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Urban trees under climate change

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Urban trees under climate change

Potential impacts of dry spells and heat waves in three German regions in the 2050s

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Content

Abstract

Urban parks provide considerable benefits to cities and its inhabitants by improving microclimatic conditions and providing shade as well as recreational and aesthetic value. Trees – essential components of parks and the cityscape of many German cities – have their greatest benefits if they are healthy and vital. Yet, it is a fact that growing conditions are more challenging in cities than in the open landscape. Among other factors, this is due to altered microclimatic conditions, excess heat, pollution, limited water availability, salt contamination, and poor soil quality. In order to grow healthily, trees need to be sufficiently adapted to these stresses. On top of that, climate change impacts may increase heat and drought stresses for urban trees, to which some species are possibly not adapted.

First of all, this work aims to analyse these potential climate change impacts in three climatically distinct German regions in the 2050s (i.e. 2036-2065) using regional climate projections of the EURO-CORDEX ensemble. Increases in the number of hot days and heat waves during growing season in the 2050s compared to the reference period (1971-2000) are projected for all regions. Yet, for all other analysed climate indices, especially those based on precipitation, the ensemble results are rather ambiguous and comprise a broader bandwidth of possible developments for the future. Concerning tree species selection this means that practitioners should be prepared for a range of possible changes.

Secondly, ten broadleaf tree species were chosen based on a field mapping of an urban park in Lower Saxony. This work aims at analysing their future suitability under climate change in the three regions with a focus on drought and heat tolerance. During the general assessment of the species' tolerances, a range of existing tolerance classification systems which were compared and compiled into a consolidated classification scheme. The ten selected species were subsequently classified according to their respective drought tolerance or sensitivity, using the four classes 'very tolerant' (*B. pendula*), 'moderately tolerant' (*A. platanoides, F. excelsior, Q. robur*), 'moderately sensitive' (*A. hippocastanum, A. pseudoplatanus, F. sylvatica*) and 'very sensitive' (*A. glutinosa, P. nigra, S. alba*). Concerning heat tolerance, the same classification was compiled with the following results: 'very tolerant' (*B. pendula, F. excelsior*), 'moderately tolerant' (*A. hippocastanum, A. platanoides, Q. robur*), and 'moderately sensitive' (*A. pseudoplatanus, F. sylvatica*). Due to insufficient information, no assessment of heat tolerance was possible for *A. glutinosa, P. nigra,* and *S. alba*.

It is particularly noticeable that drought tolerant species tend to be more heat tolerant as well, while rather drought sensitive species likewise appear to be rather sensitive to heat. Nevertheless, tolerance and sensitivity strongly depend on local conditions and can vary between different provenances or even between individuals. Projected bandwidths of climatic changes combined with vague information on stress tolerances complicate generally valid ratings of future tree species suitability. Definite recommendations for or against the selected species for the specific case study regions are therefore currently not possible. Even so, a focussing on 'very tolerant' or at least 'moderately tolerant' species and refraining from 'moderately sensitive' or even 'very sensitive' species is advisable. Since many local factors influence tree vitality, suitability assessments should be made on a case-by-case basis and implementation should ideally be supported by a long-term monitoring process. The general classification presented here provides a basis for a further evaluation.

1. Introduction

1.1. Context

Future climate change impacts can no longer be ignored. Adequate adaptation to the expected changes is therefore needed in virtually all areas of our life (Noble et al. 2014). The IPCC AR5 defines adaptation as a "*process of adjustment to actual or expected climate change and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effect*." (Agard et al. 2014: 1759). Given that cities are home to an increasingly large share of the world's population and form centres of the economy, adaptation will gain particular importance in urban areas (EEA 2012a). Today, three quarter of the population in Europe inhabit urban areas and will be confronted with diverse climatic impacts (World Bank 2014, EEA 2012a). With 75 % urban population in 2013, this development can also be seen in Germany (World Bank 2014). As the urbanisation trend is ongoing, an even larger share of the population will be living in cities in the future.

Germany consists of climatically distinct regions from a more maritime Northwest to a more continental Southeast. The large-scale climate is additionally modified by topography (DWD 2015a, Schuchardt et al. 2008). As Umweltbundesamt (2015) and Jacob et al. (2014) have shown, projected climate changes in Germany are regionally and seasonally diverse. Therefore, general statements on expected changes for the entire country are only possible with limitations. In summary, it can be said that concerning mean air temperature (annual and seasonal summer/winter values) increasing trends are projected for the whole country, yet, regional and seasonal differences in magnitude of change exist. Moreover, hot days and tropical nights are generally projected to become more frequent. Projected changes in precipitation are even more spatially and temporally heterogeneous including trends in both directions depending on the region and considered time frame (annual or seasonal summer/winter values). Summer dry spells are projected to increase throughout Germany with spatial differences in the magnitude of change (Umweltbundesamt 2015). Due to the possible combination of dry spells and heat waves, an increased risk of drought conditions in summer is expected (European Commission 2009).

Compared to the rural surrounding, urban climate is characterised by higher ambient air temperatures, known as urban heat island effect, lower relative humidity, reduced wind speed, as well as increased air pollution (Doick & Hutchings 2013, Kleerekoper et al. 2012, Heidt & Neef 2008, Kuttler 2008, Oke 1988). Problems arise because high temperatures and air pollution are known to negatively affect public health and human well-being (Kleerekoper et al. 2012, Mavrogianni et al. 2011, Matzarakis & Amelung 2008). The microclimatic conditions in urban areas, which are already stressful today, are expected to worsen further under future climate change impacts (Gill et al. 2014). In addition to a growing percentage of people living in urban areas, demographic changes result in an increased share of elderly population, which are particularly vulnerable to heat waves. Adaptation to future conditions is therefore urgently necessary to provide healthy living conditions in cities (EEA 2012a). One possibility is the use of urban green infrastructure, which includes parks, green spaces, gardens, green roofs or walls as well as vegetation alongside streets (Demuzere et al. 2014, Gill et al. 2014, Wittig et al. 2014, EEA 2012a). It is widely recognized in literature that vegetation can improve the urban microclimate by diminishing the overheating of urban areas and by lowering air pollution (Demuzere et al. 2014, Doick & Hutchings 2013, Kleerekoper et al. 2012). Urban green therefore represents one adaptation option to the impacts of climate change.

Healthy vegetation has the highest economic, social and microclimatic benefit (Gillner et al. 2014). For this reason, well adapted tree species generally entail larger benefits than species which cannot cope with the urban environment and can therefore not develop to their full potential (Gillner et al. 2013). In theory, adequate management practices of green spaces, integrated urban planning and careful selection of species are therefore needed for effective implementation of climate change adaptation measures. Generally, trees in an urban environment already face harsher conditions than forest trees due to soil compaction, reduced water availability, altered microclimatic conditions and wind patterns, limited root space, mechanical damage, and salt contamination (Gillner et al. 2014). Even though overall park trees experience more favourable conditions than trees alongside streets or in containers, they still have to cope with more challenging conditions than trees in a natural environment (Sæbø et al. 2005). Since drier summer conditions and higher temperatures are expected under climate change, further challenges arise for already stressed urban trees (Roloff et al. 2009).

At the same time, other factors in urban green planning are of great importance, e.g. selecting trees with high aesthetic value or using a sufficiently high number of different species to avoid monocultures, which are more prone to pest infestations and diseases (Roloff 2013a). However, further influencing factors or restrictions have to be faced in practice when establishing or managing urban green, e.g. monetary constraints, plant availability, maintenance requirements, specifications by associations or public authorities, and inclusion of local traditions or personal preferences (Chen & Jim 2008, Ottitsch & Krott 2005). Owing to climate change, practitioners will face an additional challenge of increasing importance besides the existing considerations: the selection of tree species for urban parks that are most suitable in the future, taking into account regional and local climatic conditions. Accordingly, this thesis investigates two major aspects that are important for species selection: the analysis of future climate change conditions as projected by an ensemble of regional climate models, as well as the tolerance of selected tree species to heat and drought stress.

1.2. Research aim

In this study, three climatically distinct case study regions within Germany are analysed for expected climatic changes in the near future, also referred to as the 2050s (2036-2065). The analysis is based on an ensemble of regional climate models of the EURO-CORDEX initiative. The focus is on projected changes in the frequency and duration of heat waves and dry spells in summer, i.e. during the vegetation period (May – September).

Secondly, ten broadleaf tree species are selected based on a vegetation survey in an urban park in Friesoythe, Lower Saxony. They are analysed for their respective drought and heat tolerance or sensitivity based on a comprehensive literature review. The objective of this analysis is to estimate the tree species' future suitability for the case study regions under changing climate conditions with a focus on changes in dry spells and heat waves. The suitability of species according to winter hardiness, storm susceptibility, and other criteria relevant in the urban context (e.g. aesthetic value and allergenic potential) are excluded from the analysis, but are important for the final decisions with respect to urban planning.

So far, there are different classifications of tolerance and sensitivity to drought or heat. Further classification approaches focus on related characteristics, e.g. suitability for dry habitats or ability to adapt to drought stress. This thesis aims to join, compare and standardize exiting classification schemes. In the next step, the available information for the ten selected species shall be consolidated into an overall assessment of their drought and heat tolerance and sensitivity. The results are intended to identify the best climate-adapted tree species for three German test sites with regard to projected climate condition in the 2050s.

The question of tree species suitability under changing climatic conditions is in progress in current research (Böll et al. 2014, Gillner et al. 2014, Gillner & Roloff 2011, Kölling et al. 2009a, Roloff et al. 2009). This work uses state-of-the-art climate information in combination with available data of the selected tree species, including scientific, peer-reviewed publications, reports from practice, and databases e.g. for forest owners or other practitioners. Therefore, possible gaps in information on tree species and further research needs will also be addressed.

The following questions summarise the research aim of this study:

1. *What climate change impacts are projected for the selected case study regions in Germany for the 2050s (2036-2065)?*

2. *How will the ten selected tree species be generally affected from dry spells and heat waves and what do these results mean with respect to climate change impacts in the case study regions?*

3. *Future outlook: in the face of climate change, is there a need to replace all the popular tree species which currently characterise our cityscape?*

2. Theoretical background

2.1. Urban climate

It is a widely accepted fact that the build-up structures and activities within urban areas influence both regional and microclimatic conditions (Kleerekoper et al. 2012). The phenomenon most frequently described in this context is the urban heat island (UHI), which is characterised by higher ambient air temperatures compared to the rural surrounding. Incoming solar radiation is absorbed by building material, released in form of long-wave radiation, and in combination with anthropogenic heat emissions causes a rural-urban temperature gradient (Kuttler 2008, Memon et al. 2008). The temperature difference is most pronounced during night time (Doick & Hutchings 2013). It reaches between 1 °C and 4 °C on average but can be as high as 9 °C in extreme situations, e.g. during heat waves or in specifically dense parts of the city (Doick & Hutchings 2013, Heidt & Neef 2008). Additionally, urban areas are characterised by a lower relative humidity than rural areas caused by reduced evapotranspiration, increased air pollution, high heat storage of building material as well as altered wind patterns and reduced wind speed due to building obstructions (Kleerekoper et al. 2012, Kuttler 2008).

The main cause for the altered bioclimatic conditions is the altered energy balance as a result of the replacement of natural green areas and vegetation by sealed surfaces and buildings. On top of this, anthropogenic emissions exacerbate the situation (Doick & Hutchings 2013, Kleerekoper et al. 2012, Chen & Jim 2008, Heidt & Neef 2008, Kuttler 2008, Wittig 2008, Larcher 2001, Oke 1988). A more detailed discussion of causes and consequences of the urban heat island is provided, among others, by Doick & Hutchings (2013), Kleerekoper et al. (2012), Memon et al. (2009), Heidt & Neef (2008), Kuttler (2008) and Memon et al. (2008). Generally, elevated temperature can have serious negative implications for public health and thermal human comfort. Recent hot extremes such as the heat wave in 2003 have led to an increase in heat-related mortality (Doick & Hutchings 2013, Kleerekoper et al. 2012, Mavrogianni et al. 2011, Matzarakis & Amelung 2008). This is a clear hint for the importance to provide more comfortable and healthy living conditions in our cities.

2.2. Urban green

2.2.1. Urban green in the context of climate change adaptation

Among other technical and non-technical measures for climate change adaptation in cities, which are discussed e.g. by EEA (2012) and Kleerekoper et al. (2012), urban green provides considerable improvements for microclimate and distinct benefits for human well-being (Kleerekoper et al. 2012, Dimoudi & Nikolopoulou 2003). If used sensibly, urban vegetation can reduce high summer air temperatures and thereby help to attenuate the urban heat island effect (Dimoudi & Nikolopoulou 2003). Urban green includes parks, smaller public green spaces, private gardens, street trees and green facades and roofs (Kleerekoper et al. 2012). In literature, the term “urban forest” is often used to describe the entirety of urban trees, whether they grow as single trees along a street or within urban woodland.

Furthermore, the term “green (urban) infrastructure” (GUI) is often used to describe measures and intervention that use vegetation to provide human and ecosystem benefits (Demuzere et al. 2014, Revi et al. 2014).

Vegetation provides cooling in several ways namely plant transpiration, evaporation, shading of surfaces, and reflectance of radiation (Doick & Hutchings 2013, Kleerekoper et al. 2012). Trees are especially important for shading and interception of rainfall (Gill et al. 2014, Bowler et al. 2010). Mature trees are also effective for cooling under dry conditions, as they dry out slower than grass and can consequently provide a cooling effect over a longer period (Gill et al. 2014). Different quantitative cooling effects have been reported in literature. According to Doick & Hutchings (2013) green infrastructure can cause a lowering of air temperature from 2°C to 8°C. Dimoudi & Nikolopoulou (2003) suggest an air temperature reduction of 0.8 K when increasing the ratio of green to build up area by 10 %. Urban parks can act as “park cool islands” (PCI) within a warmer city (Kleerekoper et al. 2012). Bowler et al. (2010) report from observational data that parks were found to be on average 1 °C cooler than their surroundings. Kleerekoper et al. (2012) even indicate a cooling effect of 1 to 4.7 °C, which may spread up to several hundred metres beyond the park boundaries into neighbouring areas. However, the spreading effect strongly depends on airflow patterns within the city and abundant water supply for the park vegetation. Generally, studies have shown that larger parks were cooler than smaller green spaces (Bowler et al. 2010). Because many local factors play a role for the effect of a park, Bowler et al. (2010) point out further research on the specific benefits of different measures is needed.

Furthermore, a decrease in outdoor temperatures simultaneously reduces a building’s energy demand for cooling, which again reduces the emissions for the electricity usage of air conditioning (Chen & Jim 2008). Increasing the share of green infrastructure within a city usually gains widespread acceptance of citizens, as urban trees and parks increase living conditions perceptibly. However, an adequate water supply for vegetation is necessary to enable an effective evapotranspiration (Kleerekoper et al. 2012). Thus, the benefit of urban green is largest with optimal water supply. On the other hand, vegetation does not only help to adapt to heat. It increases water buffering capacity of an area, which helps to reduce the effects of urban flooding after heavy rain events. Green infrastructure and rain water management should therefore be considered combined (Kleerekoper et al. 2012). Moreover, urban green offers several other benefits, including air quality improvement due to a reduction of air pollution, atmospheric CO_2 reduction, water quality improvement, erosion reduction, biodiversity increase, and socioeconomic benefits such as recreational, psychological, and educational value (Demuzere et al. 2014, Schmidt 2014, Berland 2012, Leuzinger et al. 2010, Escobedo & Nowak 2009, Chiesura 2004). A more detailed discussion of ecosystem services provided by urban forests is published e.g. by Chen & Jim (2008).

