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The European Corn Borer in Sweden: A Future Perspective Based on a Phenological Model Approach

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The European Corn Borer in Sweden: A Future Perspective Based on a Phenological Model Approach

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Master thesis, 30 credits, in Physical Geography and Ecosystem Analysis

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Abstract

The European Corn Borer (ECB) has the potential to markedly reduce the yield from corn plants and in turn affect the economy of farmers. The human world population is increasing and there is consequently an increased number of mouths to feed on a limited area, the Earth, and this makes this an important topic to study. It is thus important to find out whether the ECB likely will be an important pest for farmers in Sweden throughout the 21st century, and, further on, whether the temperature requirements for a permanent population will be met. This was studied using a phenological ECB model driven with climate model data based on RCP scenarios 2.6, 4.5 and 8.5, together with gridded observational data. This study found that the temperature conditions will support a semi-permanent to permanent population of the ECB in large parts of southern Sweden by the end of the 21st century, given RCP 4.5 and RCP 8.5.

Keywords

Ostrinia nubilalis (Hubner), European corn borer, degree days, life-stage, diapause, Bt corn, pest management

Abbreviations

ECB – European Corn Borer
IPM – Integrated Pest Management
ECAMON – Environmental Change Assessment model for *Ostrinia nubilalis*
DD – Degree days
RCP – Representative Concentration Pathways
RCM – Regional Climate Model
GCM – Global Climate Model
IPCC – Intergovernmental Panel on Climate Change
MSLP – Mean Sea Level Pressure
Hist – Historical driving climate data
Eval – Evaluation driving climate data
UC – Uncorrected
LS – Linear scaling
Δ – Delta change
std – Standard deviation

1. Introduction

Insects are of importance for crop productivity due to e.g. pollination and infestation, and thus also for the agricultural sector and economies relaying on that. It is critical to study insect pests due to the importance of the agricultural sector; a sector which is thought to become even more important in the future with a growing global population and, consequently, a growing number of human mouths to feed (UN, 2013). Insect pests can have a significant impact on a local to regional scale and it is in a strategic interest to consider that when planning and estimating future agricultural production.

The European corn borer, *Ostrinia nubilalis* (ECB), is the insect pest that causes the most damage to corn in Europe (Meissle et al. 2009). The ECB is relatively arduous to control with pesticides. This is because of the non-synchronous nature of insect pests, i.e. several life-stages can coexist. The 3rd to 5th instars live inside the stalk and are thus relatively protected from direct contact with pesticides (Pioneer, 2014). Attempts have been made to quantify the damage done by the ECB. One example is from Minnesota, where farmers growing corn lost about 107 million USD due to the ECB in 1983, and about 285 million USD in 1995. Extrapolated to the whole country, these figures indicate that the total loss from uncontrolled ECB in USA is more than 1 billion USD/year (Gianessi et al. 1999).

The ECB is believed to originate from southern Europe. It is presently concentrated to the southern and central parts, where a considerable amount of corn is grown, and it has spread to the USA. Up to four generations has been observed in the USA, while in Europe three generations can be found where the climatic conditions are particularly favorable, e.g. Hungary, the northern part of Italy and eastern Romania (Kocmánková et al. 2011; Iowa state university, 2013a). In northern Europe, e.g. Sweden, at present the climate is generally not warm enough to support the development of one ECB generation per year, and the question is if climate change can lead to the establishment of a permanent population. Further south, e.g. in Hungary, the question is how many generations there will be in a given year.

The relationship between temperature and insect development is a concept which, formally, dates back to Charles Bonnet’s research in 1779 in which he investigated the reproduction rate of *Aphis evonymi, F* (Bonnet, 1779 cited in Damos and Savopoulou-Soultani, 2012). This concept has been found to agree relatively well with what is observed for the ECB (Durant, 1990; Got et al. 1996, cited in Trnka et al. 2007; Trnka et al. 2007;).

A degree day model which has been developed and validated by Trnka et al. (2007) is used to simulate the development and timing of the ECB. Temperature sums in combination with photoperiod and temperature stress thresholds are used to estimate the timing of the different ECB developmental stages. In addition, the number of heavy precipitation days was included, serving as extra information which could be used to explain possible discrepancies between the modeled results and what is observed, even though observations do not exist in large enough quantities in the study area, Sweden, presently.

The ECB model predicts that a warmer climate will lead to earlier timing of completed development. This may potentially lead to a northward range expansion. Further on, it is very likely that the conditions for growing corn[1] in the future in many places in Europe, including Sweden, will be more favorable (Parry et al. 2004).**The aim** of this study is to assess the potential northward spread of the ECB in response to climate change. **The hypothesis** is that the ECB will be able to establish a permanent population in parts of Sweden.

2. Background

2.1 Impact Assessments Using Climate Model Data

In order to be able to estimate how e.g. a specific insect's areal extension will change in the future it is necessary to estimate how the climate will look like in the future. This is done by using data from climate models. It is important to note that we did not run the climate models ourselves but instead focused on the impact of the data produced by them (see method description for more detailed information). There are both global and regional climate model data, used for different purposes and with different advantages and disadvantages. Data from global climate models (GCMs) is more coarse scaled and less computationally demanding and is used to get an overview of large-scale changes. Data from regional climate models (RCMs) is more fine scaled and therefore more computationally demanding and it is used when more complex and fine-scale processes are of importance, such as local temperature or precipitation events (Rummukainen, 2010). To be able to incorporate different future developments and their effects, the climate models are combined with climate scenarios.

In this study three different representative concentration pathways (RCPs) where used, ranging from slight global warming to significant global warming. The global observed trend for CO_2 emissions today is following the trend of the significant global warming scenario, named RCP 8.5 (NCA, 2014). The naming of the RCPs emphasizes that it is not different specific future developments, but the carbon dioxide equivalent concentration or resulting change in radiative forcing. By doing this the RCPs incorporate a number of different futures fixed to a certain end point, rather than the opposite, different set scenarios (e.g. political and economic movements), fitting radiative forcing and resulting climate change to that (Cubasch et al. 2014).

2.1.1 Climate Models

RCMs is an important tool when it comes to modelling complex processes and trying to predict how different factors will change in selected, smaller regions. RCMs are chosen when wanting to have a high spatial resolution, capturing more complex and small scale processes, while still keeping the computational cost down. They work in the way that they are fed with boundary-condition data from one or an ensemble of GCMs, which the

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[1] The ECB has been seen feeding on other plants as well, where in Europe the E-race only sporadically attacks corn and the Z-race mainly attack corn (Lehmhus et al. 2012).

RCM then uses to simulate the conditions and climate processes inside the region of interest (Rummukainen, 2010).

Modelled data is the grid mean, so the actual mean or minimum at a specific point is probably different. This is something that can cause a divergence between the modelled and observed pattern when it comes to e.g. insect appearance. This is also an important feature to bear in mind when discussing potential impacts of changed extreme event patterns in the future, when it comes to the intensity, frequency as well as areal distribution. Many regions will probably notice a changed extreme event pattern, with dry zones thought to experience more frequent and severe dry spells, and wet zones more frequent and severe wet spells, in general (Rummukainen, 2012; Collins et al. 2013). An extreme event is defined, in this context, as an event located in either of the tails of the normal distribution curve: i.e., an event located away from the mean. The further away from the mean, the further out in either tail it is, the rarer it is, and the rarer the event is the more damage it is thought to cause since e.g. infrastructure is not adapted to such events (Zhang et al. 2011).

2.1.2 Data Fitting, Observational Data vs. Modelled

Due to the different properties of observed point measurements and grid cell averages, it can be problematic to compare observed values to modelled ones. This is particularly true for variables which can vary drastically over small spatial scales, such as precipitation. The grid mean will tend to have a lower amount of precipitation but over more days, while the point observations will tend to have fewer days with precipitation but with a larger amount recorded, in general (Zhang et al. 2011). E-OBS used in this study, retrieved from the EU ENSEMBLES project (the reader is referred to http://www.ensembles-eu.org/ for more information), have been interpolated, global kriging (see Hofstra et al. (2008) for details), and adjusted to be comparable with the output from the RCM used, SMHI RCA4-v1.

The interpolation methods that were chosen in the E-OBS initiative to adjust the data has been discussed and compared to other methods which could have been used in Hofstra et al. (2008). Global kriging was chosen, according to Hofstra et al. (2008), because, overall, it was the best performing method. However, the station density varies noticeably over space. In general, where the stations are more sparsely located, the greater is the difference between the different interpolation methods. This is further complicated by that they want to choose one method for the different variables, precipitation, maximum/minimum/mean temperature and Mean Sea Level Pressure (MSLP). In Hofstra et al. (2008), it can be seen that the global kriging method is in general the best performing method across Sweden, but the result differs over space and between variables. What difference this makes in absolute numbers in Sweden is not well known and it is something worth bearing in mind when analyzing the results.

It is important to note, though, that since Hofstra et al.'s paper in 2008 there has been noticeable and continues improvements. Especially the density of the observational sites has been improved. The effect of a more sparse density of the observational sites is that it leads to an over-smoothing and an underestimation of the extremes (ECAD, 2013).

2.1.3 Bias-Correction

There can be discrepancies between modelled and reference observational data sets. If the discrepancies are too large for a specific study purpose, then the use of bias-correction is a method to improve the fit between modelled and observational data sets. The original modelled data set values in this study were found to underestimate the observed temperature in the area of interest, Sweden, and bias-correction was therefore used to improve the fit.

The two different bias-correction methods that were used in this study have different pros and cons. The advantage of *linear scaling*, a direct approach, is that the baseline is the simulated climate and that it thus takes into account possible changes in the pattern of extreme values/events, as well as changes in the correlation between different variables. The disadvantage, which is the advantage of *delta change* approach, is that if the quality of the RCM model's result is not 'good enough', then those advantages can turn into a weakness (Lenderink et al. 2007). What is 'good enough' is a relatively vague and subjective term since it has to be put in relation with the application of the data.

2.2 Insects and Temperature

The ongoing climate change will likely affect insect pests in a number of ways (Porter et al. 1991);

a) Extension of geographical range
b) Extension of the development season
c) Changes in population growth rates
d) Increased over-wintering
e) Changes in the crop-pest synchrony
f) Change in interspecies interactions

It is important to assess the interactions between the above listed factors and their net effect regarding, within and between seasons, on the insect and its host plant. The main focus is on the climate driven points above, a, b, c and d. However, the other points are, in varying degrees, also considered in the study. When assessing how the ongoing climate change will affect the insect it is important to consider not only the direct effect of climate change on the insect, but the indirect effects as well (Figure 1). Indirect effects involving e.g. the climate effect on the host plant and possible changes in the insect – host plant synchrony. Figure 2 displays the different life-stages and how they relate to each other over time.

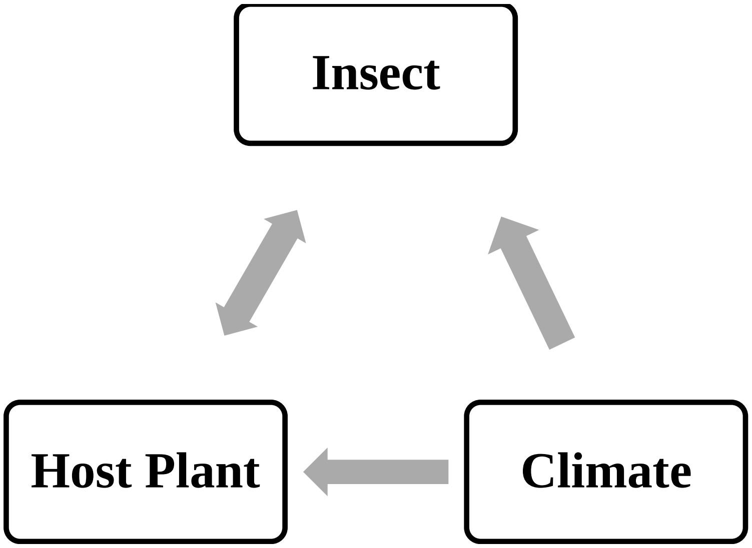


Figure 1 Illustration of the relationship between the insect, host plant and climate. The insect's development throughout the season is closely related to the temperature, and they are directly affected by temperature since, in most cases, they are exothermic (Porter et al. 1991). The host plant is also affected by temperature and can suffer from e.g. drought or extended wet periods which negatively affects the plant, and might lead to it decaying because the water content in the soil is at or below the wilting point, i.e. not available for the plant, or above the field capacity which may cause aeration problems (Nielsen et al. 1959; Spectrum, 2013;). The insect is dependent on the host plant and thus is affected by the health of it. The host plant is affected by the insect through e.g. leaf feeding and stalk damage.

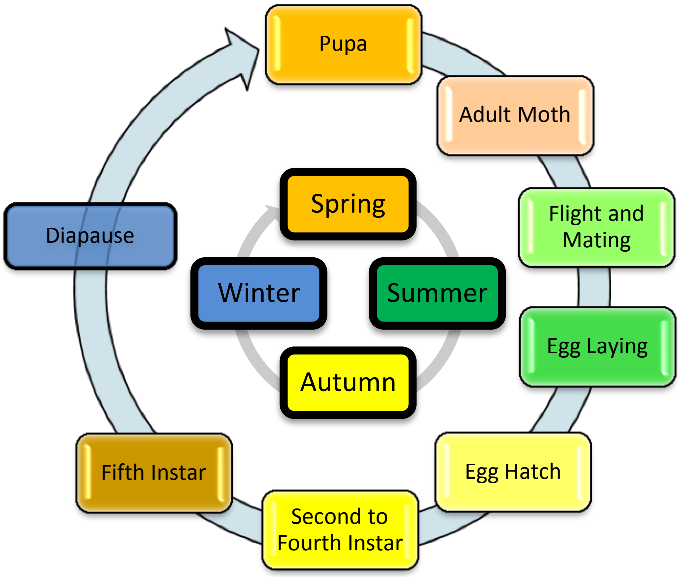


Figure 2 A general sketch of the ECB's life cycle (outer circle), including the diapause, with an approximate timing of the year when it occurs (inner circle), with the colors of the different life-stages in the outer circle further illustrating this.

2.2.1 Pest Insects, Globalization and Pest Control

With increased traffic of goods and humans, there is an increased risk of introduction of new species and of anthropod pests spreading even more rapidly than they would on their own, which in combination with the expansion of the pest's population boundaries due to increased temperatures, makes so that the pest pressure is likely to increase in the future (Meissle et al. 2009).

Pesticides

Pesticides remain a relatively well-used and efficient method to combat ECB attacks (Wilson and Tisdell, 2001). However, the negative side effects are recently getting an increasing amount of attention which in turn affects the end consumers' awareness and willingness to pay for such products, and in effect affects the whole product chain (Consmüller et al. 2010). The negative effects of using pesticides involve the non-specific nature of its effect, and development of resistance for the ECB to the pesticide in question which leads to higher doses being used, or alternatively, using a different pesticide, and the cycle is started over again. The non-specific nature of the effect means that pesticides affect not only the target pest but other living organisms as well (Meissle et al. 2009). The decrease in the bee population lately, a key species in the pollination of plants, has been suggested to, in large parts, be due to the use of pesticides (Pettis et al. 2013).

The ECB is due to its non-synchronous nature, i.e. several life-stages coexist, and because it during parts of the season remains comparatively protected in the interior of the corn (stalk), difficult to target with pesticides. There are two main periods when the ECB is most vulnerable and when, consequently, the pesticides commonly are applied, in a short window right after egg hatching and/or during the second instar before the larvae bores into the plant (Mason 1996, cited in Merrill et al. 2013; Merrill et al. 2013).

Bt Corn

A method which more specifically targets the ECB is the use of genetically modified (GM) corn. The GM corn named Bt corn has been genetically modified to produce the proteins of *Bacillus thuringiensis* which is a toxin to the ECB, and which is derived from a naturally occurring soil bacterium. The Bt corn has a high efficiency which means it does not need to be used in combination with pesticides, and while pesticides in many cases, by nature, target non-pests as well, the Bt corn is highly specific in its targeting and only targets a few number of species (Hunt and Echtenkamp, 2006; Meissle et al. 2011). However, this gives rise to one of the downsides of using Bt corn, that secondary insect pest outbreaks can occur. Though, it should be noted that in the majority of cases in Europe natural enemies is sufficient to confine the secondary pest outbreaks to low enough levels (financially speaking).

