate.

Changes to the length of the growing season, $G_{\text{length}}$ (Figure 6(g)–(i)), are the combination of these two indices. This means that the growing season is on average projected to be extended by 20–30 days in northern and middle Sweden as well as in most of Finland. In a coastal zone along the northern Baltic Sea, the growing season is extended by 30–40 days. In southern Sweden, $G_{\text{length}}$ is on average projected to become 40–50 days longer, with the exception of the cooler interior elevated plains of southern Sweden where the increase is 30–40 days. The overall patterns for the ensemble maximum are broadly consistent but with an additional extension of about 10 days. The same goes for the ensemble minimum, for which instead about 10 days have to be subtracted.

The temperature sum index, $T_S$, combines the effect of the prolonged growing season and the warming into one measure. In the northern half of Sweden (Figure 7), the ensemble mean change ranges from about 200 growing degree-days (GDDs) in high-altitude locations in the Scandinavian mountains to just above 300 GDDs along the Baltic coast. In Finland the change is rather uniform, in the range 300–350 GDDs, with an area in the north dropping just below 300 GDDs. In southern half of Sweden, the
change gradually increases towards the south, from 300 to 400 GDDs at some locations along the coast. The ensemble maximum change shows a similar but amplified geographical pattern with high altitude minima dipping just below 200 GDDs in the mountain range and maxima of 500–600 GDDs in southeast Finland and along the coast of south Sweden. The ensemble minimum change shows less geographical variation and instead a clear west–east zoning, where much of Sweden have an increase of 100–200 GDDs. Virtually all of Finland as well as both the southeast and northeast of Sweden have TS change in the range 200–300 GDDs.

The projected precipitation changes (Table 5) behave differently to temperature. The annual total precipitation is projected to increase with 92 mm year\(^{-1}\) (interquartile range is 76–100 mm year\(^{-1}\)) over Sweden, and 67 mm year\(^{-1}\) (interquartile range 61–74 mm year\(^{-1}\)) over Finland. Geographically, in Sweden (Figure 8) the ensemble mean increase is larger towards the Scandinavian mountain range and the western slopes of the south Swedish plains. In addition to this large-scale topographic influence, there is small-scale variations related to the topography. Although the ensemble minimum change shows less geographical variation, the ensemble maximum shows the same but enhanced overall spatial gradient from a lower increase in the east and to a large increase in the west. The geographical pattern of the seasonal total precipitation is similar to that of annual precipitation. Similar to what was found for the observed change in precipitation totals, the projected future changes do not influence the dry spell indices, which instead remain virtually unchanged (not shown).

To assess the model projections in comparison to observational data, we condense the overall average for seasonal temperature changes in Sweden into one graph (Figure 9). From this, it is clear that the average of the 35 stations and PTHBV data set is very similar in their observed climate change signal (1988–2007 minus 1961–1990): a strong warming in winter 2.0–2.3°C in the two observational data sets, gradually dropping to 0.4–0.5°C in

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**Table 4. Overview of the performance of the bias-adjustment procedure.**

| Index               | Sweden (PTHBV domain) |                  | Finland (FINADAPT domain) |                  |
|---------------------|-----------------------|------------------|---------------------------|------------------|
|                     | Mean  | St.dev. | P25  | P75  | Mean  | St.dev. | P25  | P75  |
| T\(_{\text{mean}}\) (°C) |      |        |      |      |       |        |      |      |
| raw                | 0.0   | 0.0    | 0.0  | 0.0  | 0.0   | 0.0    | 0.0  | 0.0  |
| dbs                | -0.6  | 1.6    | -1.4 | 0.1  | -0.7  | 0.6    | -0.9 | -0.3 |
| T\(_{\text{diff}}\) (°C) |      |        |      |      |       |        |      |      |
| raw                | -0.1  | 0.1    | -0.1 | 0.0  | -0.1  | 0.0    | -0.1 | -0.1 |
| dbs                | -0.6  | 1.8    | -1.5 | 0.2  | -1.0  | 1.0    | -1.4 | -0.4 |
| T\(_{\text{mam}}\) (°C) |      |        |      |      |       |        |      |      |
| raw                | -0.9  | 1.7    | -2.0 | 0.1  | -1.0  | 0.8    | -1.4 | -0.5 |
| dbs                | 0.0   | 0.0    | 0.0  | 0.0  | 0.0   | 0.0    | 0.0  | 0.0  |
| T\(_{\text{jja}}\) (°C) |      |        |      |      |       |        |      |      |
| raw                | -0.7  | 1.6    | -1.4 | 0.1  | -0.8  | 0.5    | -1.1 | -0.5 |
| dbs                | 0.0   | 0.0    | 0.0  | 0.0  | 0.0   | 0.0    | -0.1 | 0.0  |
| T\(_{\text{son}}\) (°C) |      |        |      |      |       |        |      |      |
| raw                | -0.2  | 1.6    | -0.9 | 0.5  | 0.2   | 0.8    | -0.1 | 0.7  |