Besides all positive effects, undesirable side-effects and trade-offs between these different benefits have to be kept in mind. Street trees can for example provide shade and cool their surrounding whilst, on the other hand, blocking air pathways and trapping pollutants under their canopy at street level if they are planted in the wrong places. Demuzere et al. (2014) stress the importance of careful urban planning to avoid trade-offs and aim at co-benefits. In addition, the quality of urban green – and hence its benefit – depends on size, location, species composition, their stress resistance, as well as linkage and distribution of different types of vegetation on a city scale (Heidt & Neef 2008). Furthermore, some negative aspects such as allergenic potential, emission of volatile organic compounds (VOCs), which are involved in ozone formation, maintenance costs, and costs occurring from damage to infrastructure (e.g. through tree roots) have to be mentioned (Escobedo & Nowak 2009). However, as Berland (2012) points out, it is still profitable to invest in urban green, as the overall benefits outweigh management costs.

2.2.2. Urban trees – challenges and requirements

Urban trees have to cope with a large range of additional stresses that are less strong or non-existent in forests. This is because environmental conditions within a city are overall more extreme and harmful to trees and can cause vitality loss and increase mortality risk (Gillner et al. 2014). Among other factors, trees have to deal with soil compaction, poor soil quality, limited soil volume, soil and air pollution, salt contamination, excess heat, mechanical damage, vandalism, local wind gusts, an altered groundwater table, reduced soil nutrient contents, reduced water availability as well as drought stress (Böll et al. 2014, Forman 2014, Schmidt 2014, Wittig 2008, Benedikz et al. 2005, Sæbø et al. 2005). **Fig. 1** displays natural factors that are altered in the urban environment compared to forest ecosystems, as well as additional human influences that affect urban trees. Generally, conditions become harsher with decreasing closeness to nature (Roloff 2013a). Urban woodland e.g. is exposed to relatively low stress levels and shows relatively high tree longevity. Trees alongside streets or in containers, on the other hand, are subjected to very intense stress. Consequently, those trees do not reach old age. Trees in parks are in between these extremes and have to cope with more moderate stress compared to street trees but still with harsher conditions than urban woodland (Sæbø et al. 2005). Trees that are suitable for urban parks are therefore not necessarily suitable for plantation alongside a street (Roloff 2013a).

This thesis focuses on two challenges for urban trees, namely drought stress and heat stress. Drought stress in urban areas typically results from limited water availability due to increased surface runoff and/or a lower ground water table, while heat stress occurs due to the urban heat island effect and excess heat back radiated from buildings (Böll et al. 2014, Schönfeld et al. 2011, Wittig 2008). Additionally, high temperatures intensify drought conditions by increasing evaporative demand of the surrounding air. Both stresses could be intensified in the course of projected climatic changes (see section 2.4). An additional factor that must not be neglected is the exposure to herbivores, pests and pathogens (Forman 2014). The warmer and drier urban environment offers a habitat for invasive pests and pathogens for which the cooler rural area may not be suitable. Trees that are pre-stressed by the extreme conditions of an urban area are more prone to infestation (Böll et al. 2014).

Benedikz et al. (2005) divide urban trees into three categories: street trees, park trees and patches of woodland within the city or on the periphery. When selecting tree species for the urban environment – whether for large parks, small green spaces or street trees – several factors have to be considered at all locations: heat and drought tolerance, soil requirements, winter hardiness as well as pest-, disease-, and pollution-tolerance. The degree of these stresses may vary from place to place (Doick & Hutchings 2013). In addition to their environmental requirements, other factors have the same importance in the urban context, such as aesthetic value, allergic potential, risk of wind break, fall of leaves or fruits, toxicity, shading, and sensitivity to artificial light (Roloff 2013a). However, not all criteria are objective. Aesthetic value for example is also a question of personal preferences. Nevertheless, some criteria are necessary to consider, because they are affecting traffic security of security of pedestrians (e.g. risk of breakage or fruit fall) (Roloff 2013a). An extensive list of criteria can be found in Roloff (2013a).

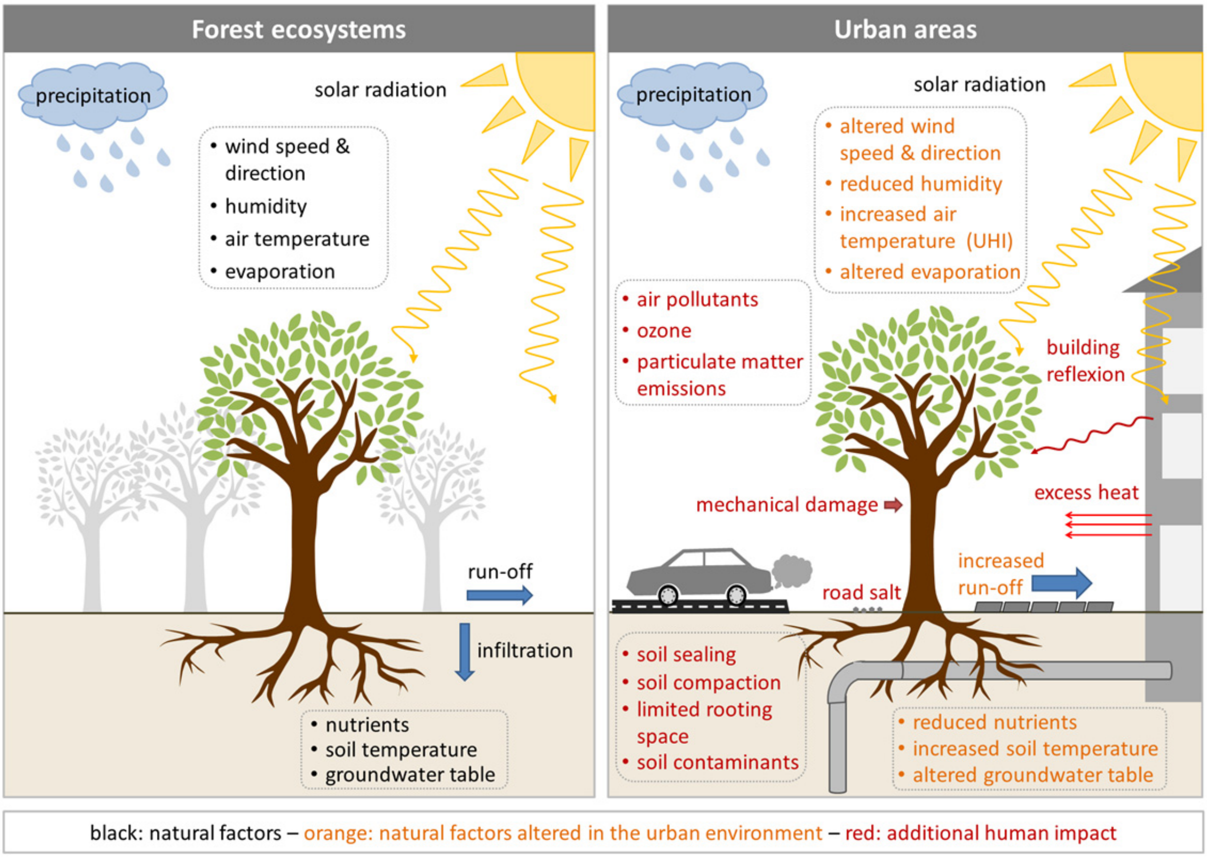

Fig. 1 Influences on urban trees in comparison to forest trees. Urban trees are influenced by natural factors (some altered by human influence) and additional human influences in urban areas compared to forest ecosystems (source: own illustration).

2.3. Trees under stress: stress factors and climate resistance

2.3.1. The concept of stress

Tesche (1992: 279) describes *climate resistance* as the "*resistance of plants against exceptional stress due to weather conditions, such as temperature, extreme drought, water logging of soil, radiation etc.*". Biotic stresses include diseases, herbivory, competition, and parasitism. Abiotic factors comprise – among others – temperature, water availability, radiation, chemical influences, and mechanical stress such as wind or soil movement (Schulze et al. 2005). In this thesis only the stress factors heat and drought are considered. Heat and drought during the vegetation period put many tree species in the temperate zone under stress. This causes plants to react by adapting to the stress until stress becomes too severe and causes serious damages (Roloff 2013a).

"*Tolerance of an environmental factor*" was defined by Simms (2000: 563) as "*the ability to maintain fitness in the face of stress imposed by that factor*". According to Roloff & Grundmann (2008a), tolerance furthermore implies the ability to withstand stress without suffering serious, irreversible damage. As opposed to tolerance, sensitivity to heat or drought stress is understood in this thesis, as the inability to maintain fitness under stress or the occurrence of irreversible damages as a consequence, respectively. According to Roloff (2013b: 83), a tree is adapted to certain environmental conditions if it "*can cope with its environment, which can be variable up to a certain extent*". On the other hand "*a tree or tree population is adaptable if it can also cope with larger changes in environmental conditions over a long period of time e.g. a long-term rise in air temperature*" (Roloff 2013b). Together these two traits form the adaptation potential.

In case of stressful conditions, plants rather invest in preserving their current state without suffering damage, instead of promoting further growth (Tesche 1992). The degree to which a plant is stressed depends on intensity, point in time, and duration of stress as well as on the plant's ability to react adequately. Other internal and external factors such as a combination of different stresses can additionally affect the stressor's impact (Roloff 2013a, Larcher 2001, Tesche 1992). Because trees are fixed in their location and can reach high ages, they are exposed to a number of stressors and have developed various mechanisms to protect themselves from stress-induced damage (Roloff 2013a, Roloff 2010). These mechanisms used by plants to cope with stressful conditions are often distinguished in 'avoidance', i.e. anatomical or morphological protection mechanisms that serve to avoid or delay the strain, and 'tolerance', i.e. bearing of stress through adjustment of physiological processes (Schulze et al. 2005, Tesche 1992). Please note that the notations 'tolerance' and 'tolerant' are used in the course of this thesis according to the definition by Simms (2000) mentioned above. These terms do not imply such tolerance mechanisms as opposed to avoidance mechanisms. Instead they just identify the ability of a tree to maintain fitness under stress. When dealing with ongoing stress, trees undergo a process comprising an alarm phase (destabilizing, acute damage possible if stress is too severe), phase of resistance (regeneration towards normal state due to adaptation processes) and a phase of exhaustion (overstraining of adaptive capacity). If the stress is too intense and / or lasts too long, permanent damages occur. Nevertheless, it is still possible for trees to recover in the phase of exhaustion if stress is reduced again (Roloff 2013b, Roloff 2010, Schulze et al. 2005, Larcher 2001).

For all that, stress is not necessarily negative. A positive, beneficial ‘eustress’ can promote restabilising and cause the tree to be better adapted towards future phases of stress. In contrast, ‘distress’ is detrimental stress, which further destabilizes or even destroys the organisms (Roloff 2010, Niinemets & Valladares 2006, Schulze et al. 2005, Larcher 2001). As adaptation to a certain stress involves a cost for the tree, developing tolerances to multiple stresses is very challenging. If water and nutrient resources are for example needed to preserve the current state without suffering any damage, less resources are available to promote further growth (Niinemets & Valladares 2006, Tesche 1992). Depending on the type of stress and the adaptation strategy, additional stresses can enhance or attenuate a first stress factor. Furthermore, two stresses can have different effects depending on whether they occur simultaneously or sequentially (Copolovici et al. 2014). It should be noted in this context that very different strategies can lead to similar levels of stress tolerance or avoidance, and that tolerance is overall difficult to measure (Roloff & Bonn 2008).

The microclimatic conditions of urban areas can cause predisposition of trees and make them more susceptible to diseases and pests. Additionally, thermophile insects are favoured by the warmer environment of the city (Siewniak & Kusche 2009, Roloff & Grundmann 2008a). Insect pests can be distinguished into primary, secondary, and chronic parasites, depending on the type of tree they affect. While primary parasites also choose healthy individuals, secondary parasites concentrate on already weakened trees, which are more prone to infestation. The latter can cause rapid decline in the tree’s condition and lead to die off rather quickly. Chronic parasites focus on weakened trees as well, but feed on the tree’s resources for years (Siewniak & Kusche 2009).

A tree’s origin and typical geographical distribution is often taken as an indication of the climatic conditions under which the species is able to grow (Roloff 2013b). Nonetheless, beyond the physiological basis, tolerance is also influenced by various environmental factors and can also vary with age and the individual’s disposition (Siewniak & Kusche 2009, Niinemets & Valladares 2006). This instance makes it difficult to define a specific threshold of a factor that a tree can endure (Niinemets & Valladares 2006). Typically, vital trees are more resistant to external influences. Vitality is higher, the better the tree’s ecological requirements and the existing environmental conditions coincide (Reif et al. 2010). In many cases knowledge gaps still exist on the tolerance to primary abiotic stresses, especially if several stresses occur simultaneously or sequentially (Niinemets & Valladares 2006). One reason for this is that still only few studies focus on the impact of multiple stresses and plant vitality, especially when both abiotic and biotic stresses occur (Copolovici et al. 2014).

2.3.2. Heat stress

Heat stress influences the tree’s metabolism and vitality (Roloff 2013b). Overheating occurs in plants if too much inflowing energy cannot be released fast enough. High temperatures in plants can occur due to direct solar radiation or high temperatures of the surrounding air (Larcher 2001). Sealed surfaces in urban areas, especially asphalt and concrete, can strengthen the heat stress. Surfaces in temperate zones were found to reach temperatures of up to 60-70 °C (Larcher 2001). Mature tree crowns and leaves are less affected by surface temperatures than shrubs and herbaceous vegetation, however, high temperatures near the ground can also affect tree seedlings and younger trees (Roloff 2010, Schulze et al. 2005, Larcher 2001). In case of simultaneously occurring drought stress, another cause for overheating is the closing of stomata to prevent water loss. In this case, transpiration decreases and the required cooling of the leaf cannot be provided. This may induce leaf temperatures that largely exceed air temperatures (Bréda et al. 2006).

A decline in photosynthetic rate at peak temperature has been observed in temperate zones (Roloff 2013b). Consequences of temperatures above the tolerated threshold furthermore include loss of membrane integrity, denaturation of enzymes with a consequent loss of enzyme functioning, and tissue necrosis (Jones 2014). Deciduous trees in temperate zones generally experience heat damage during the vegetative period at approximately TL_{50} = 50 °C (50 % damage after at least 30 minutes of heat treatment) (Roloff 2010, Schulze et al. 2005). Trees that are adapted to shaded locations may already be damaged at 40 °C (Roloff 2010). The time of the year or the growth stage can make a difference to whether a tree can cope with the stress or is damaged by exposure to heat (Umweltbundesamt 2015). Schulze et al. (2005) describe the example of poplar hybrid (*Populus deltoidis x simonii*) leaves, which were damaged in late summer but not during the preceding weeks. One possible explanation is that in late summer the tree may already be transitioning to the phase of frost hardening and may therefore be more prone to heat stress. Physiological responses of forest trees to heat are reviewed and discussed in more detail in Rennenberg et al. (2006).

Heat stress can be avoided by trees through different mechanisms, including leaf shape and position i.e. consequently the exposure to direct sunlight. Cooling is achieved via transpiration, resulting in water loss, which is problematic if at the same time water supply is limited. The combination of heat and drought is therefore especially challenging and secondary effects of high temperatures therefore need special attention (Schulze et al. 2005). Allen et al. (2010) point out that heat and drought in combination can have complex effects depending on severity, duration and frequency of both stresses.

2.3.3. Drought stress

In this study, dry spells are defined as "*periods of at least five consecutive days with daily precipitation below 1 mm*" (Jacob et al. 2014: 566). Accordingly, a day with a daily precipitation sum below 1.0 mm is called a dry day. The term drought has been defined in various ways depending on the research question, area of interest, and type of drought impacts. A comparison can be found in Bender & Schaller (2014). The definition coming closest to what is meant by 'drought' in this thesis is the agricultural drought. It considers not only a lack of precipitation, but also a lack of soil moisture content. It occurs if a precipitation deficit coincides with high evaporation during the vegetation period (Bender & Schaller 2014). The onset of an agricultural drought may occur a few days after the onset of a meteorological drought due the remaining soil moisture content (Heim 2002).Thus, a dry spell alone does not necessarily cause an agricultural drought; it can however trigger drought conditions depending on the circumstances. When using the term 'drought' in this thesis, it is assumed that drought stress can develop as a consequence of a dry spell in combination with other factors. Nevertheless, 'drought' is not used as a synonym for dry spell in this work.