In USA, though, there has been a marked increase in a secondary insect pest, western bean cutworm, *Striacosta albicosta* (Smith), which is less susceptible to Bt corn and one explanation is that it is then able to fill the gap in the ecological niche brought by the reduced numbers of e.g. the ECB population. There are other drawbacks as well, though, such as that the ECB can grow resistant to the Bt toxin, as with pesticides, and it comes with an increased administrative work-load. In Europe still [2011] it is difficult to get a permission to grow Bt corn, and is prohibited [2009] in some of the largest maize producing countries such as Germany, Italy and France, additionally growing of it is further dampened by the fact that the public is believed to be against the propagation of

GM crops (Meissle et al. 2009; Meissle et al. 2011; Consmüller et al. 2010). One method to delay the ECB developing a resistance to the Bt protein is the use of refuge areas, areas which are neither treated with Bt corn, in any form, or pesticides. The idea is that this refuge area will supply the potentially Bt resistant individuals in the treated field with none-Bt resistant individuals, i.e. with a none-Bt resistant gene-pool (Hunt and Echtenkamp, 2006).

When deciding if to use the Bt corn there are several things to bear in mind, one is e.g. that the Bt corn is more expensive (cost of using the Bt corn versus the benefit in terms of increased yield) and that the ECB can develop a resistance to the modified corn. Meissle et al. (2009, 2011) and Obopile and Hammond (2013) describe different methods e.g. farmers can use to minimize the damage done (see 'Alternative Methods' below). On top of this there is the end market dimension, i.e. that end users may be less willing to buy genetically modified crops (Consmüller et al. 2010). This all highlight the complexity of the issue at hand and the many dimensions one has to keep in mind when deciding what methods to use.

Hutchison et al. (2010) evaluated the financial benefit with Bt corn and found that the direct cumulative benefit was in the order of Billion American dollars by 2009. This benefit did not solely go to the Bt farmers but, arguably, to a greater extent to non-Bt farmers since they got a share of the regional decline in the ECB population while not paying the premium price that comes with the Bt corn.

Alternative Methods

There are several methods available as a way to reduce the use of pesticides. They involve e.g.

a) biological control,
b) genetically modified crops,
c) crop rotation,
d) trap crops,
e) early/late planting,
f) mowing stalks and/or ploughing,
g) synthetically produced sex pheromones

One example of biological control is to release small wasps whose efficiency (>75 % destroyed eggs) and cost (35-40 euros per hectare (1st generation)) is on the same level as pesticides as long as there is not an immense pest pressure. Another method is to plant susceptible trap crops around the corn fields which attracts the ECB which in turn, given the possibly concentrated amount of eggs there, gives raise to less pressure on the corn field but also attracts natural enemies of the ECB. Yet another method is ploughing and mowing of stalks; it reduces the overwintering population (Meissle et al. 2009). Fadamiro et al. (1999) studied a fourth method which involved the use of synthetically created sex pheromones and the possible use of that in fighting the ECB population, and they found that a significant degree of mating disruption was attained.

Temperature Dependent Development, ECB

The ECB's different life-stages are depicted in figure **2**. The development starts from the pupa stage which then, depending on the climatic conditions, can reach the fifth instar, the final larvae stage. At that point, depending on light and temperature conditions, the ECB either goes into diapause or into pupa and starts a second generation. The ECB only goes into diapause from the fifth instar, which is the life-stage that determines the overwintering. That is why the fifth instar is chosen as the focus point in this study; it determines whether the ECB will overwinter and in turn whether an area can support a permanent population. A permanent population is determined to when the population overwinters the vast majority of years; ideally all years.

Diapause

To withstand the low temperatures experienced in some regions during late autumn and winter, the ECB goes into a stage called diapause. The diapause stage is defined as a dormancy (Beck, 1968 cited in Gelman et al. 1980). A dormancy which more precisely involves reduced movement, oxygen consumption and water content, increased fat reserves as well as a lowered rate of metabolism. With that said, though, there are several different kinds of diapause ecotypes for the ECB; one is to diapause at some point in each generation, obligatory diapause, and a second is to, depending on the environmental conditions at the site, diapause or not, facultative diapause, and a third is a homogeneity towards non-diapause. These are then combined with different life-cycle ecotypes, only one generation per year (univoltine), and generally more than one generation per year (polyvoltine), which gives rise to a number of different combinations (Gelman et al. 1980).

Both the onset and offset of diapause are affected by several factors. In order to not get overwhelmed by relatively sudden temperature changes, the ECB has through natural selection become sensitive to changes in day length for initiation of diapause, and the triggering photoperiod displays local variability depending on temperature and relative humidity. The importance of the photoperiod has been shown by keeping the larvae, up to the fifth stage, in photoperiod conditions which would induce diapause and then transferring them to non-diapause-rearing conditions. This caused 70% of the larvae to not complete the diapause (Gelman et al. 1980). The diapause rearing conditions, and thus the non-diapause rearing conditions, were said to be related to the scotophase, described as the dark part of a dark-light cycle (Gelman et al. 1980; Circadian Rhythm Laboratory, 2013). A scotophase of 12 h was shown to generate the maximum diapause, even when combined with photophases from 5 to 18 h – and cycles other than 24 h. The scotophase dependency was found to be relatively sensitive: if it was interrupted by 0.5 h the individuals failed to diapause.

As stated above both the temperature and the photoperiod are vital factors contributing to the diapause's being or not being, and the timing of it. For a population in Wisconsin e.g. an inverse relationship between the diapause and temperatures other than between 20 and 30 °C was found. Furthermore the importance of large temperatures changes was also found; and overrules the effect of the photoperiod. With that said, though, it is again important to stress the differences in response to these factors between different ECB ecotypes. One example portraying this is the comparison between Delaware and Iowa. In

Delaware a majority of the ECB population went into diapause when reared in photophases ranging from 11 to 13 h at 30˚C, while in Iowa a relatively low number, percentage wise, of the population went into diapause at temperatures above 26˚C (Gelman et al. 1980). This shows that a variety of different factors cooperate in an intricate fashion.

The number of generations per year is the number of times the life-cycle in figure **2** has been completed. The damage and yield loss from the different generations is believed to look like the following (Iowa state university, 2013b);

a) Leaf feeding (first generation)
b) Midrib feeding (first and second generation)
c) Stalk tunneling (first and second generation)
d) Leaf sheath and collar feeding (second and third generation)
e) Ear damage (second and third generation)

2.3 Different ECB Types

There are two different pheromone races, E and Z, of the ECB which visually are indistinguishable, but which has different traces, where the Z-race is accountable for most of the damage done to corn. Pheromones is a chemical substance secreted by the insect which affects other members of the same specie; different pheromone races means that they secrete different types of pheromones (Regnier and Law, 1968). The E-race can also attack corn, but in Germany, Sweden, France, Spain, Serbia and Croatia the damage is mainly caused by the Z-race. The E-race has only been occasionally observed in corn fields located close to its main host plants mugwort and hop in e.g. Germany and France. In Italy and Greece on the other hand corn is attacked by the E-race. The ECB had up until recently not been observed in corn in Sweden, albeit having existed in other plants, and the genus of the species that recently was found in southern Sweden was determined to be the Z-race (Lehmhus et al. 2012).

2.4 Models in Mapping Future Pest Insect Changes

Impact models are important since with them it is possible to study and incorporate the effects of that e.g. the temperature and precipitation change will very likely be spatially not homogenous (Collins et al. 2013).

2.4.1 Linear Response Model

The linear response degree day model which is used in this study describes the timing and distribution (area-wise) of the ECB’s different life-stages, but it does not estimate the population size. Trnka et al. (2007) found that the model was suitable to accurately estimate both the onset and duration of the different life-stages for a wide range of sites. Furthermore, the use of linear response degree day models have been determined to be performing equally well as more statistical models such as regression models, and more mechanistic models such as multiple threshold models (Got et al. 1996, cited in Trnka et al. 2007).

3. Methods and Data

3.1 The ECB Model

To model the ECB, the degree day model by Trnka et al. (2007) (Figure **3**) was used. The model has been developed for central European conditions, and was applied to simulations of northern Europe as the ECB is expected to in the future spread northwards in response to climate change. Since only a few ECB individuals so far have been observed in Sweden, there is not yet enough data to support model evaluation for this region. Northward migration may, however, induce selection and adaptation, most likely favoring individuals with a low temperature requirement for development. This study therefore mainly focused on the temperature requirement of the 10% earliest developed ECB individuals, i.e. the individuals with the lowest temperature requirement, the individuals with the greatest capacity to spread northward (Table **1**) (Lehmhus et al. 2012).

Table 1 The temperature thresholds (accumulated degree days) used in ECAMON model which are based on Brown (1982), Mason et al. (1996) and SPA (1999) according to Trnka et al. (2007). In Trnka et al (2007) the terms 10, 50 and 95%'s development were used, which is when 10%, 50% and 95% of the individuals in the population, respectively, has reached a certain stage. In this study, the terms have been translated into individuals with lower temperature, intermediate temperature and greater temperature requirement, respectively.

Stage	**Pupa**	**Adult moth**	**Flight and mating**	**Egg laying**	**Egg hatch**	**2nd instar**	**3rd instar**	**4th instar**	**5th instar**
1st generation									
Lower temperature requirement	**121**	**216**	**288**	**321**	**388**	**447**	**512**	**585**	**710**
Intermediate temperature requirement	**199**	**316**	**393**	**454**	**516**	**599**	**677**	**754**	**827**
Greater temperature requirement	**293**	**404**	**482**	**532**	**588**	**654**	**732**	**810**	**882**

The accumulated degree days were used in combination with empirical ECB parameters (Table 1). Eq. 1 and eq. 2 shows how degree days are accumulated, and is further explained below. These empirical ECB parameters include the accumulated degree days estimated to be needed to reach a certain stage in the insect's development. The empirical values are dependent on the base temperature. The base temperature, T_{base}, the temperature from which the model starts to accumulate degree days, was set to 10°C, used in Maiorano (2012); Matteson and Decker (1965); Got and Rodolphe (1989); Mason et al. (1996) and Trnka et al. (2007). The accumulation of degree days per day was thus calculated as the sum of the daily mean temperatures, T_{mean}, above the T_{base}. However, there is another condition which needs to be fulfilled in order for the ECB to develop. When the daily minimum temperature is less or equal to 0.2°C, defined as *cold* below, for three days in a row, the ECB starts developing from the beginning of the cycle again. This is because part of the ECB population is assumed to still be in the cold resistant pupa diapause stage. So another step/term was added to the degree day calculation, *cold*, and is simplified in this study as the last day where the temperature sum of three days in a row was less than 0.6°C. The equation then looks like the following;

$$cold(d) = x$$

$$Degree\ days\ (d) = T_{mean}(d > x) - T_{base}\ [\mathbf{eq.1}]$$

$$Degree\ days\ (d_j) = \sum_{i=1}^{j} T_{mean}\ (d_i > x) - T_{base}\ [\mathbf{eq.2}]$$

Eq.**1** is the number of degree days accumulated in a given day; a day occurring after the last cold day, x. Eq. **2** is the total number of accumulated degree days at a given day, dj, for days occurring after the last cold day, x.

Trnka et al. (2007) also used an additional model to check the snow cover depth; as the development of the ECB does not start until the snow is fully melted. In this study, though, such a model was not used since there is in general a good approximation to assume that there is no snow left when the temperature has reached 10°C in southern Sweden, which is the region at greatest risk of being affected by a permanent ECB population.

In accordance with the ECAMON model used by Trnka et al. (2007), the drought and water stress was counted for each of the sensitive stages. Two levels of water stress was used, dry and extremely dry, which, respectively, were deemed to be when the actual evapotranspiration to the crop evaporation ratio was less than 0.4 and 0.2 for two consecutive days. The stress caused by heavy rainfall was defined as precipitation more than 20 mm in a day. The drought sensitive stages are adult moth to the 2nd instar. Between the 3rd and 5th instar the ECB is protected in the interior of the corn stalk (Trnka et al. 2007). However, a preliminary analysis indicated that the drought stress days were close to none in Sweden, over time and across RCP scenarios and is therefore not included in the result section of this study. It is mentioned in short in this section due to the possible importance of the drought stress days.

The ECB only goes into diapause as fifth instar larvae (Glover et al. 1992). With that said, though, the model used in this study does not keep the previous year's fifth instar larvae has reached and continues from that point the next year. The development each year starts from the cold resistant pupa diapause stage.

The flow chart (Figure 3) depicts the phenological model used in the study. Daily mean temperature constitute the basis of the degree day (DD) model, which is then combined with ECB parameters, day-length model and minimum temperature to create a phenological model, where the stress module acts as extra information and makes it possible to compare different years and stages with each other, and further on offer a possible explanation for given results.

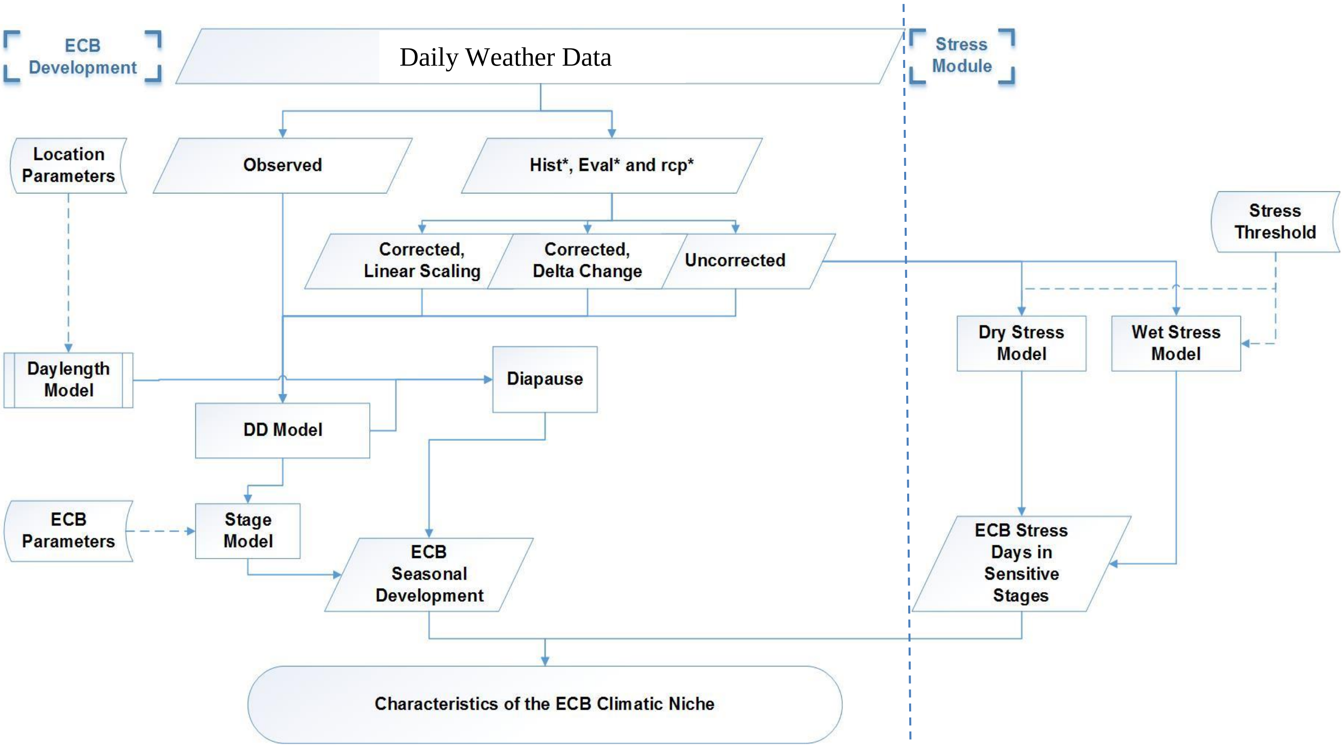


Figure 3 Flow chart of the model used in the study, based on ECAMON used in Trnka et al. (2007). The left side of the flow chart [ECB Development] shows the core model. Daily Weather Data (driving climate model data) is fed into the DD Model (degree day model) whoch in combination with the ECB parameters returns values for the ECB Seasonal Development (for the different life-stages). The right side of the flow chart [Stress Module] does not impact the ECB Seasonal Development results, but is included to give extra information and to make it possible to explain possible discrepancies between modelled values and observed values, for the different life-stages. The flow chart is based on the flow chart depicted in Trnka et al. (2007).