The statistical measures are the same as in Table 3. Rows show ensemble summary statistics of bias in the unadjusted (‘raw’) and bias-corrected (‘dbs’) regional climate projection data. The reference period is 1961–1990, and the reference data are PTHBV and FINADAPT.
autumn. The reanalysis downscaling shows a similar seasonal cycle although not as marked a change. In winter and spring, the difference to the observed change is largest, 0.7–1.0 °C. In summer, the difference is at its lowest, 0.3 °C, and again increases to 0.5–0.6 °C in the autumn. For the same recent period, the scenario ensemble mean of the all-Sweden temperature average shows a similar seasonal variation of the change as the reanalysis run for all seasons except winter. In the winter, the scenarios exhibit less warming, 0.6 °C, compared to 1.3 °C in the downscaled reanalysis. For the other seasons, the difference between the ensemble mean and the observational data sets is in the span 0.3–0.7 °C depending on season, which can be compared to a total within ensemble span (between the six members) of ±0.4 °C or less. For the future period, the ensemble mean shows the strongest warming in winter, +3.0 °C (2.0–3.9 °C) and a least warming in summer, 1.7 °C (1.1–2.2 °C). Compared to the other data sets focusing on recent changes, the seasonal warming shows a different pattern in that there is a strong autumn warming, 2.3 °C (1.8–2.9 °C).

4. Discussion
We have analysed two high-resolution gridded observational data sets, which together cover Sweden and Finland, in combination with an ensemble of RCM projections to produce a consistent set of climate indices suitable for operational forestry applications in these countries. As the indices have to cover both the recent past and the future, and at the same time be consistent with observational data sets, an efficient calibration procedure is required. To adjust biases in the raw RCM output, we employ the DBS method (Yang et al., 2010a, 2010b), which is found to perform very well. After bias-adjustment, the temperature bias in both Sweden and Finland lies within ±0.1 °C, in many instances much lower. Similarly, the precipitation bias is substantially reduced, typically one to two orders of magnitude (when measured as mm per season). These results are in line with the results of Themeßl et al. (2012), who analysed the performance of similar bias correction methods based on nonparametric quantile mapping. They concluded that bias correction significantly improves the historic climate change signal in derived climate indices, in particular if they involve thresholds and other non-linear components. Drawing on their result, we applied the bias correction procedure without specifically performing a similar analysis. In some of the maps showing bias corrected scenario data, in particular Figure 8(a), the original coarse resolution regional model grid can be seen. This is not an indication of poor performance of the bias correction procedure, rather an effect of weak spatial gradients close to the boundary between two levels of the colour scale.

The observed climate change signal (1988–2007 minus 1961–1990) found in the temperature-based growing season indices (Table 3; Figure 3) is consistent with earlier studies. On analysing station data for the Greater Baltic Area, Linderholm et al. (2008) found that the growing season had increased by about 1 week between 1951 and 2000 where most of the increase took place in the spring. Moreover, they found the strongest signal along the Baltic and North Sea coasts, and most pronounced for Danish stations.

Høgda et al. (2013) used remote sensing data, calibrated to white birch, *Betula pubescens* Ehrh., to study the growing season in Fennoscandia during the period 1982–2011. They found that the average start of the growing season across their domain and averaged over the study period was day number 140 or 141. In the present study, which focuses on a more limited region (that includes also the southern part of Sweden), the average start is day number 123. Despite this difference, there is good agreement in the observed changes during the study period. Høgda et al. (2013) concluded that for the whole region (which is larger than in the present study), the remotely sensed onset of the
Figure 6. Same as Figure 5. (a)–(c) Gstart, start of the growing season [number of days]; (d)–(f) Gend, end of the growing season [number of days]; (g)–(i) Glength, length of the growing season [number of days].
vegetation period is on average advanced about 12 days, more in the south (~19 days) and only a few days in the far north. They found strong statistically significant correlations between the growing season (start and length) and 30-day temperatures averaged over different spring periods (from 1 April to 30 June) depending on geographic region and bioclimatic zone. However, the strong correlations apply only to average conditions during the study period. For the observed temporal trends only weak, statistically nonsignificant correlations are seen.