Drought stress is often the result of high solar radiation and low air humidity, which cause high evaporative demands and low soil water availability. Other factors such as wind and soil properties also have an influence (Gartner et al. 2009, Roloff & Grundmann 2008a). High temperatures increase evaporation due to a higher vapour pressure deficit of air, which again fosters the formation of drought conditions (Ryan 2011). Therefore, heat waves also contribute to the formation of drought conditions and can severely aggravate drought if they coincide with a dry spell. Drought is one of the most frequent stressors for trees, especially in urban areas where water availability is reduced (Kleerekoper et al. 2012, Roloff 2010). Drought stress can damage a tree directly, e.g. by restricting growth, and indirectly, e.g. by predisposing trees to pathogens (Roloff 2010).

Depending on the species, various effects can be observed in reaction to drought (Roloff 2013b). As a short-term consequence, soil water potential decreases while soil is drying. Thus, to ensure ongoing water transport, the water potentials within the tree have to be adjusted accordingly to keep up the gradient from the roots to the crown and ensure water uptake. However, if the xylem water potential decreases below a species-specific threshold, embolisms that disturb the water transport may occur. The closing of the stomata decreases water loss. Yet, a trade-off occurs: uptake of CO_2 becomes limited, thus photosynthetic rate decreases, ultimately resulting in carbon starvation (Roloff 2013a, Roloff 2013b, McDowell et al. 2008). Furthermore, closing of the stomata can cause or intensify heat stress due to the lack of evaporative cooling (Bréda et al. 2006). At the same time this weakening predisposes trees to attacks from pathogens (McDowell et al. 2008).

If drought conditions persist, direct damages begin to occur, e.g. leaves may deform or be shed. It is generally possible for many trees to endure a few days of drought. However, the water stored in the stem is not sufficient for extended drought periods (Roloff 2013a, Roloff 2013b). On a medium term, leaves or even whole branches are shed in order to decrease overall foliage surface and thereby minimize water loss due to transpiration (Roloff 2013b). Long-term consequences include a reduction of linear growth and growth in girth, as well as the formation of short shoots. Since water is transported less effectively in short shoots , the risk of drought stress is increased in the following vegetation periods (Roloff 2013b). The crown structure usually normalises within a few years after a drought event. If a second drought occurs shortly after the first one, mortality was found to increase due to predisposition. However, the immediate cause for dieback is often unclear (Roloff 2013b).

Drought tolerance is the ability to maintain fitness under drought stress and to withstand drought conditions without suffering significant damages (Roloff & Grundmann 2008a, Simms 2000). It is mainly determined by different morphological and physiological traits (Niinemets & Valladares 2006). Plants cope with drought either through structural or physiological adjustments or a combination of both (Bréda et al. 2006). Morphological adjustments include reduction of leaf surface area, limiting of plant transpiration through a thick plant cuticle or a reduced number of stomata, and the development of deep roots (Wittig 2008). Physiological adjustments include effective transpiration control or adjusted leaf orientation to avoid direct solar radiation (Roloff 2013a). Moreover, the capability to recover after a period of stress is important (Gallé & Feller 2007). Physiological responses of forest trees to drought are reviewed and discussed in more detail in Rennenberg et al. (2006).

2.4. Climate and climate change in Germany

Germany's climate can be described as a "*warm temperate humid mid-latitude climate*" (DWD 2015a). The country is located in a transition zone between the oceanic climate of Western Europe and the continental climate of Eastern Europe. Germany is mainly influenced by westerly winds carrying humidity from the Atlantic Ocean inland, causing oceanic conditions with mild summers and winters. This influence is high in the northwestern parts of the country and low in the southeastern parts, where conditions change towards a more continental climate. Occasionally, high-pressure systems block this typical wind pattern, resulting in hot and dry summers and cold winters. In addition to the macroclimatic conditions, topography alters the regional climate characteristics, e.g. by causing orographic rainfall (DWD 2015a).

The warmest regions during the summer half of the year are the Upper Rhine Rift Valley, the Lower Rhine region and small parts of Eastern Germany (DWD 2015a). These regions, especially the Upper Rhine Rift Valley, also show the highest number of hot days (max. daily air temperature ≥ 30 °C) per year. The lowest precipitation sums during the summer half of the year can be found in Eastern Germany, especially in Saxony-Anhalt and Brandenburg. Accordingly, these regions also show the largest number of dry days (daily precipitation sum < 1 mm) per year. A more detailed description of the climate in Germany and influencing processes can be found e.g. in Liedtke & Marcinek (2002).

Days where the daily maximum temperature reaches or exceeds 30 °C are defined here as hot days. Heat waves are usually described as periods of several consecutive days with high temperatures. However, no uniform definition exists and the threshold values that define a heat wave (number of consecutive days and required temperature) vary between different countries (Bender & Schaller 2014). Following the definition used by Jacob et al. (2014: 566), a heat wave is hereafter defined as a "*period[] of more than three consecutive days exceeding the 99th percentile of the daily maximum temperature of the May to September season of the control period (1971–2000)*". Accordingly at least four consecutive days need to exceed this relative threshold for the event to be considered a heat wave.

Climate is regionally diverse in Germany and the projected climatic changes show a certain spatial variability. Therefore, making generalised statements on expected changes for the entire country is not very reasonable in the case of regional and local adaptation measures. For this purpose, regional climate models can provide a more detailed picture of projected trends for specific regions. Different sources offer information on projected regional climatic changes, based on different ensembles and scenarios: Various maps and timelines of projected changes based on an ensemble of up to 21 regional climate models are provided online by the Deutscher Wetterdienst (DWD 2015b) (currently available for emission scenario A1B). Furthermore, a recently published report on Germany's vulnerability to climate change (Umweltbundesamt 2015) also presents projected changes based on an ensemble of 17 regional climate models, using the emission scenario A1B. An overview of projected climate change impacts in Europe based on regional EURO-CORDEX ensemble projections and the Representative Concentration Pathways (RCPs) is provided by Jacob et al. (2014). Jacob et al. (2014) furthermore compare the results to previously obtained projections from the ENSEMBLES project, which uses the A1B emission scenario.

The following paragraphs only give a very brief overview of projected changes for the entire country, since this nationwide view is not the main focus of this work. For more detailed information, please refer to the cited sources. Concerning temperature, the Umweltbundesamt (2015) assumes an increase in mean air temperature for 2021-2050 and for 2071-2100. The increase is expected to be seasonally and regionally diverse. Increases in mean temperatures are projected to be generally more pronounced in winter (DJF) than in summer (JJA). Furthermore, the projected temperature increase is stronger in the south than in the north for both, annual and seasonal changes. An increase in annual mean temperature is likewise reported by Jacob et al. (2014) who project significant and robust increases in annual mean temperature in Germany for 2071-2100. Slightly stronger increases are projected towards the southern and northeastern Germany compared to the rest of the country. The projected increases are stronger under RCP8.5, with 2.5 to 3.5°C in northern Germany and 3.5 to 4°C in southern Germany. All changes are significant and robust. These projections show similar trends like the compared A1B scenario, which indicates a 2 to 2.5°C increase in annual mean temperature.

Hot days (max. daily air temperature ≥ 30°C) are projected to become more frequent in 2020-2050 and until the end of the century (2071-2100), with a stronger increase in southern Germany than in northern Germany (Umweltbundesamt 2015). Along with this, tropical nights (daily min. air temperature ≥ 20°C) are also projected to generally become more frequent until the end of the century with regional differences throughout the county (Umweltbundesamt 2015). According to Jacob et al. (2014), the mean number of heat waves (defined as more than three days exceeding the 99^{th} percentile of the daily maximum temperature of the May-September season for the control period 1971-2000) is projected to increase until 2071-2100 (changes are significant and robust). Again, the projected changes are stronger in the south than in the north of Germany (Jacob et al. 2014). Furthermore, an analysis by Christidis et al. (2014) matches the projected increase in hot days and assumes that extremely hot summers similar to the summer of 2003, will be very common by the 2040s. However, changes can differ regionally and seasonally.

Projected changes in precipitation are spatially and temporally heterogeneous. The ensemble used by Umweltbundesamt (2015) comprises some increasing as well as some decreasing projections for summer precipitation sum (JJA) in 2020-2050. For 2071-2100, the ensemble range includes increasing projections only for a few regions in the northeast, while in general, the ensemble points more towards a decrease in mean summer precipitation sum. For winter precipitation sum (DJF), increases are projected for both time periods, with the exception of only a few small areas. In contrast to temperature, changes in precipitation are more spatially heterogeneous with a smaller-scale pattern (Umweltbundesamt 2015). Jacob et al. (2014) project increases in annual precipitation for RCP4.5 and RCP8.5 with the exception of some areas in the northwest, where no large change is indicated under RCP4.5. Projected changed are significant and robust for most parts of Germany (Jacob et al. 2014).

Dry spells (defined by Umweltbundesamt 2015 as ≥ 10 consecutive dry days, please note that this thesis uses ≥ 5 consecutive dry days as threshold) are projected to become more frequent during summer in 2071-2100 according to the Umweltbundesamt (2015). Along with these changes, some regions are projected to experience an increase in heavy rain events (≥ 20 mm of precipitation), while some regions are projected to see hardly any change.

These changes are again very spatially heterogeneous on a small-scale (Umweltbundesamt 2015). The projections shown by Jacob et al. (2014) indicate increases in seasonal heavy precipitation throughout the year. Yet, especially under RCP4.5, changes are not significant in several regions. Concerning the length of dry spells, no larger changes are projected by the ensemble, yet, changes are not significant in some regions and in some cases also not robust (Jacob et al. 2014).

Climate change is expected to influence growth and fitness of several tree species. An increase in air temperature increases evaporative demand and may impair soil water availability and critically influence certain tree species that are not sufficiently adapted to drought stress (Scherrer et al. 2011, Köcher et al. 2009, Burk 2006). A tendency towards more climatic extremes such as intense and prolonged summer droughts can already be observed (Bauer 2012). Sala et al. (2010) relate global tree dieback in recent years to climate change, especially to the impact of droughts. Higher stress levels are believed to reduce tree vitality, in severe cases even lead to mortality, and decrease resistance towards pests and diseases under future climate change (Bauer 2012, Bolte et al. 2012). Yet, uncertainty remains concerning the precise effect of climate change on tree species (Allen et al. 2010). Knowledge on the impact of summer droughts on root systems is still relatively sparse and more information is needed on the drivers of tree mortality and the specific impact of climatic factors on trees (Allen et al. 2010, Burk 2006).

3. Climate projections for the case study regions

3.1. Projecting regional climate change using the EURO-CORDEX ensemble

Oftentimes, global climate models do not offer sufficiently fine spatial resolutions for regional climate change analyses. Instead, regional climate models offer information with a higher spatial resolution (Umweltbundesamt 2015). High-resolution regional climate change scenarios are particularly important for the development of climate change adaptation strategies (Jacob et al. 2014). This thesis draws upon high-resolution (0.11° / 12.5 km) regional climate change projections from the EUROpean COordinated Regional Downscaling EXperiment (EURO-CORDEX) initiative. The EURO-CORDEX ensemble simulates future climate using Representative Concentration Pathways (RCPs). These RCPs were developed by experts from the modelling community and are used in the IPCC Fifth Assessment Report (AR5) (Jacob et al. 2014, Cubasch et al. 2013, van Vuuren et al. 2011).

Four different RCP scenarios exist: RCP2.6 (low), RCP4.5 (medium-low), RCP6 (medium-high) and RCP8.5 (high) (van Vuuren et al. 2011). Each of these scenarios follows a different expected radiative forcing, e.g. RCP4.5 assumes a rise of 4.5 W/m^2 by the end of the 21st century compared to the pre-industrial situation. For comparison, the scenario A1B, which is the most frequently used SRES scenario, e.g. within the ENSEMBLES project, approximately corresponds to RCP6 with respect to radiative forcing (Jacob et al. 2014). The temporal development of radiative forcing for the different RCPs is displayed in **Fig. 2**. For a detailed discussion of the Representative Concentration Pathways see van Vuuren et al. (2011). The climate data used in this study comprises an ensemble of 21 EURO-CORDEX simulations, 10 using the medium-low scenario RCP4.5 and 11 using the highest scenario RCP8.5. Please note that in section 3.3, where the modelling results are presented, it is only differentiated between the two RCPs in case there are distinct differences between the projected medians or ranges of the scenarios. It is assumed that all individual simulations have the same probability of occurrence.

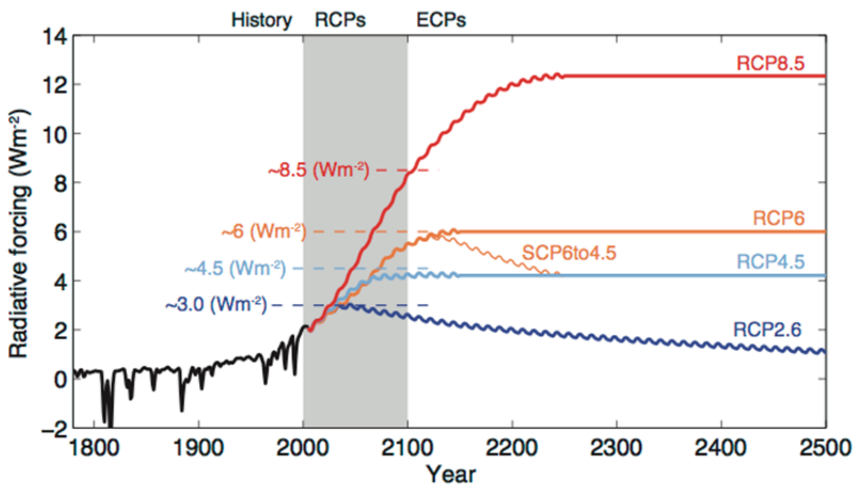

Fig. 2 Total radiative forcing (anthropogenic plus natural) for different RCPs . RCP2.6, RCP4.5, RCP6, RCP8.5 and extended concentration pathways (ECP) are displayed. This thesis uses RCP4.5 (light blue) and RCP8.5 (red). There are uncertainties in both current and future RF levels for any given scenario. S*ource: Cubasch et al. (2013).*

It has to be mentioned that different sources of uncertainty exist in climate modelling. First of all, models simplify natural processes using different model-specific simplification methods. Furthermore, uncertainties exist concerning the future development of anthropogenic greenhouse gas emissions. Moreover, many processes within the climate system are non-linear and thus include a natural non-deterministic variability (Pfeifer et al. 2015). The advantage of using a multi-model-ensemble compared to single models is a general increase in validity of results taking into account the mentioned different sources of uncertainties. By using the ensemble approach, not only one possible development projected by one model and one particular scenario is considered. Instead, a range of changes projected by different models and different scenarios is taken into account (Pfeifer et al. 2015, Umweltbundesamt 2015, Climate Service Center 2.0 2014). Yet, it must be pointed out that the ensemble results are projected possible changes – neither predictions nor forecasts. They comprise a certain bandwidth of possible changes. For climate projections, different boundary conditions can be assumed which will influence the final results. In contrast, weather forecasts also comprise a certain bandwidth but are largely influenced by known initial conditions.

Planting decisions that are made today affect species composition for several decades because of the long life spans of many tree species. Even so, the time frame most relevant to urban planners is focused on a shorter time span comprising mainly the next few decades rather than taking into account the period until the end of the century (SBI 2014, Leuschner 2009). The time period investigated in the course of this thesis was chosen accordingly. Therefore, the main focus is on the period from 2036-2065, hereafter called 2050s or near future. The 30-year time-period ranging from 1971-2000 serves as reference period. The more distant future is defined here as the period of 2071-2100. Both future periods are displayed in the results section to allow for a good visualization of possible trends as some of them may only become apparent in the more distant future. Nevertheless, according to the chosen focus, the later time period is not discussed further.