Not only does the thermal response between species differ, it also differs between populations of the same specie. The relatively wide range used for the ECB development, low/intermediate/greater temperature requirement, in this study is a way to handle intraspecific variability (Yamahira and Conover, 2002; Kipyatkov and Lopatina, 2010). Incorporating this makes the model more robust.

3.2 Driving Climate Data

The ECB model was driven by temperature data with a daily resolution from six climate data sets: gridded observational data, a) E-OBS version 9 (Haylock et al. 2008), and climate model data b) NEUR-44_ECMWF-ERAINT_evaluation_r1i1p1_SMHI-RCA4, c) NEUR-44_ICHEC-EC-EARTH_historical_r12i1p1_SMHI-RCA4, d) NEUR-44_ICHEC-EC-EARTH_rcp26_r12i1p1_SMHI-RCA4, e) NEUR-44_ICHEC-EC-EARTH_rcp45_ r12i1p1_SMHI-RCA4 and f) NEUR-44_ICHEC-EC-EARTH_rcp85_r12i1p1_SMHI-RCA4. The climate model data was retrieved from the CORDEX initiative and ECAD (for more information, Haylock et al. 2008; ECAD, 2013; Christensen et al. 2014).

The three future scenarios, RCP 2.6, 4.5 and 8.5, represented the time period 2006-2100. The Evaluation data set (1980-2010) was used in combination with E-OBS to evaluate the performance of the RCM, while the Historical data set (1951-2005) was used to evaluate the combined RCM-GCM The evaluation of the Historical data set was used as a basis for bias-correction, and the ECB model was driven by the bias-corrected data in addition to the original data sets for comparison of model performance.

The terminology used in the study for the different climate model data is shown in **table 2**. E-OBS – gridded observational data, Hist_LS – linear scaling bias-corrected historical data set, Hist_Δ - delta change bias-corrected historical data set, Hist_UC – uncorrected historical data set, Eval_UC – uncorrected evaluation data set, RCP 2.6/4.5/8.5_LS – linear scaling bias-corrected RCP scenarios, RCP 2.6/4.5/8.5_Δ - delta change bias-corrected RCP scenarios, RCP 2.6/4.5/8.5_UC – uncorrected RCP scenarios.

Driving Climate Model Data	Terminology Used In The Study		
Gridded Observational Data	E-OBS		
Linear Scaling	Hist_LS	RCP 2.6/4.5/8.5_LS	
Delta Change	Hist_Δ	RCP 2.6/4.5/8.5_Δ	
Uncorrected	Hist_UC	Eval_UC	RCP 2.6/4.5/8.5_UC

3.3 Bias-Correction

The mean and minimum temperature for the Historical, Evaluation and RCP 2.6, 4.5 and 8.5 time series were bias-corrected using two different methods, *delta change* and *linear scaling*. Linear scaling and delta change were used for the time periods 2011-2040, 2041-2070 and 2071-2100.

- T_{contr}(d) is the daily temperature of the historical driving climate data set.
- μ_m (T_{obs}. (d)) is the monthly averaged daily temperature of the observational driving climate data set.
- T_{scen}(d) is the daily temperature of the scenario driving climate data set, i.e. RCP 2.6, 4.5 or 8.5.

The corrected data is given the prefix * next to the T, the uncorrected data not.

3.3.1 Linear Scaling

The linear scaling method for bias-correcting data (Teutschbein and Seibert, 2012),

$$T^{*}_{contr.}(d) = T_{contr.}(d) + \mu_{m}\big(T_{obs.}(d)\big) - \mu_{m}\big(T_{contr.}(d)\big)\ [\mathbf{eq.3}]$$

$$T^{*}_{scen.}(d) = T_{scen.}(d) + \mu_{m}\big(T_{obs.}(d)\big) - \mu_{m}\big(T_{contr.}(d)\big)\ [\mathbf{eq.4}]$$

The linear scaling is based on the mean monthly difference for May, June, July and August, of the observations, 1961-1990, and the modelled control years, 1961-1990 (**eq. 3**). The mean difference is added to the daily temperature values for the modelled scenario years 2011-2040, 2041-2070, 2071-2100 - respectively (**eq. 4**).; each day during the months of interest, May, June, July and August (Appendix Tables **A13-A16**).

3.3.2 Delta Change

The delta change method for bias-correcting data (Teutschbein and Seibert, 2012),

$$T^{*}_{contr.}(d) = T_{obs.}(d)\ \ [\mathbf{eq.5}]$$

$$T^{*}_{scen.}(d) = T_{obs.}(d) + \mu_{m}\big(T_{scen.}(d)\big) - \mu_{m}\big(T_{contr.}(d)\big)\ [\mathbf{eq.6}]$$

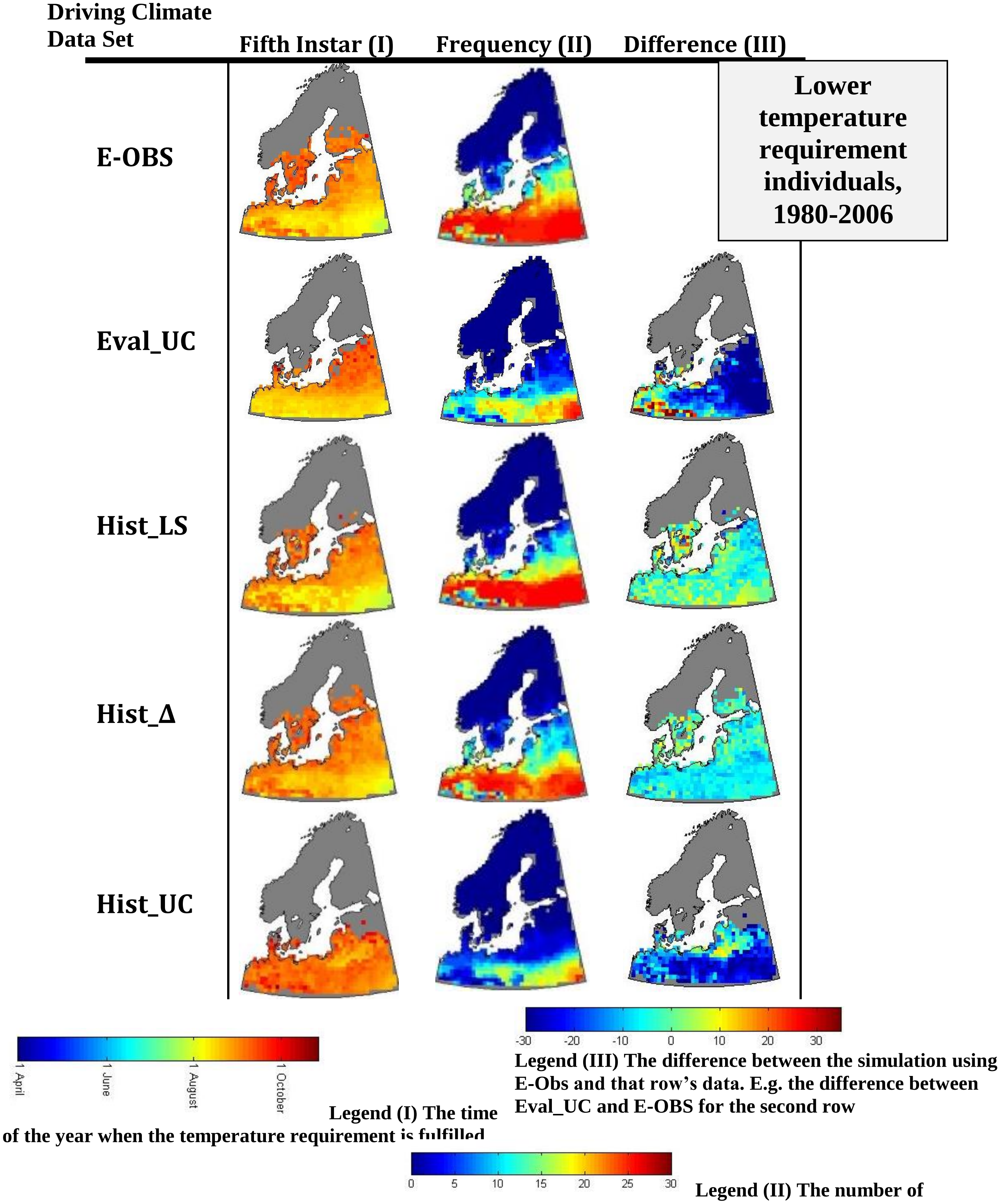
The delta change method uses the observations as a baseline (eq. **5**). The difference between the modelled scenario years (2011-2040, 2041-2070, 2071-2100, respectively) and the modelled control years (1961-1990), is added to the observation (1961-1990) (eq. **6**) each day during the months of interest, May, June, July and August (Appendix Tables A1-A12).

4. Results

4.1 The Need of Bias-Correction

When comparing the uncorrected data to reference driving climate data E-OBS, a significant underestimation of the frequency can be observed (Figures 4 and 5); the frequency for the uncorrected driving climate data is lower than the frequency for the driving climate data E-OBS. For E-OBS, parts of Sweden fulfill the temperature requirement for the fifth instar around 10 times in the given/tested 27 year period. Both Eval_UC and Hist_UC show only sporadic to no fulfillment in the same time period. The two different bias-correction methods, linear scaling and delta change, show a relatively similar pattern. The difference between the timing of reaching the temperature requirement for E-OBS and delta change is slightly lower than compared to linear scaling. The frequency, the number of times the temperature requirement is fulfilled in a given time-period, for the fifth instar life-stage, however, for linear scaling shows a slightly lower discrepancy to E-OBS than delta change. The standard deviation (std) for the different driving climate data and individuals with lower and greater temperature requirement can be found in the appendix (Appendix Figure A6).

4.1.1 Overview, Comparison of Methods

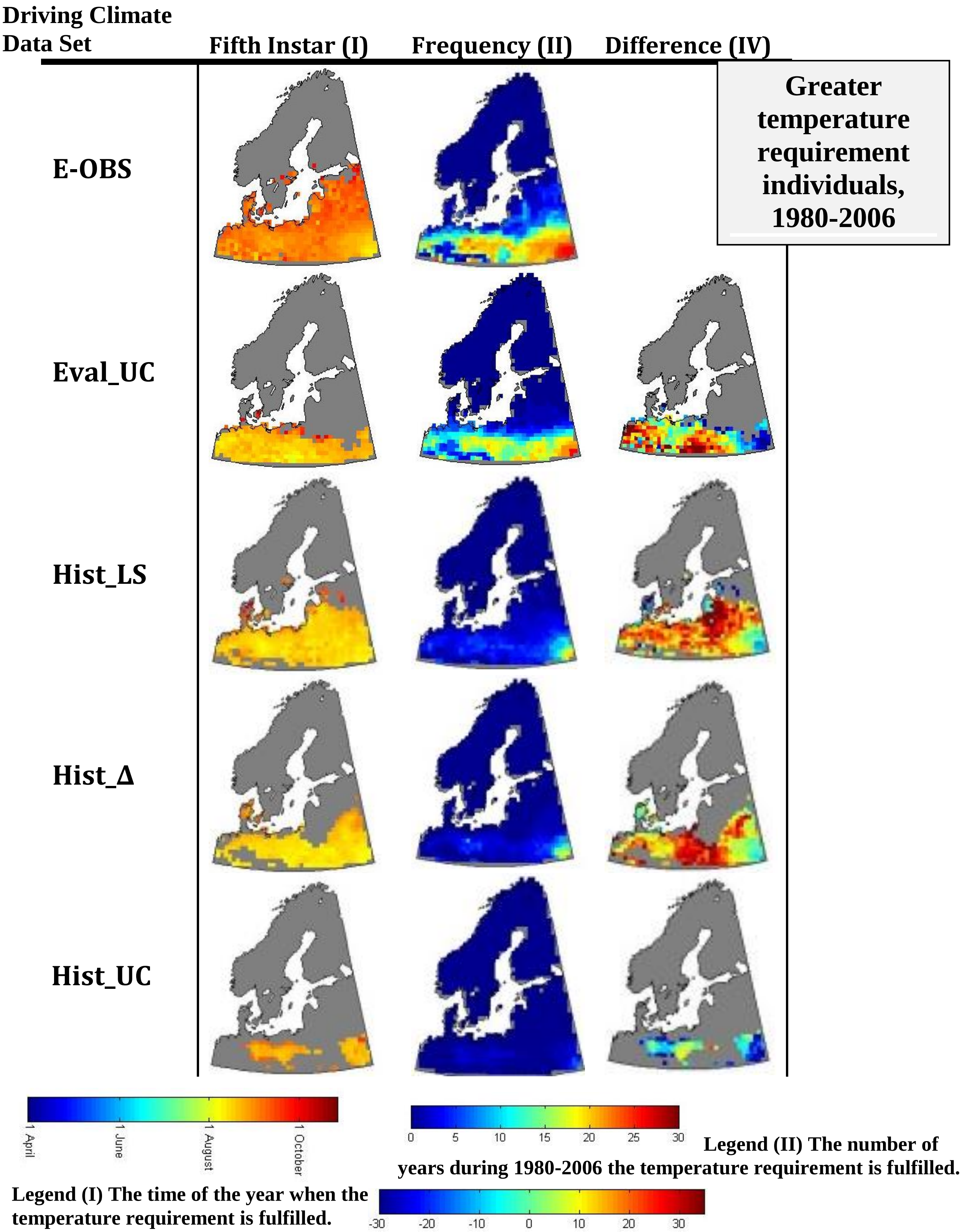


Legend (I) The time of the year when the temperature requirement is fulfilled

Legend (III) The difference between the simulation using E-Obs and that row's data. E.g. the difference between Eval_UC and E-OBS for the second row

Legend (II) The number of years during 1980-2006 the temperature requirement is fulfilled.

Figure 4 The timing of the fulfillment of the lower temperature requirement individuals (column I), the number of years in the given time-period it is fulfilled (column II), and the difference between observed and that row's scenario (column III). According to 5 ECB model simulations with different driving climate data sets.



Legend (II) The number of years during 1980-2006 the temperature requirement is fulfilled.

Legend (I) The time of the year when the temperature requirement is fulfilled.

Legend (III) The difference between the simulation using Obs and that row's data. E.g. the difference between Eval_UC and E-OBS for the second row

Figure 5 The timing of the fulfillment of the temperature requirement of the greater temperature requirement individuals (column I), the number of years in the given time-period it is fulfilled (column II), and the difference between observed and that row's scenario (column III). According to 5 ECB model simulations with different driving climate data sets.

4.1.2 Regional Scale Variability

Figure 6a and 6b give an overview and more specific information of how the spatial variability on a finer scale looks like, which in this example is southern Sweden (see appendix tables A1-A16 for the bias-correction in absolute numbers). The frequency, the number of years in the given 30 year time-period the temperature requirement for the fifth instar life-stage is fulfilled, is relatively stable for the grid cell located approximately at 56°N / 13°E, varying between 27 and 30 for all scenarios and time-periods. For the grid cell located at approximately 56°N / 14°E the early time-period, 2011-2040, and the three RCP scenarios has a noticeably lower frequency than both the later time-periods, 2041-2070, 2071-2100, and the neighboring grid cell, for both RCP_Δ and RCP_LS. The time to reach the temperature requirement, in Julian days, for the fifth instar gets lower going from 2011-2040 to 2041-2070 and to 2071-2100, for the three climate scenarios, RCP 2.6, RCP 4.5 and RCP 8.5. There is a moderate increase between 2041-2070 and 2071-2100 for RCP 2.6, this is likely because the nature of the climate scenario, it reaches its radiative maximum before the end of the 21st century, and then decrease slightly. The standard deviation (std) in Julian days varies between 7 and 14 and 8 and 14 respectively for delta change and linear scaling, with no clear temporal or between scenarios trend (Appendix Figures A1 and A2).