Compared to the station data set used by Linderholm et al. (2008), the PTHBV/FINADAPT data set has a much higher spatial resolution (4×4 km for PTHBV and 10×10 km for FINADAPT) but covers a smaller region and shorter time period. When it comes to spatial resolution is of the same order of magnitude as the GIMMS NDVI13g remote sensing data (8×8 km) used by Høgda et al. (2013). Although there is broad agreement regarding the quantitative results extracted from the three data sets, they serve different needs. A distinct advantage with the PTHBV/FINADAPT data set is that it is a high resolution gridded data set based on climate information only. Because of this it is conceptually and methodologically easy to link in a consistent ways to regional climate projections. With specific reference to that Høgda et al. (2013) make use different averaging periods related to distinct geographic regions we believe that a climate index like Gstart would enfold such geographic differences into one consistent measure that has the advantage of being able to vary smoothly over a domain.

The gridded observational data set shows a clear and consistent trend towards warmer conditions during the recent decades (i.e. from the earlier period, 1961–1990, to the recent period, 1988–2007) for all seasons, and very pronounced (+2.0°C) in winter, as well as across all climate indices based on temperature. In the downscaled reanalysis run, the warming shows a similar but weaker seasonal cycle, where the wintertime warming is consistent trend towards warmer conditions during the one consistent measure that has the advantage of being able to vary smoothly over a domain.

The change is calculated vs. the reference period 1961–1990.
Europe, which involves processes that are not described in enough detail in the regional models. In the regional climate projection ensemble, the corresponding signals of recent warming are consistent with the reanalysis run, except for winter where the ensemble mean warming is about half of what is seen in the reanalysis run. Although the underlying causes are not understood in all detail, it is clear that one key factor is biases in the large-scale atmospheric flow in the GCMs injected into the RCMs through lateral boundary conditions (Plavcova and Kysely, 2013). In particular, the representation of the North Atlantic Oscillation, NAO is important for European climate (e.g. Kjellström et al., 2013). Because of multi-decadal natural climatic variability, there was a strong trend in NAO during a substantial part of the period as discussed by Bärring and Fortuniak (2009). Although the GCMs do show multi-decadal natural variability in the simulated atmospheric flow (Riediger and Gratzki, 2014), this cannot be expected to be in phase with the observed climate state even for an averaging period as long as 20 or 30 years (Kjellström et al., 2011). This kind of multi-decadal natural climate variability will always be superimposed on a long-term climate change trend, in particular at regional scales as is of interest in the present study. Taking these limitations into account, we conclude that there is an overall consistency in the temperature trends.

The well-established approach to handle this natural variability is to use an ensemble of projections (cf. van der Linden and Mitchell, 2009). The ensemble mean is well known to often represent observed conditions, which Kjellström et al. (2011) show is the case for the same regional ensemble that is used in the present study. Furthermore, the spread of the individual ensemble members, e.g. the span between minimum and maximum shown in Figures 5–9, provides a quantitative indication of the degree of robustness in the projections. It is, however, worth pointing out that the span provides a conservative
Lind and Kjellström (2008) concluded that the six GCMs used in this study provide a good representation of the overall spread in full ensemble of CMIP3 GCM simulations of the A1B emission scenario, and that the main clusters were represented. The main source of uncertainty about the future climate is related to future emissions (cf. Figure SPM.10 of IPCC, 2013). As the SRES A1B is a medium high emission, the associated climate change signal is in the middle of the total span of projected future climates including the new RCP scenarios (Knutti and Sedlacek, 2012; Rogelj et al., 2012; Figure 33:19 in Walsh et al., 2014; http://www.globalchange.gov/browse/multimedia/emissions-concentrations-and-temperature-projections, accessed 19 May 2015, the figure is based on data from the CMIP3 and CMIP5 GCM data archives). As we pointed out in the Introduction section, the ultimate aim of the research is to develop a new generation of climate indices for operational applications in the forestry sector. As a first step towards the new generation of applications, we here present a methodology and its results on future climate change impact using a scenario that is well established in the Scandinavian forestry sector. Once the method is introduced in operational applications, it will be easier to expand it by adding further scenarios to give a more complete picture of the full range of climate change impacts and its relation to future anthropogenic greenhouse gas emissions.