3.2. Case study regions and climate indices

Three climatically distinct areas of equal size were selected within Germany to represent some of the regional climatic differences throughout the country (see **Tab. 1** and **Fig. 3**). Each region consists of 5 x 5 model grid cells at a resolution of 0.11° (ca. 12.5 km). Thus, the size of each region represents approximately 3,906 km^2 (62.5 km x 62.5 km). The coordinates in **Tab. 1** specify the geographical centre of the case study regions.

Tab. 1 Geographical coordinates of the centre of the three case study regions

Case study region	Coordinates	
	Lat.	*Lon.*
East (E)	52.5	14.2
Northwest (NW)	53.0	8.0
Southwest (SW)	49.3	8.5

The first region is located in the east of Germany and comprises parts of Brandenburg and Berlin. It represents one of Germany's hottest and driest areas during summer, resulting from the increasingly continental climate towards the Southeast of Germany (DWD 2015a, Müller-Westermeier et al. 2001). The second region represents the more maritime climate of Northwest Germany with moderately warm summer temperatures and medium amounts of summer precipitation compared to other parts of Germany (DWD 2015a, Müller-Westermeier et al. 1999). As part of the Upper Rhine Valley the third region is characterised by a medium amount of precipitation but a particularly high number of hot days (DWD 2015a, Müller-Westermeier et al. 2001). It belongs to the warmest regions with the mildest winters in Germany (DWD 2015a).

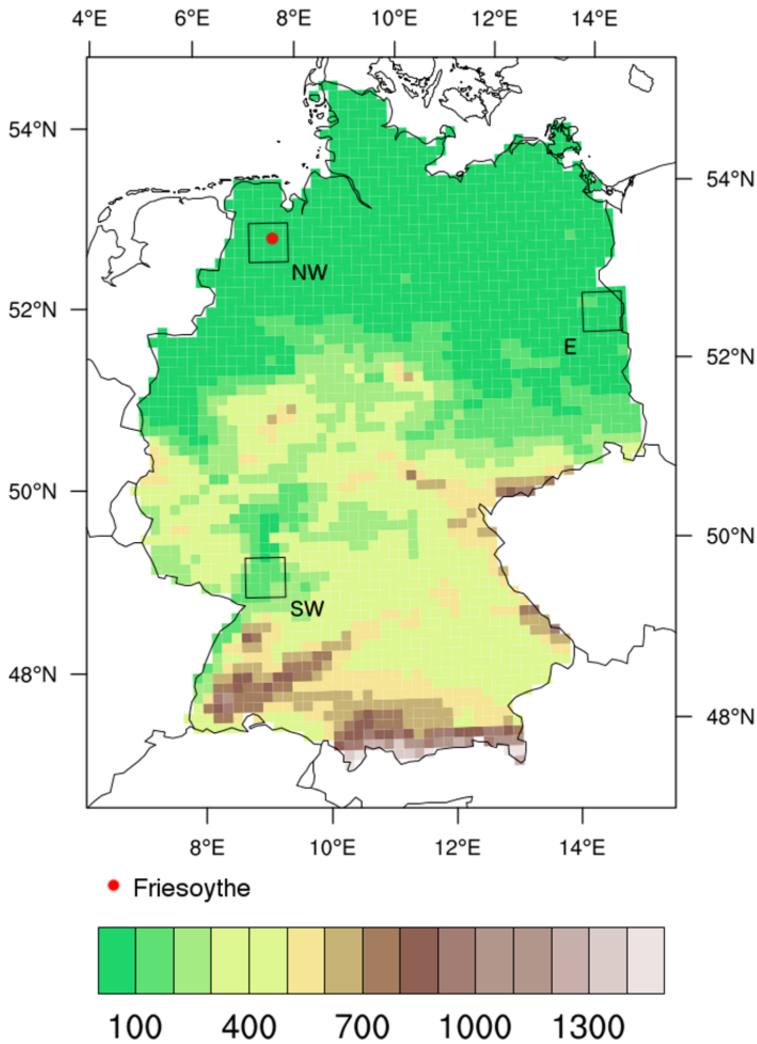

Fig. 3 Location of the three case study regions East (E), Northwest (NW), and Southwest (SW). The underlying colour scale shows the orography of Germany extracted from one regional climate model (REMO) of the EURO-CORDEX ensemble.

In the context of this work, six climatic indices, which were calculated from the simulations of the EURO-CORDEX ensemble, are selected (see **Tab. 2**). It is analysed in how far conclusions on future suitability of urban trees can be drawn from these indices and the time series and maps that were produced using the EURO-CORDEX ensemble. All indices in this thesis refer to the growing season, which is hereafter defined as the period from May to September. Projections are given either as absolute or relative changes in the 2050s compared to the reference period 1971-2000. **Tab. 3** lists the different projected time series and maps that were produced for every one of the indices to give a better overview on the available formats of the modelling results. Time series are given in Appendix A; maps are given in Appendix B. Moreover, intra-annual patterns were considered for precipitation. In addition to the already mentioned indices, changes in the mean intra-annual cycle of precipitation were projected based on monthly precipitation sums averaged over a 30-year period (see Appendix C).

Tab. 2 Precipitation and temperature indices projected by the EURO CORDEX ensemble. All indices refer to the growing season (MJJAS).

	Indices	Explanation
Precipitation	Precipitation sum	*Absolute precipitation sum (mm)*
Dry spells	Number of dry spells	*Dry spell: ≥ 5 consecutive days with daily precipitation < 1 mm*
	Maximum duration of dry spells	
Hot days	Number of hot days	*Hot day: daily maximum temperature ≥ 30 °C*
Heat waves	Number of heat waves	*Heat wave: > 3 consecutive days exceeding the 99th percentile of the daily maximum temperature of the growing season of the control period*
	Average duration of heat waves	

The three different time series that display the respective modelling results for each index show the ensemble bandwidths of projected changes, the changes projected by the individual ensemble members, and the projected absolute values of the respective indices projected by the individual ensemble members. Every value in the time series represents the mean of a 30-year period around this year, e.g. the projection for 2050 is the mean value for the time period 2036-2065. Thus, the results cannot be interpreted for one individual year but have to be seen as mean values. 30-year averages were chosen because 30 years are considered short enough to show long-term climatic trends but also long enough to filter out inter-annual variability (WMO 2016).

Tab. 3 Overview of display formats and contents of EURO-CORDEX results. The five different formats are available for all indices and are displayed in the appendices A and B.

Display format	Content
Time series	1. **Projected changes** compared to the reference period: **ensemble and likely ranges**, including boxplots for specific 30-year periods 2. **Projected changes** compared to the reference period: **individual ensemble members** 3. **Projected absolute values** of indices: **individual ensemble members**
Maps	1. **Projected absolute values** of indices: ensemble mean 2. **Projected changes** compared to the reference period: ensemble mean

The first type of time series (for a legend see **Fig. 4**) depicts the complete bandwidth of changes projected by the entire ensemble, hereafter called ensemble range. Additionally, the likely range, representing 66 % of all model projections, is highlighted. This methodology follows the approach used by Jacob et al. (2014), where the likely range is defined as the range between the 17^{th} and 83^{rd} percentile. Box plots to the right of the time series furthermore show specific 30-year periods and display the ensemble and likely ranges, as well as the ensemble ranges of RCP4.5 and RCP8.5 scenarios, respectively. The likely range is only shown for the entire ensemble and not for the two different RCPs. In general, a narrow bandwidth of changes indicates a larger agreement of the different ensemble members than a broad one. However, it must be taken into account that a broad ensemble range can be caused by high multi-decadal variability or for example by a single member deviating from the rest of the ensemble. The likely range includes only 66% of all simulations around the median. Yet, statistically all projections – also the ones not included in the likely range – have an equal probability of occurrence.

The second type of time series shows the projections of all individual ensemble members for a better assessment of the ensemble result. With the help of these time series it becomes apparent whether the ensemble results are actually widespread, or if only one or few individual models are responsible for a seemingly broad range of projected changes. Depending on the index the first two sets of time series either contain relative or absolute changes in relation to the reference period.

The projected relative changes do not contain any information concerning the projected absolute magnitudes of the indices. Models agreeing on the relative rate of change can still project considerably different absolute values. Therefore, the third type of time series provides information on the absolute values, e.g. absolute precipitation sum or absolute number of heat waves per year. Additionally, observational data (E-OBS, v 10.0) is used as reference data to relate the simulated past climate to observed climate. The E-OBS dataset provides, among others, high-resolution gridded data of daily precipitation as well as daily mean, minimum and maximum temperatures over land for most parts of Europe. It covers the time period 1950-2014. The comparisons of projected and observed data presented later on always refer to this time period. The reference data is based on interpolated observational data from meteorological stations with a spatial resolution of 0.25 ° (ca. 28 km). For more detailed information on the E-OBS data set see Haylock et al. (2008). Since the spatial resolution of the reference data differs from the resolution of the EURO-CORDEX ensemble data, the E-OBS data was adjusted to the model grid of the projected data before calculating the time series for the individual case study regions. As for the projected data, every value within the time series represents the mean over a 30-year period around the respective year. Finally, all minimum, maximum, and median values of the ensemble projections and the two RCP scenarios are summarised in **Tab. 4**.

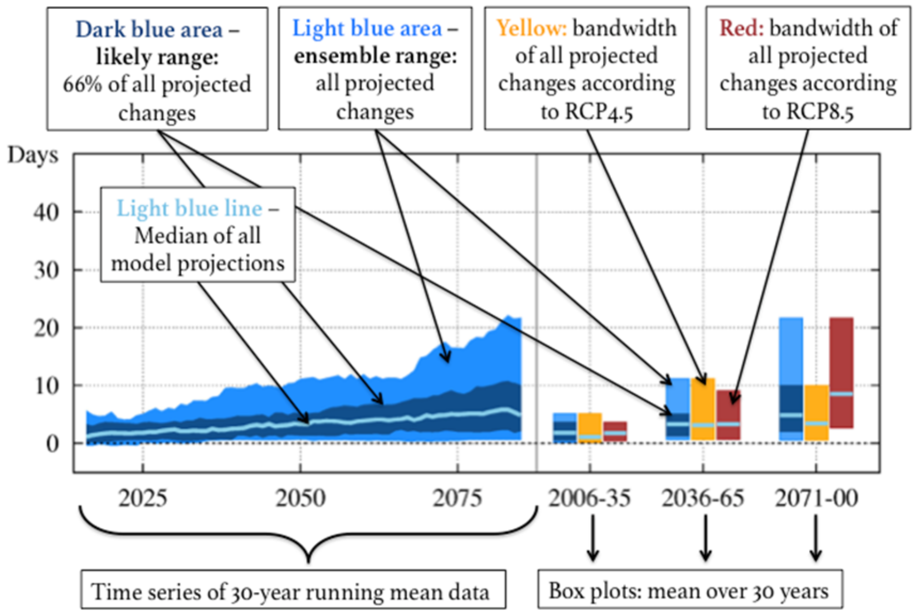

Fig. 4 Legend for projected EURO-CORDEX time series. The example shows the projected number of hot days during the growing season for the eastern region. *Source: own illustration based on Climate Service Center 2.0 (2014).*

In addition to the presented time series, there are two maps for every index, which display projected absolute mean values or the projected changes, respectively, for the 2050s (see Appendix B). They allow a comparison of projected ensemble medians of the different regions. Time series and maps are two forms of data visualisation with different aims. Time series display the temporal development of an index for only one region. Maps, on the other hand, illustrate a spatial pattern and provide information on several regions but temporal information is only given as one averaged value. The maps displayed here only give one value per grid cell at a time, thus, only mean values are displayed without any information on the ensemble range or the likely range. Furthermore, no information on individual ensemble members or differences between the two RCP scenarios is given. Instead, the presented time series display these kinds of information. Maps give an overview of the ensemble projections for the whole of Germany and allow putting the regions into a geographical context. This is particularly useful as the case study regions are rather small areas and their climate may differ from the climate of their surroundings. Both, time series and maps have their advantages and disadvantages and focus on different kinds of information. Together both visualisations of projected data give a more complete overview than is possible by either time series or maps alone.

3.3. EURO-CORDEX projections for the 2050s

3.3.1. Region 1: Eastern Germany (E)

Precipitation

The ensemble median projects an increase of +4.0 % for the mean precipitation sum during the growing season (please note that – even though not specifically mentioned hereafter – all indices refer to the growing season, defined here as May – September). This increase should merely be regarded as a tendency, especially as the likely range (+0.5 to 9.2 %) encompasses models that show barely any change (**Fig. A1**, **Tab. 4**). The absolute mean precipitation sums projected by the individual models reveal a rather large range from approximately 250 to 450 mm for the 2050s (**Fig. A1**). Compared to E-OBS data, the majority of ensemble members overestimate the precipitation sum, which ranges between approximately 250 and 275 mm at the end of the 20th century (2071-2100) (**Fig. A3**). This does, however, not affect the trend of the ensemble because the models that are projecting rather wet conditions are showing high precipitation values over the entire time series, while rather dry models likewise stay in the dry range. Thus, the relative changes of the models can still be compared. No distinct signal is visible concerning the projection of changes in the intra-annual precipitation pattern. The ensemble range encompasses both increases and decreases (**Fig. 6**).

Dry spells

With an ensemble median of -0.1 dry spells per growing season (likely range: -0.4 to +0.5 dry spells), an increase or decrease in the number of dry spells appears to be similarly possible (**Fig. A4**, **Tab. 4**). The results indicate a possible change within a magnitude of less than +/- 1 dry spell. The same is shown for the duration of dry spells with a median of +0.6 % (likely range: -7.8 to +10.5 %). In both cases the ensemble does not project a clear direction of change (**Fig. A4**, **Fig. A7**, **Tab. 4**). Compared to E-OBS data, more ensemble members tend to underestimate than overestimate the absolute number of dry spells. The ensemble range varies between approximately 5 and 8 dry spells per growing season for all except two (≈ 9.5 % of all simulations) members, while E-OBS data suggest between 7 and 7.5 dry spells per growing season. Two members show very different results and project an absolute number of dry spells close to zero (**Fig. A6**). Compared to E-OBS data this behaviour can be considered unrealistic. Yet, since these two members stay close to zero for the whole period, the projected relative change of these simulations is not necessarily unrealistic as well. The same occurs in case of the maximum duration of dry spells, which the ensemble range projects to be between about 12 and 18 days in the 2050s. E-OBS data indicate a maximum duration of 17 to 18 days while the ensemble projects a wider range between 11 and 20 days for the same time period at the end of the 20th century (excluding the two mentioned outliers).

Yet, more ensemble members tend to underestimate the maximum duration of dry spells (**Fig. A9**).

Hot days

In contrast to precipitation-based indices, the ensemble shows more distinct signals for temperature-based indices. With a median of +3.3 hot days per year and a likely range of +1.3 to +5.1, an increase in the number of hot days is projected for region E. Since no simulation projects a decrease, both likely and ensemble ranges of the ensemble only include increasing values (**Fig. A10**, **Tab. 4**). The likely range is rather narrow compared to the ensemble range, indicating a larger agreement of models than for the projected development of precipitation and dry spells. **Fig. A10** shows that two members (ca. 9.5 % of all simulations) are responsible for the upper extent of the ensemble range, as they project almost twice as many hot days for the 2050s than the next highest projection. The projected total number of hot days varies considerably between 0 and 20 days for the 2050s (**Fig. A11**).

Heat waves

The ensemble median projects an increase in the number of heat waves (+0.1 heat waves per growing season, i.e. approximately 3 additional heat waves within a 30-year time period). The likely range (0.0 to +0.3 heat waves) projects an increase, too. It should however be noted that the lower bound of the likely range points to only small changes (**Fig. A12**, **Tab. 4**). The ensemble range of -0.1 to +0.6 indicates mainly increasing values. The majority of members project increasing values, the negative minimum values are caused only by two simulations (ca. 9.5% of all simulations) (**Fig. A13**). It should also be noted that only a single simulation likewise causes the upper limit of the ensemble range. It projects an increase of approximately +0.6 heat waves for the 2050s. The second highest projection shows only half the increase (approximately +0.3 heat waves per growing season) (**Fig. A13**). The projected absolute number of heat waves in the 2050s varies between approximately 0.1 and 0.4 heat waves, except for one simulation (ca. 4.8% of all simulations), which shows an even larger number of approximately 0.7 heat waves per growing season (**Fig. A14**).