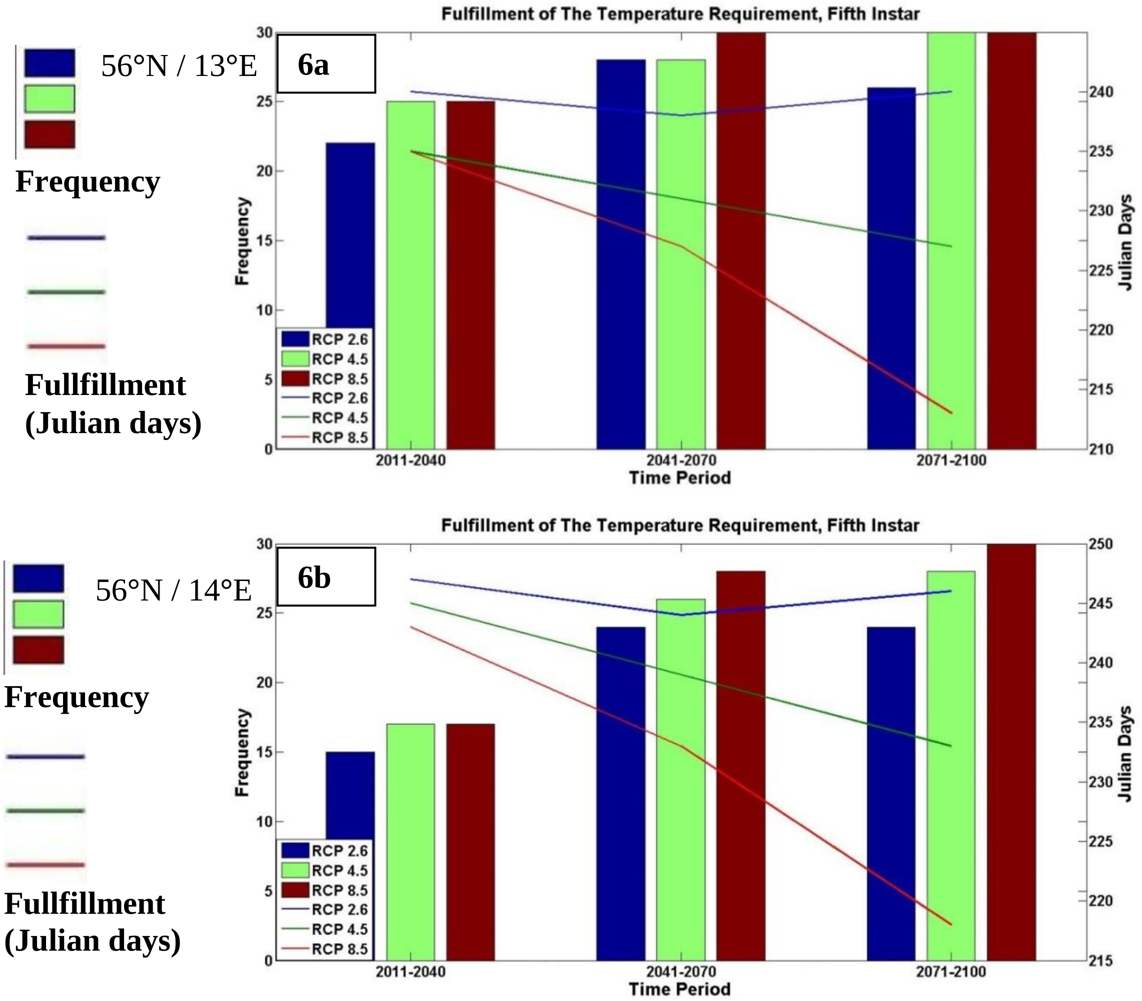
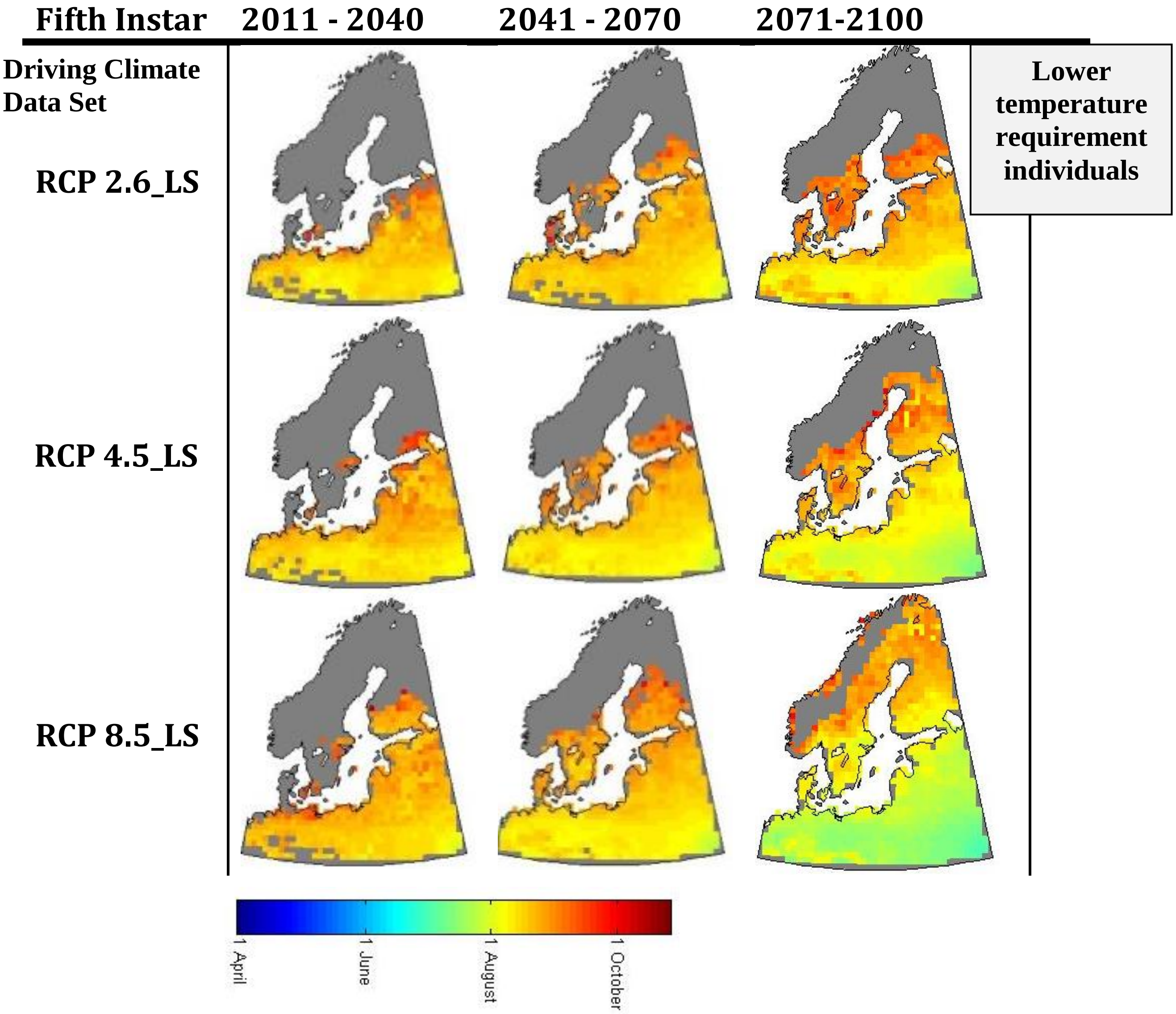


Figure 6a and 6b The fulfillment of the temperature requirement, lower temperature requirement individuals, std and frequency for two grid-cells in southern Sweden, 56°N / 13°E, 56°N / 14°E, for E-OBS, RCP_Δ, RCP_LS and RCP_UC for three different time periods, 2011-2040, 2041-2070, 2071-2100. The frequency is the number of times in a given time-period the temperature requirement for the fifth life-stage was fulfilled. The fulfillment (Julian days) is the mean timing for fulfillment of the fifth instar life-stage in the given time-period.

4.2 Climate Scenarios and the ECB development

4.2.1 Timing, Linear Scaling

An advancing northward extension of the temperature requirement fulfillment for the fifth instar life-stage is not very distinct for the period 2011-2040, but for both 2041-2070 and 2071-2100 there is a noticeable trend, in general for the three climate scenarios, RCP 2.6, RCP 4.5 and RCP 8.5 (Figure **7**). A trend of earlier temperature requirement fulfillment can also be seen from the early, 2011-2040, to the late time period, 2071-2100, for the three climate scenarios, respectively., but most distinctly so in RCP 8.5 (Appendix Figures **A7** and **A8** for Intermediate and greater temperature requirement individuals, respectively).

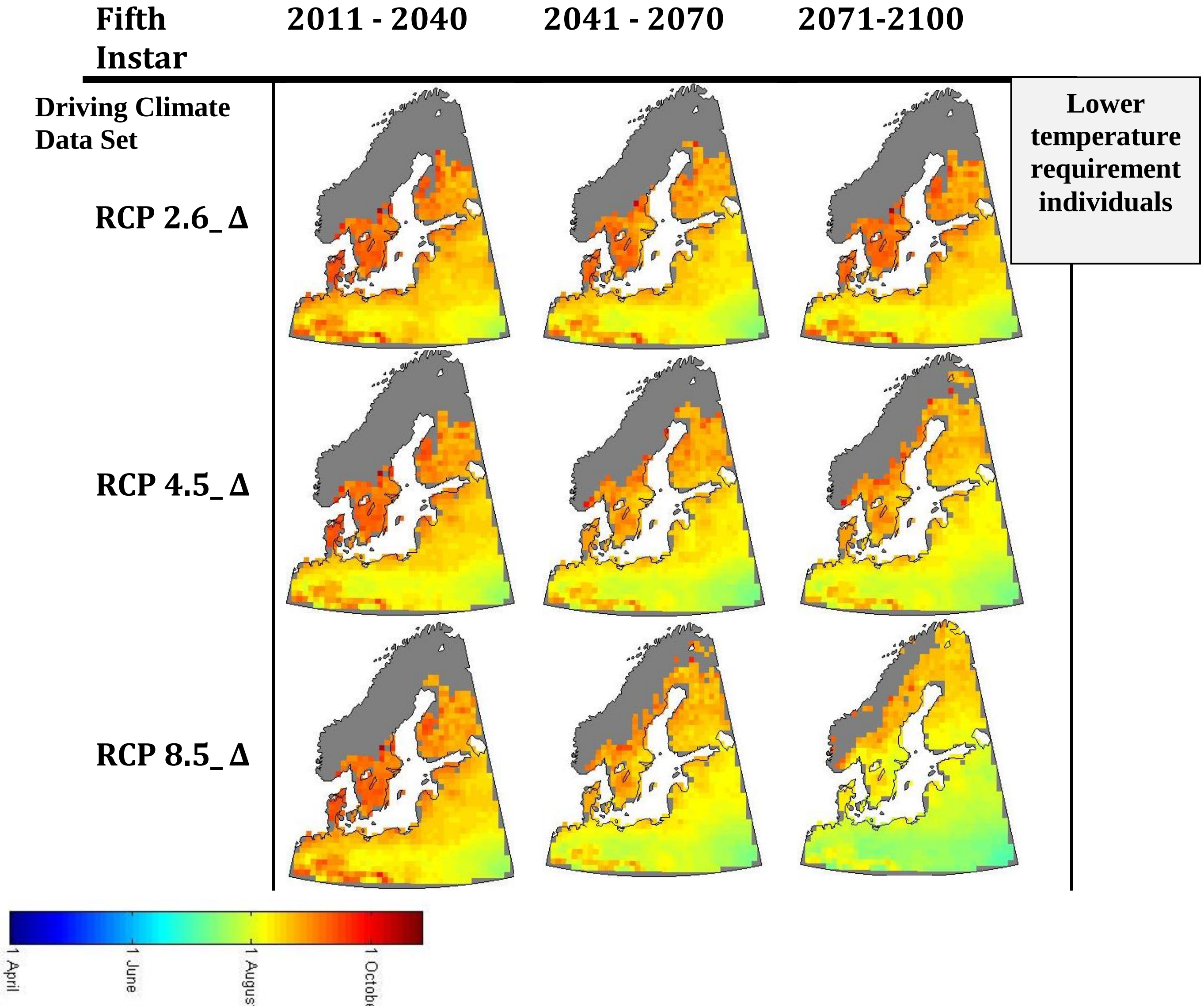


Legend The time of the year when the temperature requirement is fulfilled for the fifth instar life-stage, less temperature sensitive individuals.

Figure 7 The fulfillment of the temperature requirement for lower temperature requirement individuals for the fifth instar life-stage changes over three different 30 year time-periods and RCP_LS model simulations.

4.2.2 Timing, Delta Change

A trend of an advancing northward extension of the temperature requirement fulfillment for the fifth instar life-stage, low temperature requirement individuals, is not very distinct for the period 2011-2040. However, there is a trend of a northward extension and earlier temperature requirement fulfillment from the early, 2011-2040, to 2071-2100, for RCP 4.5_ LS and RCP 8.5_ LS. For RCP 2.6_ LS there is a slight retreat in the northward extension between 2041-2070 and 2071-2100. This is likely because of the nature of the scenario with a radiative forcing peak before the end of the century, which moderately starts to decrease afterwards (Appendix Figure **A9** for greater temperature requirement individuals). Linear scaling and delta change produce relatively similar pattern when it comes to the timing (Figures **7** and **8**).



Legend The time of the year when the temperature requirement for the fifth instar life-stage, less temperature sensitive individuals, is fulfilled.

Figure 8 The fulfillment of the temperature requirement for less temperature sensitive individuals for the fifth instar life-stage changes over three different 30 year time-periods and RCP_ Δ model simulations.

4.2.3 Frequency, Fifth Instar

Frequency is the number of years the individuals with a lower temperature requirement will meet the temperature requirement for the fifth instar life-stage. This means, in other words, the number of years the overwintering requirement is fulfilled (Figure **9**). If the temperature requirement is fulfilled often enough the region can, temperature wise, sustain a permanent population.

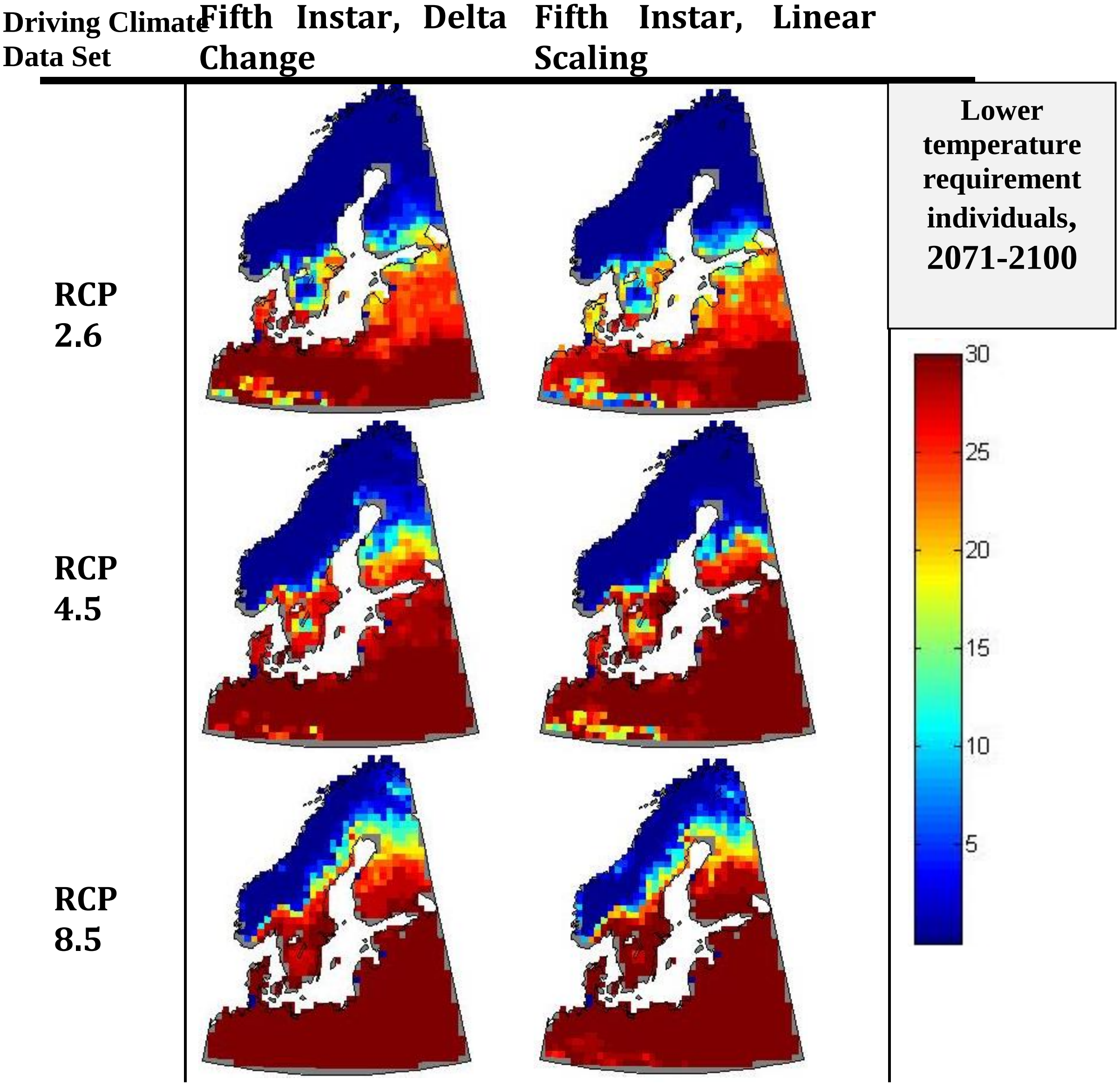


Figure 9 The number of years the temperature requirement for the fifth instar life-stage is fulfilled for the lower temperature requirement individuals during the time-period 2071-2100 for three RCP scenarios and the two bias-correction methods, delta change and linear scaling. See Appendix figures **A3** and **A4** to also see the time-periods 2011-2040 and 2041-2070 for both delta change and linear scaling. And Appendix figure **A5** for linear scaling and greater temperature requirement individuals.