Skaugen and Tveito (2004) explore growing season conditions in Norway for the future period 2021–2050. The used one GCM projection that was downscaled to 1 × 1 km using an empirical statistical method in combination with an interpolation procedure. Focussing on the spatial pattern, their results are similar to our results in low and intermediate altitudes (0–20 days advance in the start of the growing season, and a change in $T_S$ of 200–300 GDDs, with patches of lower $T_S$ towards the Swedish border). However, their results also indicate a very strong change in the start date in high mountains which is not confirmed in our results. In Finland, Ruosteenoja et al. (2011) used an ensemble of 19 GCMs to analyse changes projected for 2070–2099 under SRES A2 and B1 emission scenarios. There is very good agreement in the spatial pattern (their Figure 5 vs our Figure 5(g)–(i)), but it is difficult to compare in more detail the quantitative agreement because of the different emission scenarios and the different future time periods.

Studies in both Sweden and Finland have shown that global warming can potentially induce large increases in forest production (e.g. Kellomäki et al., 2008; Bergh et al., 2010) but this potential is dependent on using well adapted genetic material (e.g. Beuker, 1994; Persson and Beuker, 1997; Persson, 1998; Rehfeldt et al., 2002). In our study, the effects of climate change according to the medium high A1B emission scenario on the climatic indices developed and calculated here suggest a profound effect on boreal forest tree growth and adaptation already at 2050. For example, $T_S$ is a strong indicator of growth in boreal forests (e.g. Beuker, 1994; Morén and Perttu, 1994; Persson and Beuker, 1997) and has also been considered a key factor in transfer effect models in Sweden and Finland (e.g. Persson and Ståhl, 1993; Persson, 1994a, 1994b; Tapio, 2006; Andersson et al., 2007). Depending on the geographical location, the ensemble mean in this study shows an increase by 200–400 GDDs by mid-century. As a comparison, Persson and Beuker (1997) showed that a gradual increase from 900 GDDs (a moderately harsh site in northern Sweden or Finland) to 1200 GDDs over a rotation (assumed to be 100 years) would result in an increased Scots pine yield of 16%. At the same time, temperature
include climate change aspects in various activities related to forest management and development of decision support tools and systems.

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For the future period 2035–2065, representing the middle of the 21st century, the projected temperature increase consistently carries over to changes in the climate indices. Contrary to this, the projected increase in seasonal precipitation, in the order of 10–15 % for spring, summer and autumn, the three drought indices are projected to decrease only marginally by one or two days. This point towards that during the summer half year (April–October) the precipitation change is mainly affecting the amount of precipitation during rainy days rather than having any major influence on the frequency and distribution of dry spells. This conclusion is consistent with the result of Catiaux et al. (2012) that state that the GCM simulations do not project any major change to the atmospheric flow regime over Europe. However, we point out that although there is some agreement in the overall trend towards wetter future conditions in Sweden and Finland, there is considerable uncertainty related to the future extreme spell length because of their crucial dependence of blocking frequency and other aspects related to the large-scale synoptic flow (e.g. Zolina et al., 2013).

5. Conclusions

Within the overall framework of providing climate data for climate-proofing an operational forestry application, this study presents a way to use an established procedure for calibration of climate model data to merge high-resolution gridded observations with an ensemble of regional climate projection data. A consistent high resolution data set has been developed spanning from the recent past into the future for use in the climate-proofing of operational forestry applications. In the presentation of this data set, we have focussed on exploring the emerging climate change trends in the recent past and projected climate changes towards the middle of this century according to a medium high greenhouse gas emission scenario. For seasonal temperature and related climate indices, there is a clear change towards warmer conditions between the two periods 1961–1990 and 1988–2007, most clearly seen in the observational data and less pronounced in the RCM ensemble. For seasonal precipitation, the changes between the periods are more complex and less consistent across data sets. But marked future changes, to 2035–2065, of seasonal precipitation total only marginally carries over to the summer drought indices. In contrast, for the future period 2035–2065 projections based on the medium high emission scenario SRES A1B indicate substantial changes to several key indices related to forest growth and adaptation. This clearly points to the need to already today
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