There is no distinct signal for a change in the average duration of heat waves. The ensemble median of -0.2 days projects barely any change, while the likely range comprises values from -2.1 to +0.8 days. The ensemble range even projects a range of -3.8 to +1.8 days (**Fig. A15**, **Tab. 4**). **Fig. A16** and **Fig. A17** show abrupt significant changes in the time series of projected values. These changes are partly responsible for the large ensemble ranges. Since heat waves occur aperiodic with just few events – even though regarding more than a century – they can have a significant influence even on 30-year running mean values, resulting in the described abrupt changes in the time series.

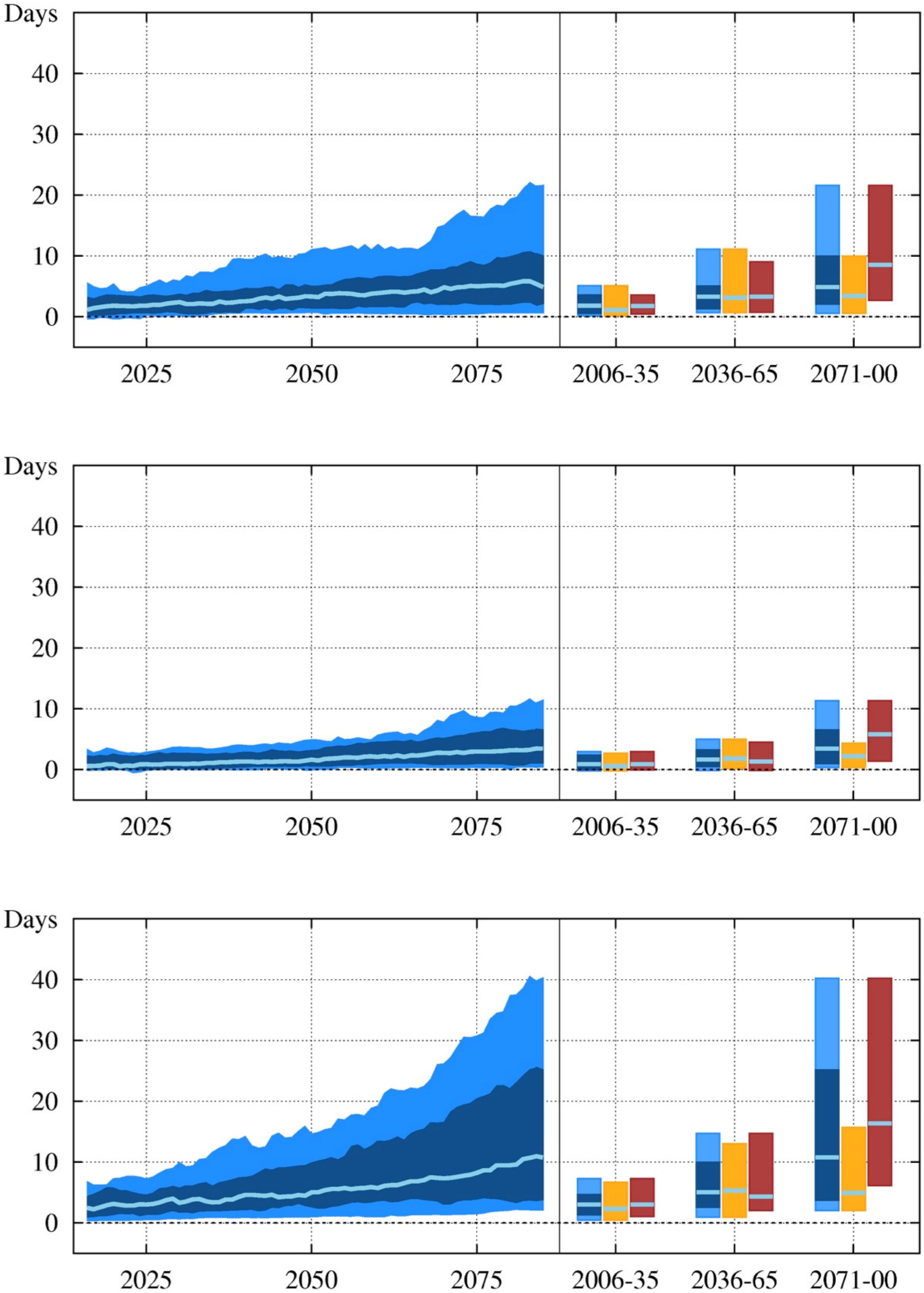

Fig. 5 Projected changes in the mean number of hot days per year in the 2050s (time series of the ensemble range) during the growing season (in days) for regions E (top), NW (middle), and SW (bottom). Statistical values are averaged over a 30-year period referenced to 1971-2000. Time axis values represent the mid-year of the 30-year periods. The time series includes the ensemble median (light blue line), the likely range (dark blue shaded area) and the ensemble range (light blue shaded area). The box to the right shows specific 30-year periods of the time series itemized to the ensemble mean (blue), RCP4.5 (yellow), and RCP8.5 (red) ensemble members.

3.3.2. Region 2: Northwestern Germany (NW)

Precipitation

With respect to the projected change in mean precipitation sum, no clear statement can be made for the NW. The ensemble median is -1.3 %. The likely (-4.2 to +8.3 %) as well as the ensemble range (-13.0 to +10.9 %) comprise both, projected increases and decreases, concluding no distinct signal towards any direction of change (**Fig. A1**, **Tab. 4**). Compared to E-OBS data, the absolute projected precipitation sum is overestimated by the majority of simulations. While E-OBS data report mean precipitation sums of approximately 350 mm during the growing season, the ensemble shows a range of approximately 300 to 575 mm (**Fig. A3**). This does however not affect the validity of projected relative changes because those models that project rather wet conditions, show high precipitation values over the entire time series, while rather dry models likewise stay in the dry range (**Fig. A3**). Therefore, the relative changes of the models are still comparable. No distinct signal is visible concerning the projection of changes within the annual precipitation cycle since the ensemble range encompasses both increases and decreases (**Fig. 6**).

Dry spells

Concerning the number of dry spells, the median of +0.1 and the likely range of -0.2 to +0.7 dry spells per year during the growing season do not permit a distinct conclusion on the direction of change (**Fig. A4**, **Tab. 4**). In either direction, the possible projected change barely exceeds +/-1 dry spell. A change in maximum duration of dry spells is projected in the likely range of -5.0 to +16.6 % with a median of +0.08 %. Thus, no distinct sign of the direction of change is visible (**Fig. A7**, **Tab. 4**). The projected mean number of dry spells varies between approximately 4 and 7.5 dry spells (**Fig. A6**). Furthermore, the ensemble projects a mean maximum duration of dry spells between approximately 10 and 18 days. As for the East, results of two simulations (ca. 9.5 % of all simulations) differ considerably from the rest of the ensemble with a mean number of dry spells close to zero and a mean maximum duration of only about 5 days (**Fig. A6**, **Fig. A9**). Compared to E-OBS data, which indicate about 6.5 to 7 dry spells with a mean maximum duration of just below 16 days, the majority of simulations underestimate the number as well as duration of dry spells (**Fig. A6**, **Fig. A9**). Overall, similar to the East, no distinct signal is visible for changes in number and maximum duration of dry spells.

Hot days

With a median of +1.6 days and a likely range of +0.5 to +3.2 days, the ensemble projects an increase in the mean number of hot days (**Fig. A10**, **Tab. 4**). The result is, however, less pronounced than in the East. The narrow likely and ensemble ranges furthermore reveal a large agreement of the ensemble members (**Fig. A10**, **Tab. 4**). As in the East, no model projects a decreasing trend. Yet, the total number of hot days is likewise underestimated by the majority of ensemble members since E-OBS data report about 4 hot days in the NW while the ensemble projects between 0 and 4.5 hot days for the same period of time. The number of hot days ranges between approximately 0 and 8 days for the 2050s (**Fig. A11**). Since the majority of members tend to underestimate the total number of hot days when compared to E-OBS data, it might be even more likely to expect occurrences of hot days at the upper bound of the projected range.

Heat waves

The projected changes in the mean number of heat waves are similar to those of the East. The ensemble median projects an increase in the number of heat waves per year during the growing season (+0.1 heat waves, i.e. approximately 3 additional heat waves within a 30-year time period). The likely range from 0.0 to +0.3 heat waves only includes increasing values. The ensemble range of 0.0 to +0.4 includes mainly increasing values, too (**Fig. A12**, **Tab. 4**). In comparison to E-OBS data, more simulations overestimate than underestimate the number of heat waves (**Fig. A14**). Concerning the average duration of heat waves there is, however, no distinct indication for a change. The ensemble median of -0.3 is close to zero while the likely range of -1.2 to +0.7 includes increasing and decreasing values (**Fig. A15**). The time series of the individual simulations show abrupt jumps similar to those already discussed for the East in section 3.3.1 (**Fig. A16**, **Fig. A17**).

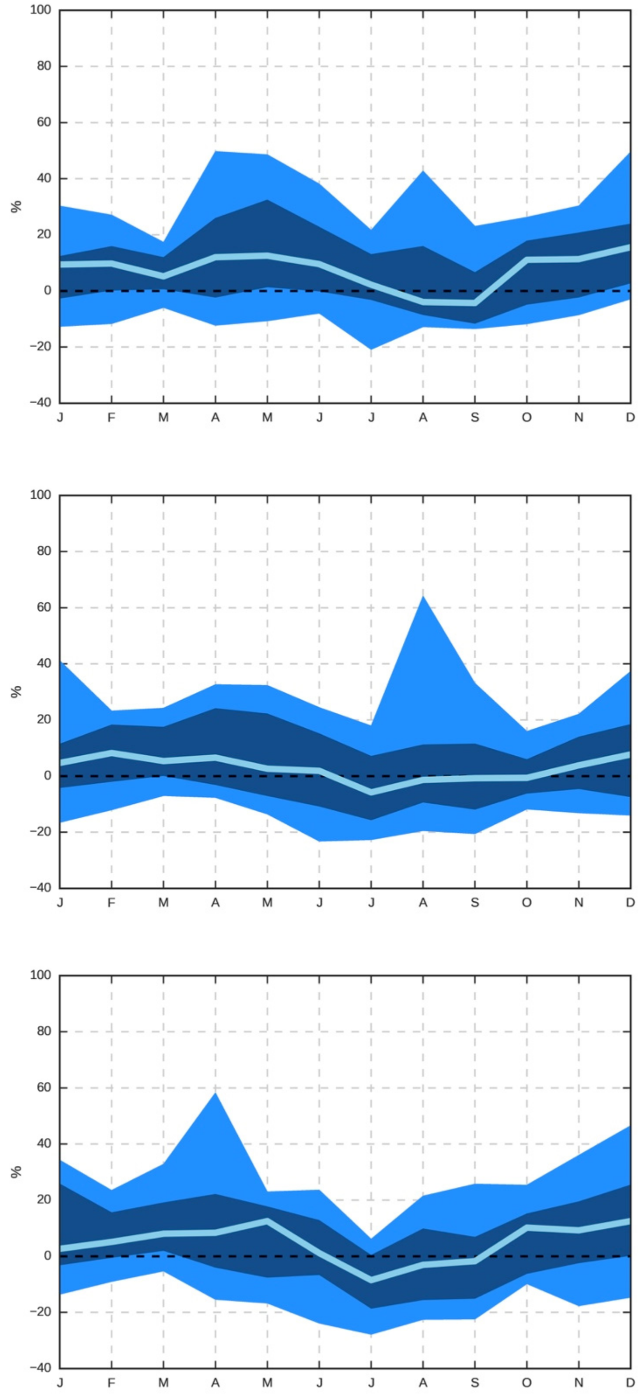

Fig. 6 Projected changes in mean monthly precipitation sums in the 2050s compared to 1971-2000 (in %) for regions E (top), NW (middle), and SW (bottom). Displayed are the ensemble median (light blue line), the likely range (dark blue shaded area), and the ensemble range (light blue shaded area).

3.3.3. Region 3: Southwestern Germany (SW)

Precipitation

Similar to the NW (see section 3.3.2), the ensemble does not show a distinct signal towards an increase or decrease for the SW. With a median of -0.7 % and a likely range of -6.6 to +4.0 %, no clear indication for a change is visible for the mean precipitation sum (**Fig. A1**, **Tab. 4**). Compared to E-OBS data, the projected absolute precipitation sum is overestimated by all but two (≈9.5 % of all simulations) simulations. While E-OBS data report mean precipitation sums of approximately 325 mm during the growing season, the ensemble shows a range of approximately 300-500 mm (**Fig. A3**). This does however not affect the relative changes projected by the individual ensemble members. No distinct signal is visible concerning the projection of changes in the annual precipitation cycle since the ensemble range encompasses both increases and decreases (**Fig. 6**).

Dry spells

The ensemble median of +0.4 dry spells in the 2050s projects an increase. The likely range (-0.2 to +0.9) includes mainly increasing values. However some ensemble members also project a decrease or almost no change. The median of RCP4.5 scenarios is lower (+0.1) than for RCP8.5 (+0.5) for the 2050s. The respective ranges are however of similar extent. For the time period of 2071-2100, the difference between the medians of the two RCP scenarios becomes more pronounced (RCP4.5: +0.1, RCP8.5: +1.3) (**Fig. A4**, **Tab. 4**). The projected absolute number of dry spells varies between about 4.5 and 7.5 dry spells per growing season. As for the first two regions (see sections 3.3.1 and 3.3.2), two outlier simulations (ca. 9.5 % of all simulations) project almost no dry spells (**Fig. A6**). Nevertheless, this does not affect the projected relative change since these simulations show this order of magnitude throughout the entire simulation period. Similarity to this behaviour is present for the mean maximum duration of dry spells. The median of +7.3 % projects a slight increase. Additionally, the likely range (0.0 to 14.6 %) projects an increase rather than a decrease (**Fig. A7**, **Tab. 4**). This does not exclude a decrease, yet, the majority of simulations point towards an increase or at least an almost constant maximum duration of dry spells.

As for the other two regions, E-OBS data reveal a higher occurrence (approximately 7.5 to 8) and a longer mean maximum duration of dry spells (approximately 15 to 16 days) than most of the simulations within the ensemble. As for the first two regions, the results of two simulations (ca. 9.5 % of all simulations) differ considerably from the rest of the ensemble for both indices. The mean number of dry spells is projected close to zero while the mean maximum duration is projected to be only about 5 to 6 days (**Fig. A6**, **Fig. A9**). As mentioned before, this does not influence the relative projected changes (see section 3.3.1 and 3.3.2).

Hot days

With a median of +5.0 hot days the projected increase is larger than for the other two regions. At the same time, the likely range of +2.6 to +10.0 days encompasses a wider range of possible increases. Yet, all simulations agree on an increasing trend concerning the number of hot days (**Fig. A10**, **Tab. 4**). For the 2050s no distinct difference is visible between the RCP scenarios; RCP8.5 scenarios only project a stronger increase than RCP4.5

scenarios towards the end of the century (**Fig. A10**). As seen before, most ensemble simulations tend to underestimate the total number of hot days and suggest a range from 0 to 20 hot days (except for two simulations (≈9.5 % of simulations) projecting approximately 30 hot days) (**Fig. A11**). Since the majority of members tend to underestimate the total number of hot days when compared to the E-OBS data, it might be even more likely to expect occurrences of hot days at the upper bound of the projected range.