4.3 Stress Days

4.3.1 Overview, Performance Relative to Gridded Observational Data

The distribution of total number of heavy precipitation (>20mm/day) stress days using three different driving climate data, and in three different life-stages which are sensitive to heavy precipitation events (Figure **10**). The overall pattern is relatively similar, E-OBS compared to Eval_LS and Hist_LS; less precipitation over northern Sweden and large parts of Norway, more precipitation along the coast in southern Norway. However, Eval_LS seems to overestimate the number of heavy precipitation events in large parts of Sweden, and both Hist_LS and Eval_LS seem to underestimate the observed coast line effect in southern Norway. Norway is included in the comparison to be able to say more about how the different driving climate data perform compared to the reference driving climate data E-OBS, for heavy precipitation events.

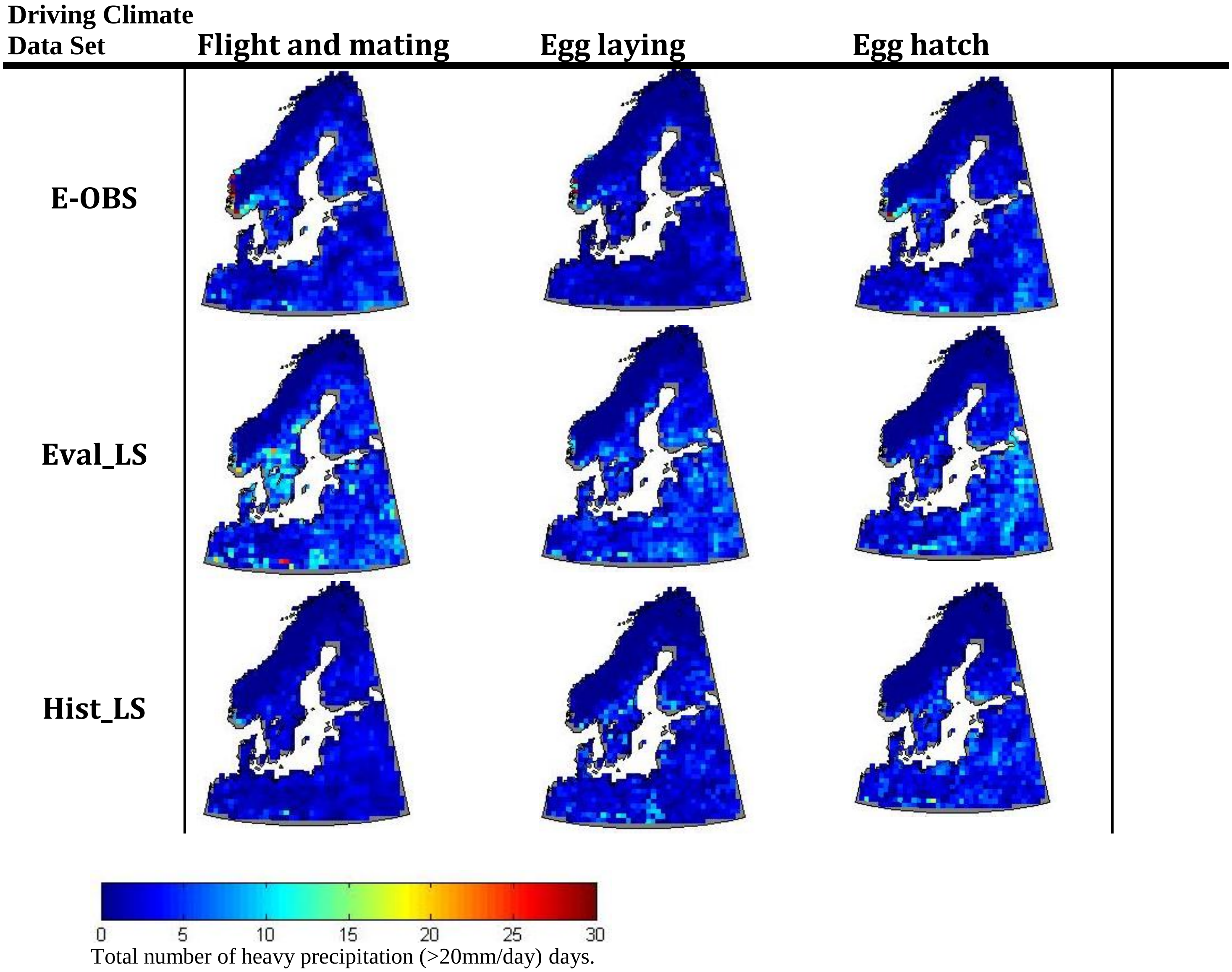


Figure 10 The total number of heavy precipitation days (>20mm/day) that occurred between 1980-2006 given simulations based on E-OBS, Eval_LS, Hist_LS, and three sensitive life-stages, respectively.

4.3.2 Climate Scenarios and the Stress Days Development

A similar pattern, but a noticeable increase in the magnitude, can be seen in the figure for all three sensitive life-stages and RCPs, compared to E-OBS and Hist_LS (Figure **11**). The temporal differences, i.e. differences of the number of heavy precipitation stress days between the three sensitive life-stages, is relatively low in general, but show a distinct increase in magnitude for flight and mating for RCP 8.5_LS.

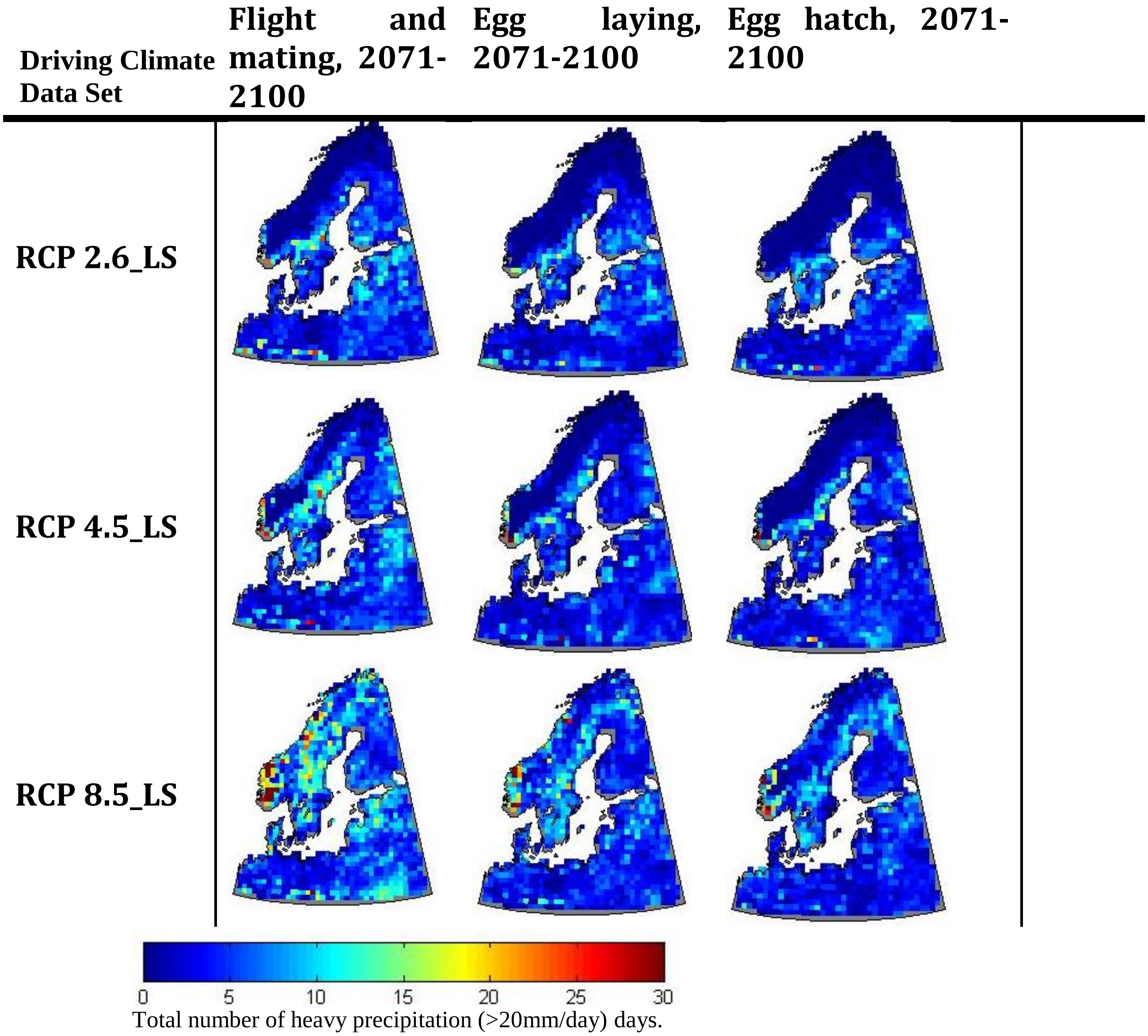


Figure 11 The total number of heavy precipitation days (>20mm/day) that occurred during each of the three 30 year time-periods, RCP scenarios and sensitive stages, respectively.

5. Discussion

This study used bias-corrected climate data to investigate if, and if so when and for what parts of Sweden, the climatic conditions in the future will fulfill the requirements for the fifth instar life-stage. The focus was on the fifth instar which determines if the ECB will be able to over-winter or not, and consequently if it will be able to form a permanent population. What was found was that the climatic conditions by the end of the century, 2071-2100, given RCP 4.5_LS and RCP 8.5_LS will very likely support a permanent ECB population in large parts of southern Sweden.

5.1 Findings – The ECB Population in Sweden in the Future

5.1.1 Permanent Population

The ECB can only reach diapause and winter survival (overwintering) from the fifth instar life-stage which is why that stage is of particular importance and why it was chosen as one of the focus-points in this study. It determines if the ECB population will be able to develop a permanent population or not. The lower temperature requirement individuals will, according to RCP 4.5_LS and RCP 8.5_LS reach the fifth instar life-stage in large parts of Sweden at some point during the period 2071-2100 (Figure 7). To determine if the temperature requirements for a permanent population will be met, the frequency (Figure 9) has to be taken into account as well. The frequency for the time periods 2011-2040 and 2041-2070 for the three RCP scenarios can be seen in Appendix A3 and A4. If the temperature requirement for the fifth life-stage is fulfilled, i.e. for ECB overwintering, enough years in a given time period, ideally all years, the temperature requirements for a permanent population is met. The maps depicting when, in Julian days, the temperature requirement is fulfilled for a certain life-stage gives solely by themselves a skewed impression of the result in the outer parts of the area that meets the requirement. This is because of the dynamic nature of climate with the relatively large inter-annual differences; in the outer parts it might very well be only the extremely warm years that are captured, i.e. if in a given grid cell it is one extremely warm year in a given 30 year time-period which well meets the temperature requirement of a given life-stage, but that the other 29 years does not. Then the mean of the timing of the temperature requirement for that region is in fact the value of one extremely warm year. That further stress the importance of incorporating the frequency in the analysis and conclusion-drawing as well.

It is important to keep the distinction between lower/intermediate and greater temperature requirement individuals and the relation between them since it can be used as an estimate of the natural selection-pressure by the second half of the 21st century. The law of the survival of the fittest which is a term coined by Charles Darwin and Alfred Russel Wallace in 1858, means that the individuals that are more adapted to the local climate and conditions will, due to their advantage, constitute a larger part of the population over time (Claeys, 2000). How large depends on how harsh the local conditions are for the other part of the population; the harsher the more the adapted individuals are favored and the larger the part of the population that will be adapted to the local climate and conditions. This factor was included in this study by simulating lower temperature requirement individuals for the life-stage of particular interest, the fifth instar. These lower temperature requirement individuals are assumed to constitute the part of the population that over time will be, where conditions are harsh enough, favored and thus give an indication of where the conditions are thought to be suitable in the future given different time-periods (2011-2040, 2041-2070 and 2071-2100) and RCP scenarios (2.6_LS, 4.5_LS and 8.5_LS). This can be seen in figure **7**, in combination with appendix figure **A3**.

These results should be combined with the stress days in figure **11** as well. In figure **11** it can be seen that there is a noticeable increase, from E-OBS and Hist_LS in figure **10**, in the number of stress days in sensitive ECB life-stages for the period 2071-2100, for RCP 4.5_LS and RCP 8.5_LS for the upper part of southern Sweden, and middle Sweden. Heavy precipitation stress days can sharply increase the death rate of the ECB and this is thus an important aspect to include on top of the temperature requirement fulfillment. However, even though there is a noticeable future increase in the amount of heavy precipitation stress days compared to E-OBS and Hist_LS in figure **10**, the number of stress days is relatively low for the parts of Sweden affected by a permanent to semi-permanent population according to RCP 4.5_LS and RCP 8.5_LS. The numbers are around 10-15 per sensitive life-stage, in total for the entire 30 year period, 2071-2100. It is an important aspect which can have a marked effect in single years, but, based on the results, probably less so over a longer time-scale.

5.2 Uncertainties and Assumptions

5.2.1 Models

Models are always a simplification of reality, and parameter uncertainty can lead to systematical bias (Smith and Smith, 2007; Refsgaard et al. 2012; Teutschbein and Seibert, 2012). This is thus also the case for climate models, and this difference between e.g. the observed values/trend and the modelled ones is called discrepancy, or bias. There are several bias-correction methods that can be applied (Teutschbein and Seibert, 2012). Teutschbein and Seibert (2012) note that “Bias correction methods are assumed to be stationary, i.e., the correction algorithm and its parameterization for current climate conditions are also valid for future conditions”. The bias-correction was only made for the months May, June, July and August. This was done because of the assumption that the increase in computational cost would not noticeably improve the result in the region of interest, Sweden, since the time of the year when the empirical conditions are met, i.e. when the DD accumulation occurs, is mainly during these four months. With climate change and increasing temperatures – RCP 2.6, RCP 4.5 and RCP 8.5, the period when the DD accumulation occurs will expand. However, it is assumed that the period for DD accumulation will not expand to a degree large enough to have a significant impact on the results.

There is a noticeable northward extension of the area meeting the temperature requirement of the lower temperature requirement individuals’ fifth instar life-stage given RCP 8.5_LS for the period 2071-2100, compared to the reference driving climate data E-OBS, 1980-2006 (Figures 7 and 4, respectively). However, it is important to keep in mind that this is an extension of the area that meets the ECB's empirical requirements, and that it does not take into account the ability for the ECB to migrate in general, or if local conditions dampens or promotes this ability. Nor does it, since it is a phenological model, take into account the interspecific interrelationships that undoubtedly exist between climate/host plants/pests/natural enemies, which is, in part, visually depicted in figure **1** (see also Porter et al. 1991).

The study by Gelman et al (1980) shows that there are regional differences in the response to climatic factors. That said, it makes sense to use empirical values, already evaluated empirical values, from a more southern population due to the limited ECB observations in Sweden. This study looked at the three different temperature level requirements used in Trnka et al. (2007), and focused on the lower temperature requirement individuals with the greatest potential to spread northward.

5.2.2 Linear Response Model and Timing of Sensitive Stages

Another uncertainty may be the use of a linear response model, i.e. constant temperature threshold for each of the stages (Kelker et al. 1990), compared to more statistical models based on regression analysis, or more mechanical models using multiple thresholds. Baker et al. (1984) found that the optimal base temperature varied between 0˚C for egg hatch to the third instar, to 10˚C for mature larval (lower temperature requirement individuals) and pupal stage, for the ECB. However, the use of linear response degree day models have been found to be performing equally as multiple threshold models (Got et al. 1996, cited in Trnka et al. 2007). The expected positive trend for heavy precipitation events in the future for RCP 4.5_LS and RCP 8.5_LS compared to RCP 2.6_LS remain relatively weak. This is likely because the sensitive stages occur, contrary to the expected increase in precipitation, in the warmer half of the year. Another assumption is that of the cold days. In Trnka et al. (2007) it is defined as when the temperature is below 0.2˚C for three consecutive days, while in this study it is defined as when the cumulative temperature, in three day chunks, is below 0.6˚C.

5.2.3 Use of Linear Scaling

The discrepancy between Hist_LS, Hist_Δ, respectively, compared to the reference driving climate data set E-OBS is relatively small for both the lower and greater temperature requirement ECB individuals, when it comes to both the timing, in Julian Days, of the fulfillment of the temperature requirement, and the frequency (Figures 4, 5 and 9). Hist and Eval compare different things. Eval shows how well the RCM performs compared to E-OBS, and Hist shows how well the GCM and RCM performs in combination with each other compared to E-OBS. Hist_LS, the GCM and RCM in combination, visually captures the precipitation pattern relatively well, while underestimating the magnitude in small parts of the precipitation rich coastal area of southern Norway (Figure 10 and 11). This might very well be due to the model underestimating the precipitation in that area in general, but since, even after the bias-correction, there is a discrepancy in temperature between E-OBS and Hist_LS, the timing of the different sensitive stages do not match. This in turn complicates the comparison of how well Hist_LS represents the stochastic and complex nature of precipitation events.

Capturing the precipitation pattern relatively well is an argument for using linear scaling; the quality of the RCM seems to perform relatively well, and thus be inside what is deemed to be ‘good enough’ (section 2.1.3 for more details) Another argument for using linear scaling is that the delta change method is perturbations of observational data, while linear scaling used modelled data as the baseline. This gives rise to the fact that linear scaling captures possible changes in extreme event patterns in the future. Further on it also takes into account possible complex changes in the climate system such as changes in the circulation pattern; something which the delta change method, having the observed time-series as a baseline, misses (Lenderink et al. 2007).

5.3 Implications of Findings

The findings indicate that it is very likely that a permanent to semi-permanent population of the ECB will be present in southern Sweden by 2071-2100 given RCP 4.5_LS and RCP 8.5_LS, due to the proximity to central/central-northern Europe, and by this region of Sweden being relatively rich in agricultural fields and thus providing ‘green bridges’ – i.e. a momentary host and/or overwintering site between the temporal and/or spatial gap existing between hosts (Porter et al. 1991). Furthermore, a relatively large part of Sweden fulfills the requirement in at least some years by 2071-2100 given RCP 8.5_LS. A dedicated surveillance system should be implemented in both of those regions to increase the chance of spotting ECB infested sites early, and by so limit the economic loss. Southern Sweden, which will likely be affected by a permanent population, should on top of that make sure there are strategic damage-preventive and damage-limiting plans in place, readily accessible to all possibly affected farmers.

5.4 Further Research

Ideally one would also make a comparison between the different institutions’ models and how these seem to perform relative to each other, and to get an idea as to how robust they are, as well as to use ensemble simulations. Two examples of different ensemble simulation methods available are a) multi-model ensembles using a combined ensemble from different institutions’ models, and b) perturbed-parameter ensembles where instead one model is used but ensembles of the parameters used in it are created, which asses the relative importance of different parameters for the uncertainty for that model. The different methods have different pros and cons, and both are used in IPCC’s fifth assessment report, and both would ideally be used in combination with several statistical evaluation methods as support (Flato et al. 2013). Another step to improve the model would be to add reproduction success, emigration, immigration, mortality and countermeasures, to turn it into a population model. A population model where noticeably more attention should be spent on capturing and incorporating the effect of, and changes in, extreme events.

Even though precipitation seems to be captured relatively well, it should ideally be bias-corrected as well. This is something for continuous research in this area; to get a more robust result for the stress days, it is important to bias-correct also the precipitation, even though the timing of the fulfillment of the sensitive stages is probably more important for the stress days, than the precipitation bias. As noted earlier, if the timing of the fulfillment of different stages is skewed (in Julian days), the precipitation is checked against the wrong time. The stress days offer valuable additional information which can further serve to explain discrepancies between the modelled and observed results, though at the moment observations do not exist, as well as to make easier comparisons across time and space.

6. Conclusions

It is very likely that the spread and timing of an overwintering ECB population, i.e. the fifth life-stage, will change throughout the century to such an extent that a permanent ECB population will be supported in large parts of southern Sweden, given RCP 4.5_LS and RCP 8.5_LS, by 2071-2100, temperature wise. Furthermore, the findings support the hypothesis that the region meeting the temperature requirements of an overwintering ECB population will expand northwards given RCP 2.6_LS, RCP 4.5_LS and RCP 8.5_LS, throughout the century. This highlights the need for further research in this area; to improve the method used in this study, to expand it into a population model which includes reproduction, emigration, immigration, mortality and countermeasures as well. It also further stresses the need to include the ECB when planning future agricultural development in Sweden, as well as for e.g. affected governmental units and stakeholders to start discussing possible issues, direct and indirect, a permanent / semi-permanent ECB population may give rise to, as e.g. the view on GM crops, i.e. Bt corn.

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Appendix

Bias-Correction: Delta Change

Table A1 The bias-correction for delta change, in absolute numbers, and three different 30 year time periods, for May, RCP 2.6 and minimum and mean temperature. The std included as well for each of the time periods.

May	Mean Temperature		Minimum Temperature	
RCP 2.6	*56°N / 13°E*	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Delta Change 2011-2040	0.52	0.56	0.50	0.52
std	1.77	1.69	1.82	1.83
Delta Change 2041-2070	1.22	1.25	1.40	1.38
std	1.32	1.26	1.29	1.25
Delta Change 2071-2100	1.08	1.11	1.17	1.14
std	1.48	1.37	1.36	1.31

Table A2 The bias-correction for delta change, in absolute numbers, and three different 30 year time periods, for June, RCP 2.6 and minimum and mean temperature. The std included as well for each of the time periods.

June	Mean Temperature		Minimum Temperature	
RCP 2.6	*56°N / 13°E*	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Delta Change 2011-2040	1.00	1.02	1.13	1.10
std	1.19	1.10	1.04	1.02
Delta Change 2041-2070	1.47	1.48	1.58	1.59
std	1.38	1.25	1.28	1.25
Delta Change 2071-2100	1.55	1.55	1.63	1.63
std	1.31	1.22	1.04	1.01

Table A3 The bias-correction for delta change, in absolute numbers, and three different 30 year time periods, for July, RCP 2.6 and minimum and mean temperature. The std included as well for each of the time periods.

July	Mean Temperature		Minimum Temperature	
RCP 2.6	*56°N / 13°E*	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Delta Change 2011-2040	1.20	1.22	1.12	1.03
std	1.42	1.31	1.29	1.23
Delta Change 2041-2070	1.54	1.55	1.52	1.50
std	1.75	1.59	1.15	1.11
Delta Change 2071-2100	1.41	1.42	1.17	1.18
std	1.70	1.57	1.45	1.39

Table A4 The bias-correction for delta change, in absolute numbers, and three different 30 year time periods, for August, RCP 2.6 and minimum and mean temperature. The std included as well for each of the time periods.

August	**Mean Temperature**		**Minimum Temperature**	
RCP 2.6	*56°N / 13°E*	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Delta Change 2011-2040	1.29	1.30	1.12	1.15
std	1.49	1.40	1.38	1.33
Delta Change 2041-2070	1.79	1.76	1.64	1.62
std	1.39	1.31	1.02	0.99
Delta Change 2071-2100	1.64	1.61	1.48	1.48
std	1.77	1.70	1.37	1.26

Table A5 The bias-correction for delta change, in absolute numbers, and three different 30 year time periods, for May, RCP 4.5 and minimum and mean temperature. The std included as well for each of the time periods.

May	**Mean Temperature**		**Minimum Temperature**	
RCP 4.5	*56°N / 13°E*	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Delta Change 2011-2040	0.95	0.98	0.97	1.00
std	1.32	1.31	1.15	1.17
Delta Change 2041-2070	1.45	1.47	1.47	1.47
std	1.48	1.39	1.60	1.52
Delta Change 2071-2100	1.71	1.83	1.85	1.93
std	1.58	1.52	1.74	1.78

Table A6 The bias-correction for delta change, in absolute numbers, and three different 30 year time periods, for June, RCP 4.5 and minimum and mean temperature. The std included as well for each of the time periods.

June	**Mean Temperature**		**Minimum Temperature**	
RCP 4.5	*56°N / 13°E*	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Delta Change 2011-2040	1.01	1.05	1.17	1.23
std	1.34	1.23	1.17	1.09
Delta Change 2041-2070	1.74	1.75	1.86	1.86
std	1.14	1.07	1.08	1.09
Delta Change 2071-2100	2.30	2.32	2.38	2.41
std	1.46	1.34	1.03	0.91

Table A7 The bias-correction for delta change, in absolute numbers, and three different 30 year time periods, for July, RCP 4.5 and minimum and mean temperature. The std included as well for each of the time periods.

July	**Mean Temperature**		**Minimum Temperature**	
RCP 4.5	*56°N / 13°E*	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Delta Change 2011-2040	1.50	1.48	1.30	1.24
std	1.90	1.76	1.36	1.31
Delta Change 2041-2070	1.95	1.96	1.71	1.70
std	1.70	1.56	1.28	1.20
Delta Change 2071-2100	2.30	2.31	2.32	2.27
std	1.71	1.60	1.42	1.40

Table A8 The bias-correction for delta change, in absolute numbers, and three different 30 year time periods, for August, RCP 4.5 and minimum and mean temperature. The std included as well for each of the time periods.

August	**Mean Temperature**		**Minimum Temperature**	
RCP 4.5	*56°N / 13°E*	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Delta Change 2011-2040	1.31	1.32	1.21	1.25
std	1.04	0.96	0.93	0.91
Delta Change 2041-2070	1.86	1.84	1.83	1.83
std	1.37	1.29	1.08	1.05
Delta Change 2071-2100	2.54	2.52	2.25	2.24
std	1.42	1.35	1.05	1.00

Table A9 The bias-correction for delta change, in absolute numbers, and three different 30 year time periods, for May, RCP 8.5 and minimum and mean temperature. The std included as well for each of the time periods.

May	**Mean Temperature**		**Minimum Temperature**	
RCP 8.5	*56°N / 13°E*	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Delta Change 2011-2040	0.99	1.05	1.27	1.28
std	1.50	1.43	1.62	1.63
Delta Change 2041-2070	1.80	1.90	2.23	2.28
std	1.42	1.35	1.52	1.50
Delta Change 2071-2100	2.98	3.09	3.46	3.47
std	1.39	1.32	1.46	1.48

Table A10 The bias-correction for delta change, in absolute numbers, and three different 30 year time periods, for June, RCP 8.5 and minimum and mean temperature. The std included as well for each of the time periods.

June	Mean Temperature		Minimum Temperature	
RCP 8.5	*56°N / 13°E*	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Delta Change 2011-2040	1.14	1.20	1.40	1.46
std	1.06	1.02	1.00	1.04
Delta Change 2041-2070	2.47	2.51	2.70	2.78
std	1.52	1.41	1.14	1.12
Delta Change 2071-2100	3.47	3.57	3.76	3.84
std	1.23	1.16	1.08	1.05

Table A11 The bias-correction for delta change, in absolute numbers, and three different 30 year time periods, for July, RCP 8.5 and minimum and mean temperature. The std included as well for each of the time periods.

July	Mean Temperature		Minimum Temperature	
RCP 8.5	*56°N / 13°E*	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Delta Change 2011-2040	1.08	1.13	1.32	1.34
std	1.41	1.28	1.18	1.10
Delta Change 2041-2070	2.19	2.23	2.31	2.29
std	1.63	1.52	1.14	1.09
Delta Change 2071-2100	3.67	3.68	3.68	3.65
std	1.82	1.68	1.55	1.51

Table A12 The bias-correction for delta change, in absolute numbers, and three different 30 year time periods, for August, RCP 8.5 and minimum and mean temperature. The std included as well for each of the time periods.

August	Mean Temperature		Minimum Temperature	
RCP 8.5	*56°N / 13°E*	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Delta Change 2011-2040	1.47	1.46	1.48	1.47
std	1.55	1.48	1.13	1.10
Delta Change 2041-2070	2.48	2.45	2.29	2.35
std	1.43	1.36	1.19	1.17
Delta Change 2071-2100	4.18	4.14	3.98	3.99
std	1.60	1.52	1.20	1.17

Bias-Correction: Linear Scaling

Table A13 The bias-correction for linear scaling, in absolute numbers, for May and minimum and mean temperature. The std included as well.

May	**Mean Temperature**		**Minimum Temperature**	
	56°N / 13°E	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Linear Scaling	1.55	1.05	1.05	0.43
std	1.48	1.39	1.29	1.22

Table A14 The bias-correction for linear scaling, in absolute numbers, for June and minimum and mean temperature. The std included as well.

June	**Mean Temperature**		**Minimum Temperature**	
	56°N / 13°E	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Linear Scaling	2.79	2.45	2.02	1.51
std	1.49	1.44	1.12	1.16

Table A15 The bias-correction for linear scaling, in absolute numbers, for July and minimum and mean temperature. The std included as well.

July	**Mean Temperature**		**Minimum Temperature**	
	56°N / 13°E	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Linear Scaling	1.88	1.63	1.35	0.84
std	1.66	1.58	1.34	1.40

Table A16 The bias-correction for linear scaling, in absolute numbers, for August and minimum and mean temperature. The std included as well.

August	**Mean Temperature**		**Minimum Temperature**	
	56°N / 13°E	*56°N / 14°E*	*56°N / 13°E*	*56°N / 14°E*
Linear Scaling	1.78	1.44	0.94	0.48
std	1.58	1.55	1.13	1.16

Timing: Fifth Instar, Southern Sweden

The three different climate scenarios, RCP 2.6 (blue), RCP 4.5 (black) and RCP 8.5 (red), show a similar pattern for two grid cells in southern Sweden. As expected, the driving climate data RCP 2.6 with the lowest radiative forcing increase gives the longest time to reach the temperature requirement for the fifth instar, while RCP 8.5, with the greatest radiative forcing, gives the shortest time (Figures A1 and A2).

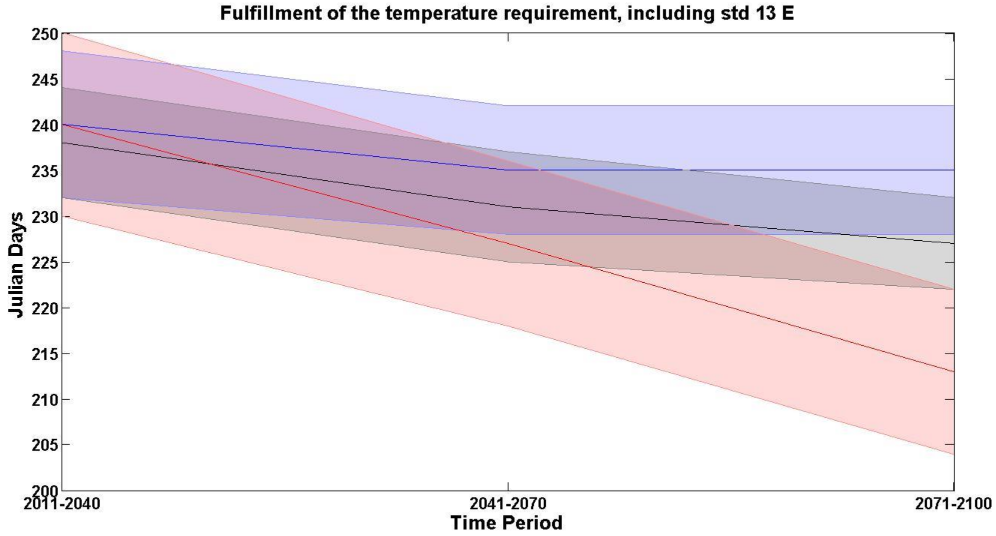


Figure A1 Three different 30 year time periods and three different climate scenarios, RCP 2.6 (blue), RCP 4.5 (black) and RCP 8.5 (red) together with shaded std, in respective colors; lower temperature requirement individuals.