Heat waves

The ensemble median (+0.3 heat waves) as well as the likely (+0.1 to +0.4 heat waves) and ensemble ranges (+0.1 to +0.6 heat waves) project an increase in the number of heat waves. The tendency for occurrence of more heat waves is slightly stronger for the SW than for the other two regions (**Fig. A12**, **Tab. 4**). Yet, the majority of ensemble members likewise underestimate the absolute number of heat waves (**Fig. A14**). For the 2050s no distinct difference is visible between the two RCP scenarios; RCP8.5 scenarios only project a stronger increase than RCP4.5 scenarios towards the end of the century (**Fig. A12**). It should also be noted that the likely range develops differently compared to the other two regions towards the end of the century. For 2071-2100 the ensemble shows a very broad likely range from +0.2 to +1.4, bearing a lower agreement of the ensemble members on the magnitude of change (**Fig. A12**, **Tab. 4**).

Concerning the average duration of heat waves, the median of +0.4 days and the likely range of -0.4 to +1.1 days do not project a distinct direction of change. The medians of RCP4.5 and RCP8.5 scenarios only show a slight difference for the 2050s, with the median of RCP8.5 scenarios (+0.9 day) projecting an increase while the median of RCP4.5 scenarios (+0.1 day) remains close to zero (**Fig. A15**, **Tab. 4**). Yet, the respective ranges do not differ considerably. The time series of the individual simulations show similar abrupt changes that were already discussed for the East (**Fig. A16**, **Fig. A17**, see section 3.3.1).

3.3.4. Comparison of the three case study regions

Precipitation

Compared to E-OBS data, precipitation sums are overestimated by the ensemble median in all regions. Furthermore, the absolute values projected by the ensemble are widespread (**Fig. A3**). Due to this large bandwidth, the projected values have to be treated with caution. To evaluate the model results, the focus should be on the projected changes. Concerning the precipitation sum an overall statement can only be made for the E, where an increase is expected, while there is no distinct signal for regions NW and SW. Therefore, a comparison of the case study regions concerning the relative changes is not truly possible.

Dry spells

According to E-OBS data, only small differences in the number of dry spells can be observed (E: 7 to 7.5, NW: 6.5 to 7, SW: 7.5 to 8) (**Fig. A6**). The comparison between E-OBS data and projected values reveals an underestimation of the number of dry spells by the ensemble in all regions. Therefore, it is more advisable to focus on the projected changes to make an assessment for the future conditions. Concerning the number and duration of dry spells an overall statement can only be made for the SW, where an increase in both indices is expected. There is no distinct signal for E and NW. A direct comparison of the regions concerning the projected changes in number and maximum duration of dry spells is therefore not truly possible.

Hot days

The number of hot days is one of two indicators where the ensemble agrees on a common trend in all regions. The largest increase in expected in the SW with a median of +5.0 days, followed by the East (+3.3 days) and NW (+1.6 days) (**Fig. A10**, **Tab. 4**). The SW is not only projected to experience the largest increase in the number of hot days, but is also projected to count the largest absolute number of hot days, followed again by E and NW. As E-OBS data show, the SW already clearly experiences the largest number of hot days (approximately 10 to 13 days observed). The E, following in second place, experiences between 6 and 8 hot days while the NW only counts 3 to 5 hot days (**Fig. A11**). This means that the SW is currently showing the largest number of hot days and is additionally projected to see the largest increase in the future. In contrast, the NW recorded the lowest number of hot days and is only projected to experience a moderate increase (**Fig. A11**, **Tab. 4**).

Fig. 7 shows a map of the projected ensemble medians for the whole country, in order to provide an overview of the ensemble results throughout Germany. It has to be noted that – as for the former indicators – the measured and projected absolute values cannot be compared directly. As has been discussed before, most models tend to underestimate the total number of hot days in comparison to E-OBS data. Therefore, the projected absolute values have to be treated with caution. Nevertheless, the changes can still demonstrate regional differences throughout the country.

Heat waves

The number of heat waves is the second indicator where the ensemble agrees on a common trend. The largest increase is expected in the SW followed by the East and the NW (**Fig. A12**, **Tab. 4**). As all likely ranges only include increasing values, it can be concluded that an increase in the number of heat waves is projected in all regions. E-OBS data reveal that currently no large differences in the number of heat waves exist between the regions, all of them experiencing up to 0.1 heat wave, i.e. heat waves do not occur every year. **Fig. B4** shows that there are barely any regional differences in the projected number of heat waves in the 2050s throughout Germany. Yet, the comparison to E-OBS data reveals an overestimation of the number of heat waves by many ensemble members. For this reason, the focus should – as for the other indicators – be on the projected changes instead of projected absolute values. Concerning the duration of heat waves, the signal is indistinct for all regions (**Fig. A15**, **Tab. 4**). A comparison of projected changes is therefore not truly possible. Unfortunately, no clear numbers can be taken for comparison from the E-OBS data, as they exhibit considerable jumps in the time series (compare **Fig. A17** and sections 3.3.1 to 3.3.3).

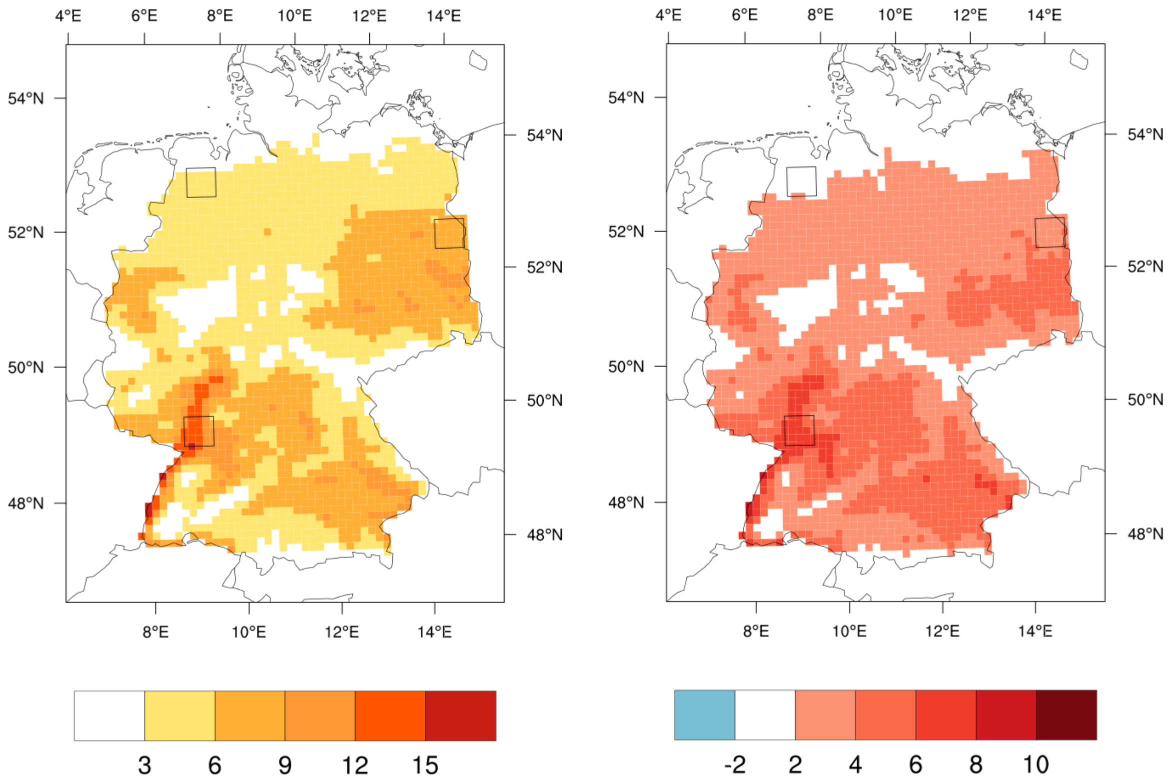

Fig. 7 Map of projected mean number hot days per year (MJJAS) in Germany in the 2050s (in days) (left) and map of projected changes in mean number of hot days per year (MJJAS) in Germany in the 2050s compared to the reference period 2071-2100 (in days) (right).

3.3.5. Summary of ensemble results

As can be seen from E-OBS data, the East is currently the driest of the three regions because precipitation sum during the growing season is lower and maximum duration of dry spells is longer than in the other regions. Furthermore, the East shows one of the highest numbers of dry spells. Concerning the number of hot days, the East ranges between the other two regions. The ensemble projects an increase in precipitation sum. However, the signals for changes in number and duration of dry spells are not distinct. The projected increase in precipitation sum could – under certain circumstances – lead to increased water availability if precipitation is evenly distributed over time. Yet, the increase in precipitation sum could also be caused by an increase in heavy rain events while dry spells are getting longer and more severe. This distribution, on the other hand, would cause a decrease in water availability. The projected precipitation sum alone does therefore not allow a forecast on any changes in water availability. Further indices that e.g. capture the simultaneous occurrence of heat and drought conditions could provide further information on water availability.

Moreover, the numbers of hot days and heat waves are projected to increase. Based on the projection, an increase in heat stress conditions could result from this change. In addition, high temperatures can cause or intensify drought conditions due to an increase in vapour pressure deficit of air and a consequent increase in evaporation. Still, there remains an uncertainty concerning the magnitude of projected changes in hot days and heat waves. Besides, without reliable information on the duration of heat waves, the sole increase in number does not allow a statement of the actual impact. As an example, the increased number and frequency of heat wave could be balanced by a simultaneous shorting of each respective heat wave. In this case the impact would be less severe than in the case of a simultaneous extension of heat waves.

The NW with its maritime climate is only moderately dry and warm compared to the other two regions. It currently receives the largest amount of precipitation during the growing season and has the lowest number of dry spells, which also have a shorter maximum duration than in the E. Moreover, the NW shows less hot days than the other regions. For the 2050s the ensemble projects an increase in the numbers of hot days and heat waves. In addition, no distinct projection can be given for the duration of heat waves, causing an uncertainty to whether the region will face more, shorter heat waves in future or more, longer heat waves. No distinct direction of change was projected for the other indices (precipitation sum, number and maximum duration of dry spells).

The SW is currently the warmest region, due to its location in the Upper Rhine Valley. Accordingly, the number of hot days is highest. At the same time, precipitation is lower than in the NW but higher than in the E. The SW is projected to experience a higher number and longer maximum duration of dry spells in the 2050s. Additionally, the numbers of hot days as well as number of heat waves are projected to increase. No certain statement can be made concerning the average duration of heat waves and the precipitation sum. Therefore it is unclear if the region will experience more frequent and longer heat waves or if heat waves occur more often but each one is shorter compared to the current situation. . According to the ensemble results, conditions in the SW in the 2050s are projected to be drier with a larger number of hot days than today. As a result, the already warmest region may experience increasingly stressful heat conditions in combination with longer and more frequent droughts. Yet, concerning the magnitude of changes there is still a bandwidth of possible changes. A summary of projected changes for all indicators and case study regions for the 2050s is provided in **Tab. 5**. The respective directions of changes are only given in cases where the ensemble shows a distinct signal towards one direction.

Tab. 4 Projected changes of the six climate indices for 2036-2065 compared to 1971-2000 for the three case study regions

Climate indices	Measure	East			Northwest			Southwest		
		Ensemble	RCP4.5	RCP8.5	Ensemble	RCP4.5	RCP8.5	Ensemble	RCP4.5	RCP8.5
Precipitation sum (%)	***Median***	**4.0**	4.0	6.5	**-1.3**	-2.3	-1.3	**-0.7**	0.0	-0.7
	Min	-6.8	-6.8	0.0	-13.0	-13.0	-4.2	-17.1	-17.1	-6.6
	Max	20.3	9.2	20.3	10.9	10.1	10.9	10.7	5.85	10.7
	Likely range	**0.5 to 9.2**			**-4.2 to 8.3**			**-6.6 to 4.0**		
Number of dry spells (no.)	***Median***	**-0.1**	-0.1	-0.1	**0.1**	0.1	0.2	**0.4**	0.1	0.5
	Min	-0.7	-0.6	-0.7	-1.0	-1.0	-0.5	-0.4	-0.4	-0.3
	Max	0.9	0.9	0.6	1.1	0.7	0.9	1.2	1.2	1.2
	Likely range	**-0.4 to 0.5**			**-0.2 to 0.7**			**-0.2 to 0.9**		
Duration of dry spells (%)	***Median***	**0.6**	-3.0	0.6	**1.3**	-1.2	2.1	**7.3**	9.9	6.6
	Min	-10.5	-10.3	-10.5	-11.3	-9.9	-11.3	-3.2	-2.7	-3.2
	Max	18.3	11.3	13.1	22.4	22.4	15.1	19.5	15.4	19.5
	Likely range	**-7.8 to 10.5**			**-5.0 to 16.6**			**0.0 to 14.6**		
Number of hot days (days)	***Median***	**3.3**	3.2	3.3	**1.6**	1.8	1.3	**5.0**	5.3	4.3
	Min	0.6	0.6	0.7	-0.1	0.2	-0.1	0.9	0.9	2.0
	Max	11.1	11.1	9.0	5.0	5.0	4.5	14.7	13.0	14.7
	Likely range	**1.3 to 5.1**			**0.5 to 3.2**			**2.6 to 10.0**		
Number of heat waves (no.)	***Median***	**0.1**	0.1	0.2	**0.1**	0.1	0.1	**0.3**	0.2	0.3
	Min	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.1	0.1	0.1
	Max	0.6	0.6	0.3	0.4	0.3	0.4	0.6	0.6	0.5
	Likely range	**0.0 to 0.3**			**0.0 to 0.3**			**0.1 to 0.4**		
Duration of heat waves (days)	***Median***	**-0.2**	-0.5	0.2	**-0.3**	-0.3	-0.5	**0.4**	0.1	0.9
	Min	-3.8	-2.8	-3.8	-2.7	-2.7	-2.3	-1.9	-1.8	-1.9
	Max	1.8	1.8	1.2	1.4	1.4	1.3	1.7	0.8	1.7
	Likely range	**-2.1 to 0.8**			**-1.2 to 0.7**			**-0.4 to 1.1**		

Tab. 5 Summary of projected changes for all indicators and case study regions for the 2050s. All indices refer to the growing season May – September. The median values of the ensemble are given for comparison.

Climate indices	East	Northwest	Southwest
Precipitation sum	increase (+4.03 %)	–	–
Number of dry spells	–	–	increase (+0.42 dry spells)
Maximum duration of dry spells	–	–	increase (+7.34 %)
Number of hot days	increase (+3.31 days)	increase (+1.63 days)	increase (+5.01 days)
Number of heat waves	increase (+0.14 heat wave)	increase (+0.11 heat wave)	increase (+0.25 heat wave)
Average duration of heat waves	–	–	–

3.4. Discussion of projected climatic changes

3.4.1. Analysis and interpretation of EURO-CORDEX ensemble projections

During the analysis of future changes projected by the EURO-CORDEX ensemble it became evident that there is no distinct trend for some indices in one or multiple regions. The only two indices where the ensemble projects a visible trend for all regions are the numbers of hot days and heat waves – both temperature-based indices. Generally speaking, precipitation is more difficult to model than temperature, as it depends on a larger variety of factors and has a higher spatial and temporal variability (EPA 2014). Latitude, altitude, prevailing wind and ocean currents, and solar radiation mainly determine temperature. Precipitation, on the other hand, is determined by large-scale circulation patterns and convective processes, but also by local topography and smaller scale processes like evaporation. Overall, precipitation can be classified into convective, orographic and cyclonic precipitation (Barry & Chorley 2009). The difficulty to correctly model precipitation is additionally increased by the fact that small-scale variations are larger for precipitation than for temperature (EPA 2014). For EURO-CORDEX projections in general, Kotlarski et al. (2014) report averaged seasonal and regional biases. While temperature biases are mostly smaller than 1.5 °C, precipitation biases are on average much larger and may be up to ±40 %.

A result can be defined as robust if it "*holds under a variety of approaches, methods, models, and assumptions and one that is expected to be relatively unaffected by uncertainties*" (Hennemuth et al. 2013: 119). Jacob et al. (2014) tested robustness of EURO-CORDEX modelling results using two statistical tests, the first on the agreement on the direction of changes and the second on the significance of changes based on the Mann-Whitney-Wilcoxon test. All projected changes of annual and seasonal mean temperatures in Europe were robust in their study (Jacob et al. 2014). Projected changes of total annual or seasonal precipitation, on the other hand, were only significant and robust in some areas. For Germany the results are particularly unclear for summer and autumn precipitation, where changes are not significant or robust for large areas within the country. Because this thesis works with a similar ensemble as Jacob et al. (2014), the projections were not statistically tested again for significance and robustness.

According to Jacob et al. (2014), total annual precipitation is overall projected to increase in Northern Europe and to decrease in Southern Europe. In between there is a zone with smaller and insignificant changes, including mainly parts of France, Italy, the Balkan Peninsula and the Black Sea region. Seasonal changes in precipitation were found to be more regionally heterogeneous. The zone with small and insignificant changes shifts northward in summer and southwards in winter. Consequently, Germany is included in the transition zone during summer and autumn. Thus, while the projected increase in winter and spring precipitation is mostly significant and robust, changes are less clear for summer and autumn. During these two seasons, no significant and robust changes are projected for large parts of Germany (Jacob et al. 2014).

The duration of heat waves is a temperature-based index. Nonetheless, it does not give a clear trend in this study, due to the fact that the statistical values are averaged over a 30-year period. Compared to dry spells, which occur several times during every growing season, heat waves are rather infrequent events. They do not occur every year, thus, statistically speaking less than one heat wave occurs per year. Mean values displayed in the time series were calculated for every 30-year period within the entire time frame. Thus, when shifting to the next time period under consideration, one year was added at the end of the 30-year period while one year was subtracted at the beginning. As a result an additional heat wave may be included compared to the previously calculated 30-year period or – on the other hand – a heat wave is excluded from the new period. Due to the fact that heat waves are currently rather infrequent events, a year with one or even more than one heat waves can strongly influence the 30-year mean, and thereby cause abrupt changes and rapid increases or decreases in the time series (compare **Fig. A16** and **Fig. A17**).

As demonstrated by the results, many ensemble members tend to over- or underestimate absolute values compared to E-OBS data. However, this does not imply that the projection of change for the future is not realistic. One model can assume very dry overall conditions compared to another models, but they can still agree on the direction and dimension of change. It is important to compare the modelled data to observational data in order to assess if a model displays a realistic range of values. Generally, absolute values should not be over-interpreted. The more ensemble members per scenario agree on the direction as well as magnitude of changes, the more reliable the projected trend becomes. Please note that many of the maps given in Appendix B display absolute values. While these have to be treated with caution, the maps can still be used for comparison of regional differences and spatial patterns of the projected changes in the indices.

RCP4.5 and RCP8.5 simulations are often projecting similar ranges and median values for the 2050s, while occasionally differences occur between the two RCPs in the later period (2071-2100) (see e.g. **Fig. 5**, **Fig. A7** and **Fig. A12**). The reason for this is related to the inertia, i.e. the delayed reaction, of the climate system to anthropogenic influences. While the near future is still dominated by decadal variations, impacts of increased greenhouse gas emissions mainly become apparent later on in the more distant future. This explains why the RCP4.5 and RCP8.5 pathways project similar results for the 2050s in many cases, but show increasingly different results for the end of the century.

EURO-CORDEX projections can be displayed in different formats. In this thesis, two kinds of time series (ensemble results or individual simulations) as well as maps are used to present the modelling results. As indicated above, time series and maps are two forms of data visualisation with different aims: displaying the temporal development of an index for one region or the spatial pattern of an index. Time series have the general advantage that different statistical measures (i.e. minimum, maximum, median values, likely range) can be summarised and visualized in one figure. For example, it becomes apparent, if the majority of ensemble members agree on the strength and direction of change (narrow likely range), or if they diverge strongly (broad likely range).

Furthermore, the entire range of projections is visible, which gives information beyond the ensemble mean or median. Especially in cases where the ensemble does not give a distinct signal concerning the projected direction or magnitude of changes, considering only the ensemble median can be misleading. A further advantage of time series is the visible development of the projections over time. While a map only displays one value per grid cell, only a time series can depict the projected temporal development of an index. It thereby allows an evaluation of the median values or ranges compared to earlier or later periods of time. The maps shown here, on the other hand, only show ensemble mean (≠ median!) values without taking into account ensemble or likely ranges. Thus, these maps do not give any information on the other statistical values. Basing interpretations solely on such singular values is critical, especially if the results of ensemble members vary largely.

Yet, maps are useful for analysing spatial patterns and comparing a case study region to its surrounding or other parts of the country. Since time series only give information on the area under consideration, it is not apparent if the surrounding is projected to experience similar changes or if the case study region is an exception, e.g. due to local differences in topography. Spatial patterns are furthermore easier to detect in a map than by comparing different time series. It is quite clear that both display formats provide different information and both have their advantages and limitations. A combination of both formats therefore gives more complete information on the ensemble projections.

3.4.2. Implications for the selection of urban tree species

For some of the indices, no robust changes could be deduced from the ensemble simulations. This is due to model uncertainties as well as natural climatic variability. Furthermore, additional indices would be needed to further investigate changes in actual water availability. The six selected indices – even provided the results were less ambiguous – do not specifically take the simultaneous occurrences of heat waves and dry spells into account. Furthermore, additional indices more focused on actual water availability (e.g. precipitation in relation to evaporation, soil moisture etc.) may give further insights. The exact implications for future climatic conditions that urban trees have to cope with remain to some extent unclear. The insufficient agreement of the ensemble on several indices allows drawing conclusions only to a limited extent and does alone not suffice for giving clear-cut recommendations for or against a certain tree species. Yet, this does not mean that the EURO-CORDEX ensemble provides insufficient information. Ensemble projections always provide a bandwidth of possible changes. Precipitation is still difficult to project, especially in transition zones such as the one in Central Europe. As Jacob et al. (2014) show, more distinct projections with a higher agreement of ensemble members are possible for other regions and in general for other indices. The partially weak agreement of ensemble members in this thesis shall therefore not be a counter-argument against using regional climate models such as the EURO-CORDEX ensemble.

The EURO CORDEX ensemble projects a larger number of hot days and more frequent heat waves. These conditions alone can already increase the risk of drought stress in plants due to reduced water availability as a consequence of increased evaporation. Furthermore, plant transpiration increases with higher temperatures. Despite the fact that the results presented here could not give a distinct indication for the other indices, other studies agree on some expected future changes in Germany. Many other studies (e.g. DWD 2015a, Christidis et al. 2014, Kovats et al. 2014, Jacob et al. 2014, EEA 2012b, European Commission 2009, Schuchardt et al. 2008), expect an increase in average temperatures in Europe, with the largest temperature increase in Northern Europe in winter and in Southern Europe in summer. Equally important, an increase in extreme events such as droughts and heat waves during summer is projected. For the whole of Europe, IPCCs AR5 (see Kovats et al. 2014) summarizes projected changes based on different studies. While for temperature there is a high agreement of climate models on a general warming trend in Europe, precipitation projections have larger variations, both seasonally and regionally. Even though uncertainty remains, the overall consensus in current literature is that vegetation will have to cope with warmer and drier summer conditions in Germany in the future. Even though uncertainties remain for precipitation-based indices, dry soil conditions can also be a consequence of increased temperatures and an increased evaporation (Kovats et al. 2014). Based on this assumption, adaptation to warmer and drier summer conditions will be necessary for the future. Anyhow, attention should be paid to the methods used in the different studies. Even though the use of ensemble simulations is state-of-the-art, some studies only consider individual models. Furthermore, not all of them have the high spatial and temporal resolution that the EURO-CORDEX data set offers. Even though a high resolution is not a guarantee for robust results, it still offers new results that were formerly not possible with coarser resolutions.

To be on the safe site, urban planners should take the general possibility of distinctly warmer and also drier summers into account when selecting tree species for urban areas – despite the remaining uncertainty. With respect to precipitation, also in the future, a large inter-annual variability is expected and could even be pronounced. Thus, adaptation to both decreased and increases water availability is needed. This thesis focuses specifically on a possible increase in heat and drought conditions, because already today trees often suffer from heat and drought stress in cities due to the harsh conditions within urban areas. It is therefore assumed, that an increase in available water may even be beneficial for trees in this context, while a decrease is generally expected to have negative impacts. Climate change adaptation is often undertaken with the objective to use *no regret* and *win-win* measures. This means that adaptation measures ideally provide more than one benefit. The adopted measures should not have any negative consequences (*no regret*) and should still be beneficial in another way (*win-win*), even if in the end climatic changes hold off or are less severe than expected (Gill et al. 2013, EEA 2012b, BMVBS 2011). In case of urban trees, selecting species that are tolerant to heat and drought can count as such a no regret measure: After all, in the worst case scenario the selected species are better adapted to stressful conditions than the alternatives. Yet, if conditions turn out to be less stressful than expected, the species can still grow well and provide their benefits as discussed in section 2.2.1.

4. Drought and heat tolerance of selected tree species

4.1. Overview of tree species characteristics

Ten broadleaf tree species are analysed for their climatological requirements, focussing on their tolerance towards drought and heat stress, in order to evaluate the future suitability under climate change impacts. The selection of species (see **Tab. 6**) was based on a vegetation survey in the urban park of Friesoythe, Lower Saxony. All species are commonly used as park vegetation all over Germany. Dry conditions and high temperatures often influence a tree simultaneously. Higher temperatures increase evaporation and thus accelerate soil drying and reduction in water availability (Roloff & Grundmann 2008a). Moreover, drought stress can not only be caused directly by a lack of precipitation and available water, but also indirectly through higher temperatures and the resultant enhanced evapotranspiration. Therefore the effects of drought and heat are not regarded separately but are discussed combined. As has been mentioned before, drought is not a synonym for dry spell, as not every dry spell necessarily causes drought conditions. Soil moisture content might be sufficiently high to provide enough water for plants during the period of lacking precipitation. On the other hand, in cases of very low soil moisture, a short dry spell may already cause drought stress in trees. Likewise, a heat wave can cause heat stress in trees, but local conditions such as moisture availability for cooling through plant transpiration influence how severely a plant is affected. Thus, not every heat wave causes the same signs of heat stress in trees. Dry spells, particularly in combination with heat waves can however cause drought conditions under certain circumstances (Bender & Schaller 2014). When using the term drought in this thesis, it is assumed that drought stress can develop as a consequence of a dry spell together with other factors.

Tab. 6 List of the ten selected broadleaf tree species.

	Botanical name	English name(s)
1	*Acer platanoides*	Norway Maple
2	*Acer pseudoplatanus*	Sycamore, Sycamore Maple,
3	*Aesculus hippocastanum*	Horse-Chestnut, Common Horse-Chestnut
4	*Alnus glutinosa*	Alder, Common Alder, Black Alder
5	*Betula pendula*	Silver Birch, European Birch
6	*Fagus sylvatica*	European Beech, Common Beech
7	*Fraxinus excelsior*	Ash, European Ash, Common Ash
8	*Populus nigra*	Black Poplar
9	*Quercus robur*	English Oak, Pedunculate Oak, Common Oak
10	*Salix alba*	Weeping Willow, White Willow

As this work focuses on projected climatological changes, other plant requirements e.g. with respect to soil conditions or light availability are excluded from the analysis. Nevertheless, in practice these factors have to be considered as well when selecting suitable species to ensure an optimal growth. An extensive literature review was carried out in order to estimate the drought and heat tolerance of the selected tree species. The sources of information include databases or publications that compare some or all of the ten species, as well as individual case studies that specifically focus on one or a few of them. As Wittig (2008) recognises, scientific literature has so far concentrated more on street trees than on trees within parks. In order to collect enough relevant information, this thesis therefore draws upon other literature as well e.g. with a focus on street trees or forestry. It also includes findings from studies on specific growth stages e.g. on seedlings, even though these may at firsts seem less relevant in an urban context. Most urban trees are cultivated in tree nurseries and are relocated to their destination within the city later on (Konijnendijk et al. 2005). Even though cultivation may take place outside the city, tree species are affected by changing climatic conditions as well. If they are very heat and drought sensitive in early growth stages, some individuals may not survive or show signs of damage that are undesirable in terms of vitality and aesthetics. This is unwanted in an urban context and may cause higher costs for the cultivation of the required number of vital trees and may affect the quality of cultivated trees. The relevant findings on tree seedlings should therefore not be left out completely.

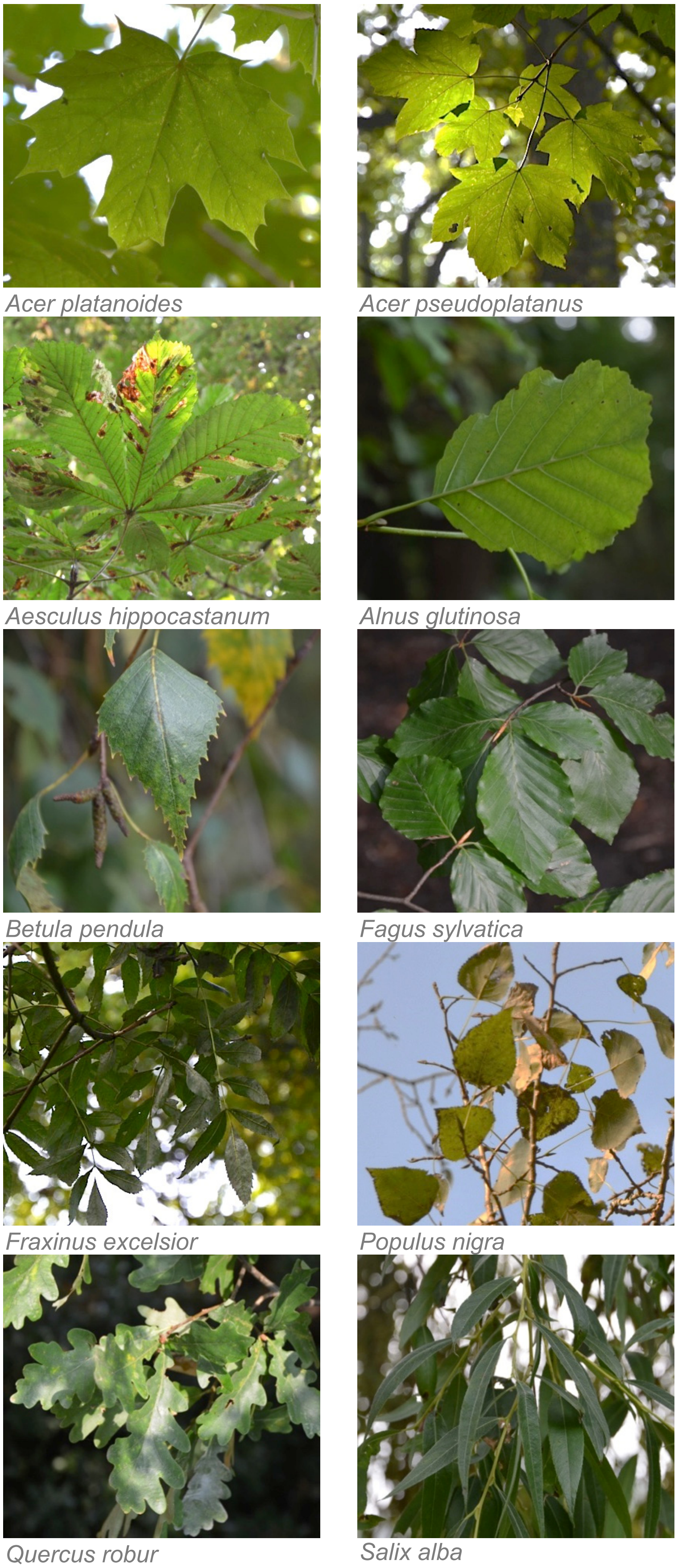

Fig. 8 Photographs of leaves of the ten selected tree species. *Source: own photos*.