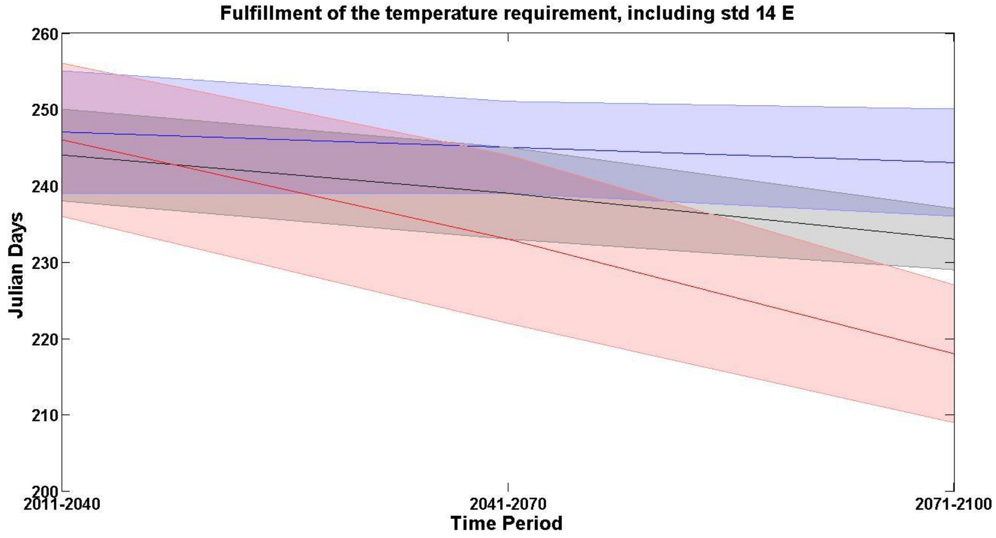


Figure A2 Three different 30 year time periods and three different climate scenarios, RCP 2.6 (blue), RCP 4.5 (black) and RCP 8.5 (red) together with shaded std, in respective colors; lower temperature requirement individuals.

Frequency: Fifth Instar Life-stage

The frequency, the number of years the fifth instar is reached in a given 30 year period, increase with increased radiative forcing, i.e. from RCP 2.6 to RCP 4.5 and further on to RCP 8.5 (Figure A3). The decrease in frequency in the period 2071-2100 compared to 2041-2070 for RCP 2.6 is due to how that scenario works. It reaches its radiative forcing maximum before 2100 and then starts to gradually decline.

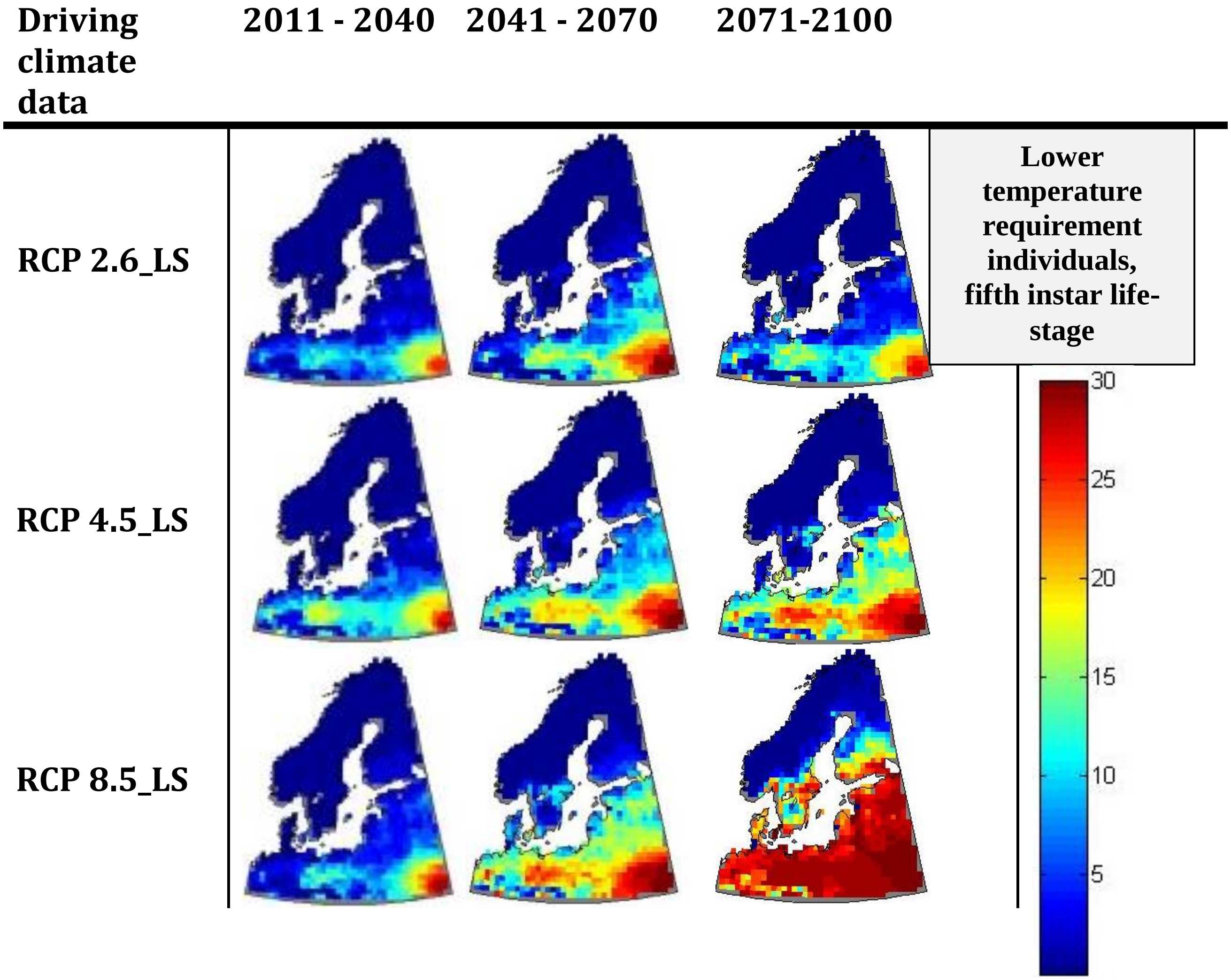


Figure A3 The number of years the temperature requirement for the fifth instar life-stage is fulfilled for the lower temperature requirement individuals during the time-periods 2011-2040, 2041-2070 and 2071-2100, given linear scaling bias-correction.

The frequency increase with increased radiative forcing, i.e. from RCP 2.6 to RCP 4.5 and further on to RCP 8.5 (Figure A4).

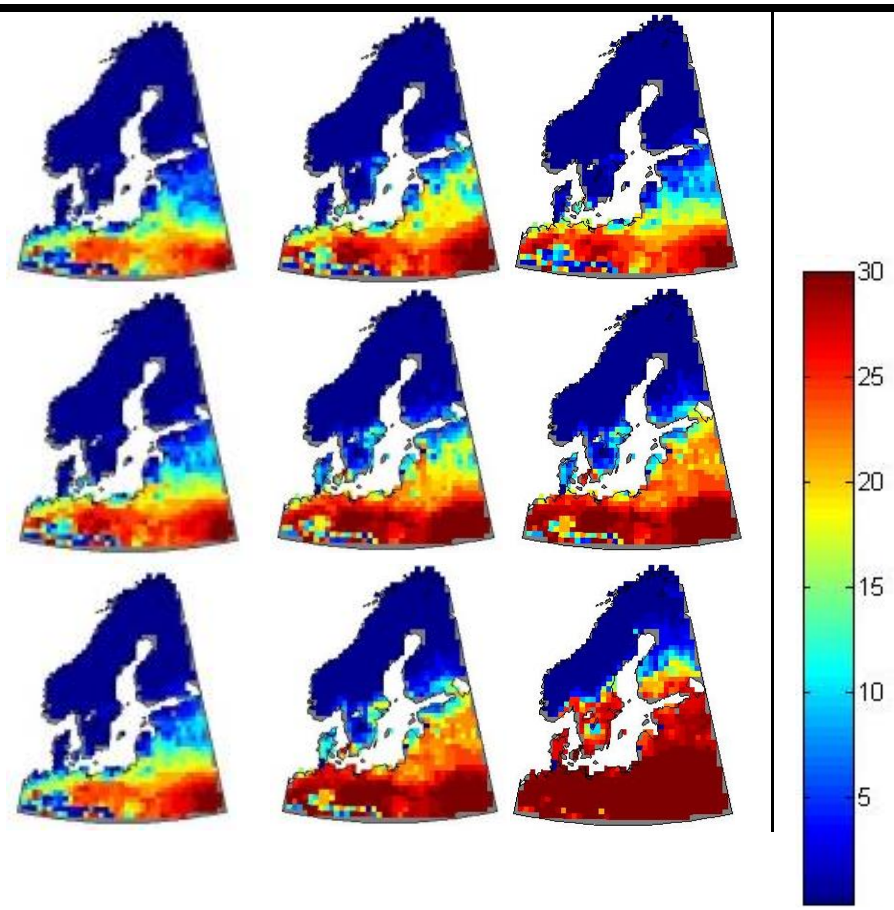


Figure A4 The number of years the temperature requirement for the fifth instar life-stage is fulfilled for the lower temperature requirement individuals during the time-periods 2011-2040, 2041-2070 and 2071-2100, given delta change bias-correction.

The number of years the greater temperature requirement individuals will meet the temperature requirement for the fifth instar life-stage means, in other words, the number of years the greater temperature requirement individuals' overwintering requirement is fulfilled (Figure A5). If the temperature requirement is fulfilled often enough the area can, temperature wise, sustain a permanent population.

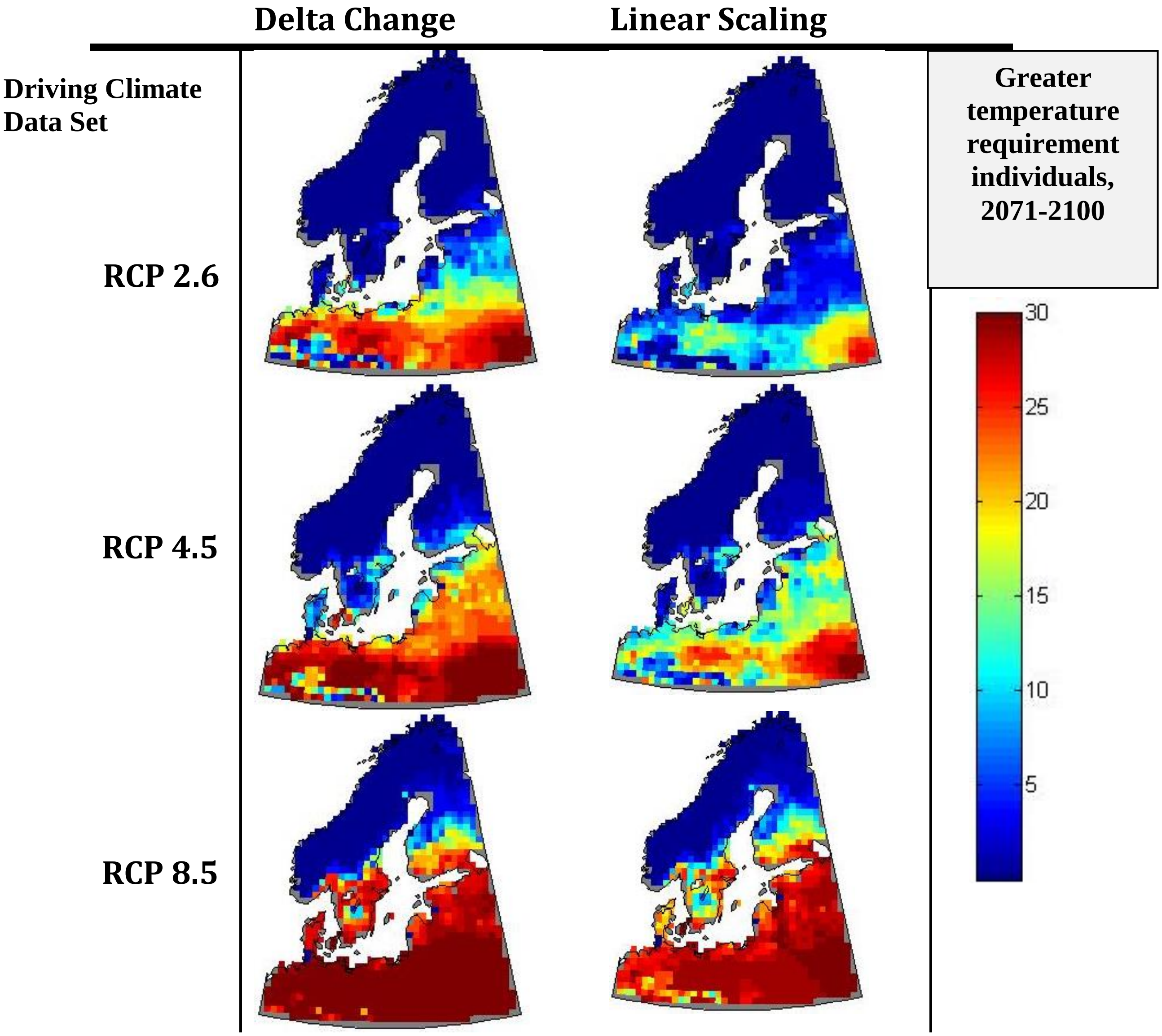


Figure A5 The number of years the temperature requirement for the fifth instar life-stage is fulfilled for the greater temperature requirement individuals during the time-period 2071-2100 for three different RCP scenarios and the two bias-correction methods, delta change and linear scaling.

Standard deviation (std): Fifth Instar Life-stage

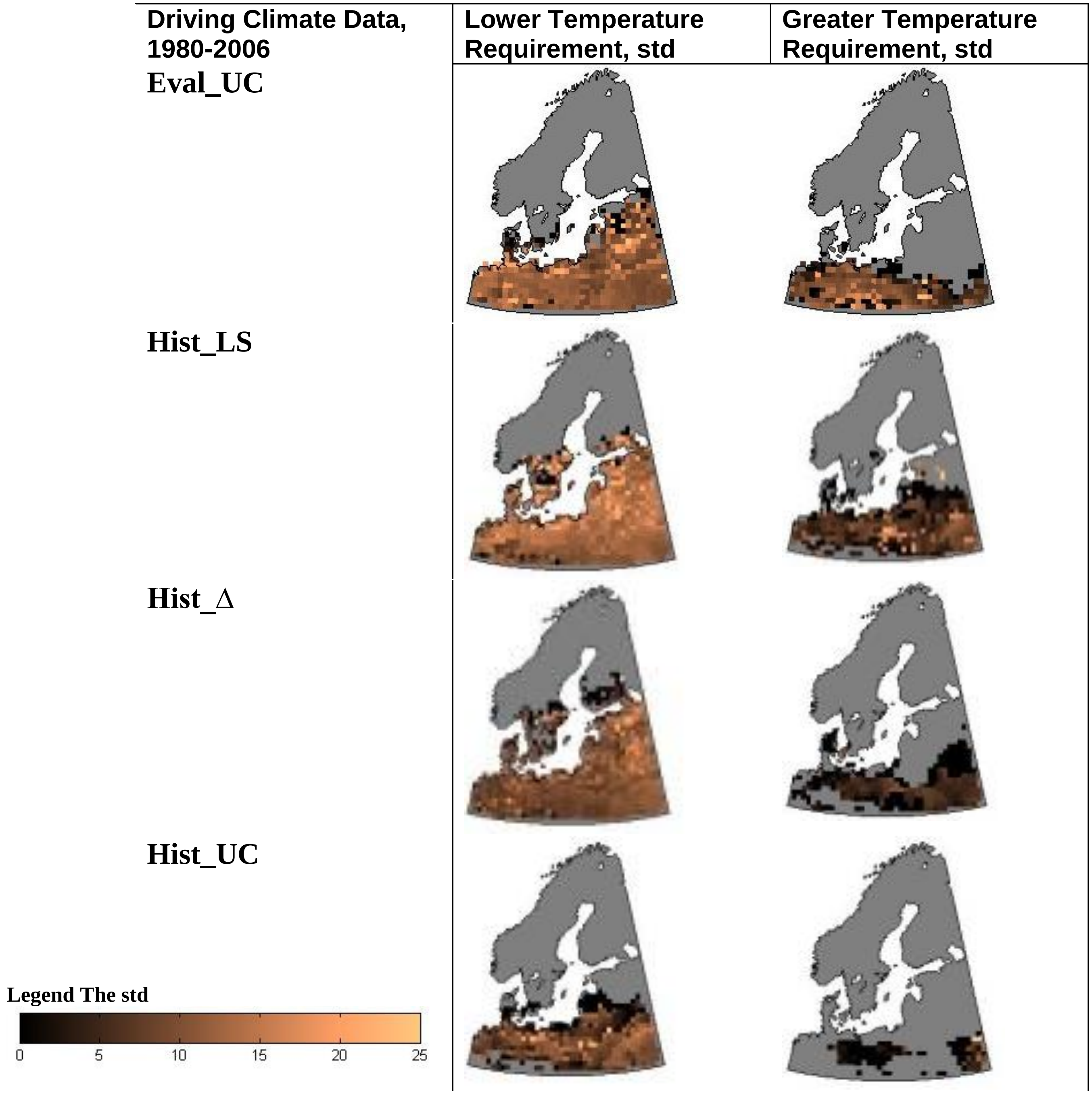
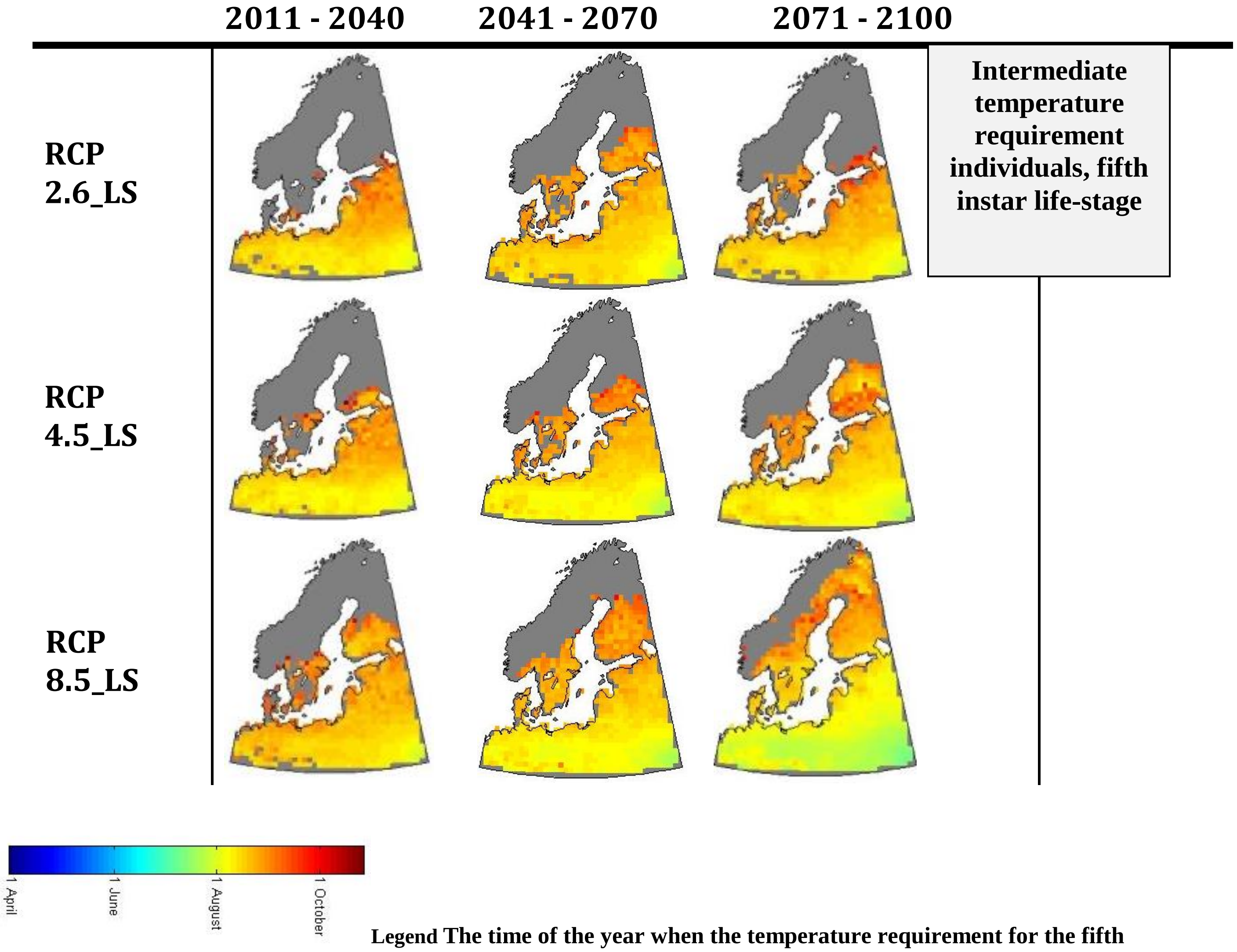


Figure A6 Depicts the standard deviation (std) for the period 1980-2006 for four different driving climate data, including uncorrected and two different bias-correction methods, for the lower temperature requirement and greater temperature requirement individuals.

Timing: Fifth Instar, Different Methods, Different Individuals

Linear Scaling, Intermediate Temperature Requirement

A trend of an advancing northward extension of the temperature requirement fulfillment for the intermediate temperature sensitive individuals can be seen moving from RCP 2.6_LS to RCP 8.5_ LS (Figure A7). An emerging trend of a northward extension and earlier temperature requirement fulfillment can also be seen from the early, 2011-2041, to the late time period, 2071-2100, for RCP 4.5_ LS and RCP 8.5_ LS. For RCP 2.6_ LS there is a slight retreat in the northward extension between 2041-2070 and 2071-2100. This is likely because of the nature of the scenario with a radiative forcing peak before the end of the century, which moderately starts to decrease afterwards.

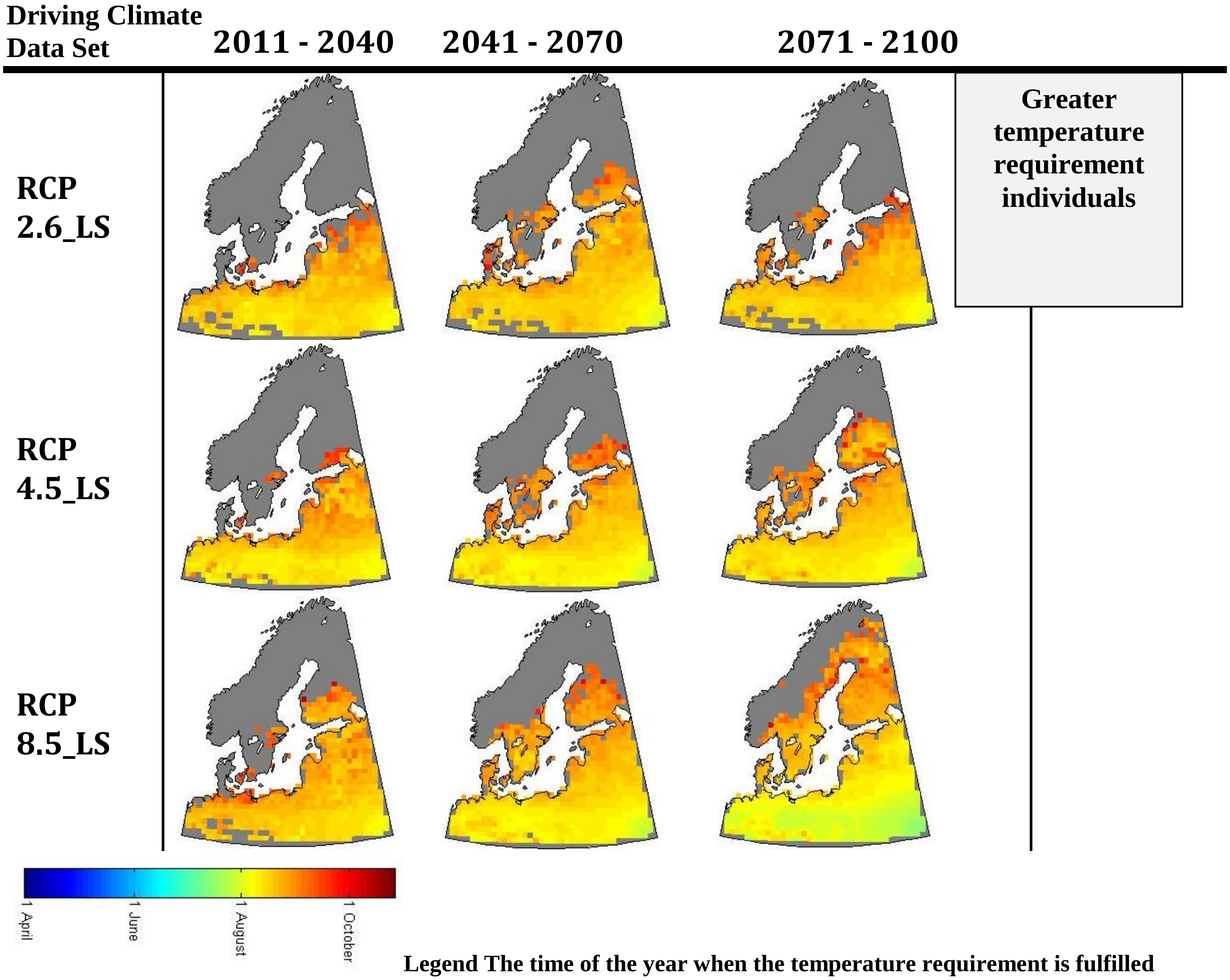


Legend The time of the year when the temperature requirement for the fifth instar life-stage is fulfilled, for intermediate temperature requirement individuals.

Figure A7 The fulfillment of the temperature requirement for intermediate temperature sensitive individuals for the fifth instar life-stage changes over three different 30 year time-periods and RCP_ LS model simulations.

Linear Scaling, Greater Temperature Requirement

A trend of an advancing northward extension of the temperature requirement fulfillment can be seen moving from RCP 2.6_ LS to RCP 8.5_ LS (Figure **A8**). An emerging trend of a northward extension and earlier temperature requirement fulfillment can also be seen from the early, 2011-2041, to the late time period, 2071-2100, for RCP 4.5_ LS and RCP 8.5_ LS. For RCP 2.6_ LS there is a slight retreat in the northward extension between 2041-2070 and 2071-2100. This is likely because of the nature of the scenario with a radiative forcing peak before the end of the century, which moderately starts to decrease afterwards.

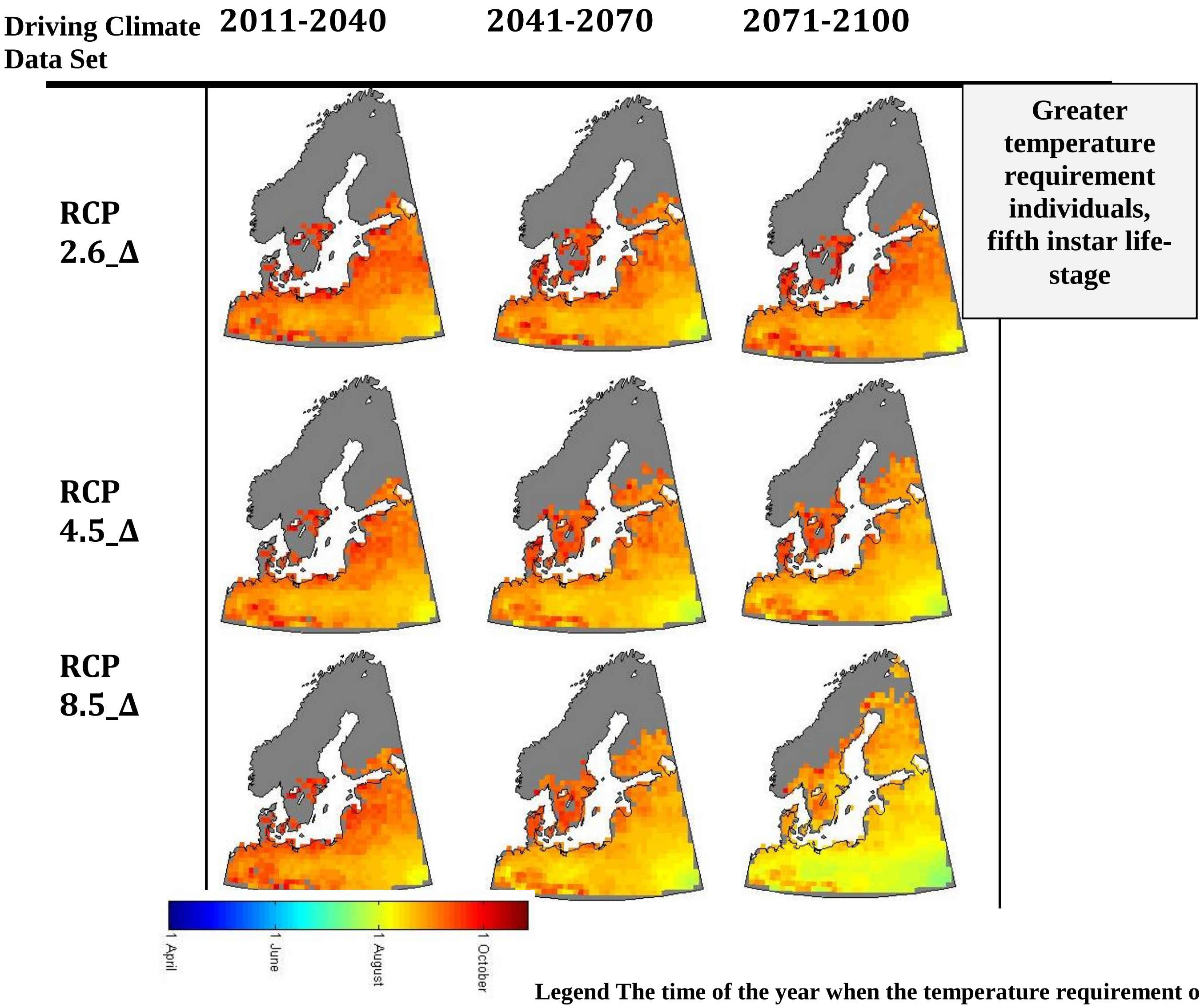


Legend The time of the year when the temperature requirement is fulfilled for the fifth instar life-stage, greater temperature requirement individuals.

Figure A8 The fulfillment of the temperature requirement for the greater temperature requirement individuals for the fifth instar life-stage changes over three different 30 year time-periods and RCP_ LS model simulations.

Delta Change, Greater Temperature Requirement

A trend of an advancing northward extension of the temperature requirement fulfillment can be seen moving from RCP 2.6_Δ to RCP 8.5_Δ, for the periods 2041-2070 and 2071-2100 (Figure A9). For the time-period 2011-2040 the visual change is relatively small for all the three RCP scenarios. An emerging trend of a northward extension and earlier temperature requirement fulfillment can also be seen from the early, 2011-2041, to the late time period, 2071-2100, for RCP 4.5_Δ and RCP 8.5_Δ; albeit relatively slight for RCP 4.5_Δ. For RCP 2.6_Δ there is a slight retreat in the northward extension between 2041-2070 and 2071-2100. This is likely because of the nature of the scenario with a radiative forcing peak before the end of the century, which moderately starts to decrease afterwards.



Legend The time of the year when the temperature requirement of the fifth instar life-stage is fulfilled, for the greater temperature requirement individuals.

Figure A9 The fulfillment of the temperature requirement for the greater temperature requirement individuals for

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