4.2. Tolerance to drought and heat stress

4.2.1. Acer platanoides

The Norway Maple (*Acer platanoides*) is native to large areas of Central and Northern Europe, the Caucasus and Asia Minor, but has also been introduced to Western Europe and North America. Compared to the Sycamore Maple (*Acer pseudoplatanus*), *A. platanoides* has a larger expansion towards Northern and North Eastern Europe, but as a typical lowland tree it does not reach as high altitudes as its relative (rarely above 1000m altitude) (BWV 2006a, Schmidt & Roloff 1998). As *A. platanoides* needs warmth, it prefers a moderate continental climate with warm summers. Best growing conditions are found on fresh to moderately moist and loose soil.

According to GALK (2015), *A. platanoides* is heat tolerant. Compared to *A. pseudoplatanus,* it is less demanding in terms of water and nutrient supply (BWV 2006a, Breunig et al. 2002, Schmidt & Roloff 1998). The UK Forestry Commission (2015) classifies *A. platanoides* as moderately tolerant, implying it can tolerate approximately one month of drought if soil moisture content is reduced to a level around the permanent wilting point. According to Roloff & Grundmann (2008a) it is suitable for dry and very dry sites, too. Likewise, Roloff (2013a) argues *A. platanoides* is not sensitive to drought and has a high drought stress adaptation. On the other hand, LÖBF (2001) classifies dry and very dry sites as unsuitable and reports best growing conditions for slightly damp to damp soil. Carón et al. (2015) investigated the effect of high temperature and drought on germination and seedling survival of *A. platanoides* and *A. pseudoplatanus*. They concluded that both species might be negatively affected by increasing temperatures and reduced soil moisture. The effect was, however, stronger for *A. pseudoplatanus* while *A. platanoides* showed a higher germination success and seedlings were bigger on average with a larger root biomass. A larger root system can facilitate water uptake under dry conditions. Yet, *A. platanoides* is describes as thermophile and heat tolerant by GALK (2015).

In urban areas, Norway Maple is popular due to its striking florescence and fructification and its higher drought tolerance compared to *A. pseudoplatanus* (Schmidt & Roloff 1998). As *A. platanoides* can however also be negatively affected by high temperatures and more serious drought, a higher soil volume and a low percentage of sealed surfaces are favourable as urban growing sites (Gillner 2012). According to Roloff et al. (2009) and Roloff (2013a), *A. platanoides* can still be used in urban green spaces in the future, even though it is only limitedly suitable as roadside vegetation.

4.2.2. Acer pseudoplatanus

The natural area of Sycamore (*Acer pseudoplatanus*) comprises Eastern, Central and Southern European Mountains. The species prefers a Sub-Atlantic and humid climate, high rainfall areas and moderately moist to wet, alkaline soils (Aid 2014, Schmidt & Roloff 2009). It therefore has its optimum on mountain pastures and thus reaches higher altitudes than any other Acer species and most other broadleaf species (up to 1800 m) (Schmidt & Roloff 2009). However, it also occurs in alkaline lowlands of the North German Plain (Aid 2014). Its environmental requirements resemble those of *F. excelsior*. For good growth, *A. pseudoplatanus* has relatively high requirements concerning nutrient and water supply and therefore avoids dry and acidic soils (Aid 2014). On the other hand, it also avoids waterlogged and flooded sites (Breunig et al. 2002).

According to Weber-Blaschke et al. (2008), water supply is especially crucial within the first years to ensure successful establishment. The higher water requirements compared to *A. platanoides* can cause problems for Sycamore especially in lowlands and urban areas. This circumstance is complicated by its demand for large rooting space. In urban areas where rooting space is often limited, drought stress can be increased (Schmidt & Roloff 2009, Schneidewind 2004). Drought sensitivity of Sycamore is reported by various studies (e.g. Scherrer et al. 2011, Köcher et al. 2009, Weber-Blaschke et al. 2008, Hölscher et al. 2005, Lemoine et al. 2001). According to Lemoine et al. (2001), it is water-consuming and shows a high vulnerability to drought cavitation. Stunted growth and premature aging were found to occur on extremely hot and dry sites (Schneidewind 2004). Generally, *A. pseudoplatanus* is not seriously threatened by pests, water stress can however increase the tree's susceptibility to fungi (Schmidt & Roloff 2009).

Several case studies report negative effects of heat and drought: According to Gurk & Hepp (2015), *A. pseudoplatanus* is sensitive to heat. Schneidewind (2004) observed sunburn damages and even die off in young Sycamores under prolonged hot and dry conditions. Damages were particularly severe in exposed locations such as southern slopes and hilltops. A case study from Murray (1978) observed death in bark following warm years with intense drought conditions. It however remained unclear, if bark death was a direct consequence of drought or a secondary effect of the observed fungal attack following the drought. Biomass measurements by Khalil & Grace (1992) indicate a weight shift under drought from shoot to root biomass. The total biomass remained unaffected. The study found an increase in root biomass and an altered root distribution under drought conditions. Shoot and leaf expansion was simultaneously reduced. Sap flow measurements by Scherrer et al. (2011) reveal a significant reduction in sap flow under prolonged drought (22 days). Reductions were more pronounced in the rather dry sites compared to the rather moist sites of the study. Stöhr (2003) likewise reports a reduction of sap flow during the day, resulting from a closing of the stomata.

A. pseudoplatanus is frequently used as urban tree due to its ability to bind particulates (e.g. ozone and nitrogen oxide) and to reduce noise (Schmidt & Roloff 2009). Yet, because of the above mentioned drought sensitivity, Gillner (2012) suggests a restriction for the use in urban areas. It should only be used in parks or other green spaces with more favourable growing conditions than roadsides. Today it is popular in urban parks and green spaces and ranks among the most frequently used tree species in cities (Schmidt & Roloff 2009). As *A. pseudoplatanus* is sensitive to heat accumulation and sealing of soils, its suitability for road space is restricted (Schneidewind 2004). Furthermore, vitality losses and increasing level of damage were observed in recent years, which were attributed to the higher water demand of Sycamore compared to other species (Schmidt & Roloff 2009). Falk et al. (2013) see only low cultivation risk under current conditions. Regardless, for 2100 an increased risk is assumed for *A. pseudoplatanus* under a projected warming and increase in drought stress. This is in line with the above-mentioned sources, which classify *A. pseudoplatanus* as a moderately drought and heat sensitive species and due to the observed increase in drought and heat related damages.

4.2.3. Aesculus hippocastanum

The Common Horse-Chestnut (*Aesculus hippocastanum*) originates from mountainous areas on the Balkan Peninsula. It was, however, introduced to Central Europe where it is widely distributed today (BWV 2006b, Schmidt & Roloff 1996). Naturally, it mainly occurs in partially shaded, wind protected sites in altitudes of up to 1300m. *A. hippocastanum* prefers moist and warm sites. Despite that, it has a large ecological amplitude and can cope with a variety of climates. It is furthermore undemanding in term of soil nutrients (BWV 2006b, Schmidt & Roloff 1996). The Common Horse-Chestnut is however sensitive to road salt, drought of upper soil layers and water logging, which can negatively affect the tree (Fischer 2005). Being economically uninteresting to forestry, *A. hippocastanum* is mainly used as an urban tree in Central Europe, primarily due to its shading potential and aesthetical value (Roloff 2005, Schmidt & Roloff 1996). Karliński et al. (2014) report a high degree of plasticity of the roots, which can adapt well to rural as well as urban soil conditions.

According to the UK Forestry Commission (2015), *A. hippocastanum* is only moderately tolerant to drought. It can tolerate approximately one month of drought if soil moisture content is reduced to a level around the permanent wilting point. Water requirements and drought sensitivity are both described as moderate. Overall, it is therefore classified as drought sensitive rather than drought tolerant (Roloff 2013a). Roloff et al. (2009) furthermore classify *A. hippocastanum* into the last category concerning drought tolerance, ranking the species as not very suitable for urban areas under increasing drought conditions. In recent years, the invasive Horse-Chestnut leaf miner (*Cameraria ohridella*) infested an increasing share of the population, causing mainly aesthetic damages (Schmidt & Roloff 1996). *A. hippocastanum* can cope with the pest infestation without lethal damage for several years, nevertheless, reoccurring stress in combination with drought stress or salt contamination in urban areas can seriously weaken the tree and diminish reproductive potential (Aas & Lauerer 2005, Schmidt & Roloff 1996). *A. hippocastanum* may be negatively affected by climate change in case of increasing drought conditions due to the mentioned drought sensitivity and the increasing infestation by the Horse Chestnut leaf miner.

4.2.4. Alnus glutinosa

The Common Alder (*Alnus glutinosa*; also: Black Alder) is widely distributed throughout Europe, predominantly in lowlands and lower mountain ranges (Aid 2014, Pietzarka & Roloff 2000). It requires sufficient light and warmth during the growing season, but also tolerates frost and late frost (BWV 2006c, Walentowski & Ewald 2003, Breunig et al. 2002). *A. glutinosa* endures temperatures of up to 44°C without damages to the leaves (Claessens et al. 2010). Because of its fast growth and short maximum life span, *A. glutinosa* can be characterised as a pioneer species (Pietzarka & Roloff 2000). It is very demanding in terms of water supply and soil moisture, as it primarily colonizes moist or temporarily flooded sites (Claessens et al. 2010, BWV 2006c, Walentowski & Ewald 2003). According to Claessens et al. (2010), its natural distribution range is limited to the East where annual precipitation fall is below 500 mm. The high water demand is due to the fact that the Common Alder is assumed to be the tree species with the highest transpiration. As this tree does not regulate transpiration, evaporation was observed to be equal to total annual precipitation (Claessens et al. 2010). It is thus very sensitive to drought and consequently mainly colonizes sites along streams or soils with sufficient groundwater influence (Copolovici et al. 2014, Pietzarka & Roloff 2000). If groundwater is not accessible, larger amounts of precipitation are required, otherwise *A. glutinosa* suffers from drought stress (Claessens et al. 2010). Growth is limited or becomes stunted on drier sites due to cavitation, which occurs especially within the root system that is more vulnerable to the formation of embolisms than branches (Hacke et al. 2014, BWV 2006c).

According to Roloff & Grundmann (2008a), *A. glutinosa* is very suitable for wet to moist sites but not suitable for slightly dry to dry sites. Its adaptation to drought is described as moderate by Roloff (2013a). Yet, the author points out that *A. glutinosa* can generally also thrive under limited water availability, but only if the individual tree has adjusted to dry conditions right from the start. Otherwise, it is more demanding in terms of water supply. According to Claessens et al. (2010), establishment of *A. glutinosa* is difficult in unfavourable sites with moisture deficits. This suggests that cultivation in dry urban areas is problematic. The UK Forestry Commission (2015) classifies it as intolerant, which means it only tolerates short drought periods and no extensive soil drying. Currently, Falk et al. (2013) estimate only a low cultivation risk for *A. glutinosa*, yet, for 2100 an increased risk is assumed under a projected warming and increase in drought stress. Due to its low drought tolerance, Roloff et al. (2009) classify *A. glutinosa* as unsuitable with respect to drought for urban areas under climate change.

4.2.5. Betula pendula

Originating from Europe, Asia Minor, the Caucasus, Northern Persia and Siberia, Silver Birch (*Betula pendula*) colonizes a range of different habitats such as dunes, clearings, heathlands and mires. It possesses a relatively wide ecological amplitude. Silver birch is a popular tree species for urban areas due to its aesthetical and cultural value, yet allergies to Birch pollen can be problematic in cities (Roloff 2013a, Roloff & Pietzarka 2000). As a typical pioneer species it has a high need for light but is not very demanding in terms of soil properties, warmth, and water availability and can grow also under more extreme conditions (Roloff & Bonn 2008, Burk 2006, BWV 2006d, Aspelmeier & Leuschner 2005, Roloff & Pietzarka 2000). Consequently, *B. pendula* can endure frost, heat, and pests and thrives on nutrient poor, dry, and acid as well as on moist soils (Burk 2006, BWV 2006d, Breunig et al. 2002). However, in terms of water availability, the individual tree has to be accustomed to dry conditions from an early age. Sudden decreases in water availability can otherwise provoke yellowing and shedding of leaves because Silver Birch has a very high transpiration rate (430-480 mm / year). Thus, closing of stomata and ultimately shedding of leaves are necessary to reduce transpiration losses (Burk 2006, Roloff & Pietzarka 2000).

A study by Aspelmeier & Leuschner (2005) recorded a reduction in leaf sizes and growth rate as response to drought conditions in two subsequent years. Furthermore, total leaf area was highly reduced due to decreased growth and shedding of leaves. In case of dehydration *B. pendula* may even shed the entire canopy, which was however found to be able sprout newly after re-watering. Therefore, shedding of leaves serves as morphological adaptation to drought and does not necessarily imply an inability to cope with drought (Aspelmeier & Leuschner 2005). Furthermore, the study identified higher mortality of fine roots due to cavitation and a reduced shoot growth suggesting that carbon allocation shifts towards the root system. The case study by Gartner et al. (2009) reports a decrease in sap flow rates and transpiration under drought stress. *B. pendula* is able to adapt transpiration and sap flow to low soil water availability quickly. Additionally, it can extract water from deeper soil horizons than spruce, to which *B. pendula* was compared in the study. Due to this adaptation to drought conditions, Silver Birch as a typical pioneer species can cope with unfavourable water supply (Gartner et al. 2009). Burk (2006) likewise describes the ability to extract water from deeper soil layers. Additionally, study results indicate that vessels that are re-filled with water after cavitation can still be functional after a period of moderate drought stress. In the same way measurements by Fort et al. (1998) reveal the ability to absorb water from very dry soils. In case water content becomes too low, shedding of leaves occurs.

Overall, *B. pendula* is classified as very suitable for dry and very dry sites (Roloff & Grundmann 2008a) as it has a fairly high adaptation to drought (Roloff 2013a). It should however be noted that drought tolerance is highest when the individual tree is used to dry conditions right from the start. Individuals that are adapted to a better water supply are also more demanding in times of drought stress (Roloff 2013a). The UK Forestry Commission (2015), on the other hand, describes *B. pendula* as intolerant to drought, implying it does not tolerate longer drought periods or severe soil drying. This estimation stands in contrast to the before-mentioned characteristics of a pioneer species and the drought tolerance evaluation of other studies. Roloff et al. (2009) classify *B. pendula* as suitable for urban areas under climate change with regard to drought tolerance. Bolte et al. (2012) estimate Birch to be a 'winner' in the face of climate change.

4.2.6. Fagus sylvatica

Because of its high competitiveness and shade tolerance, European Beech (*Fagus sylvatica*, also: Common Beech) belongs to the most widespread forest trees and is one of the economically most important broadleaf trees in Europe (Burk 2006, Felbermeier & Mosandl 2002). It is found all over Central Europe from Northern Spain, to Southern Sweden, the Balkans, and Western Russia (BWV 2006e). *F. sylvatica* prefers a moderate to moderately warm climate with mild winters and no distinctive drought periods. Thus, it favours maritime climates over continental climates (BWV 2006e, Felbermeier & Mosandl 2002). Even though European Beech outcompetes most other tree species under medium conditions (not too wet and not too dry), it is susceptible to drought, flooding, and frost. Therefore, gaps occur within the distribution on very dry or water-logged sites and regions with too severe winters (Muck et al. 2009, Felbermeier & Mosandl 2002).

According to the Bayerischer Waldbesitzerverband e.V. (2006a), annual precipitation should be at least 600mm. Aid (2014) advice against planting *F. sylvatica* on sites with a precipitation sum lower than 250 mm between May and September. The species is especially drought sensitive in early summer (Muck et al. 2009). *F. sylvatica* finds optimum growing conditions in deep, loose, alkaline, and moist soils (BWV 2006e). While European Beech is frequently used for urban parks, it has no importance as roadside vegetation, among others, due to its sensitivity to drought and road salt (Gillner 2012, Hölscher et al.

2005, Felbermeier & Mosandl 2002). According to Gurk & Hepp (2015) and Rennenberg et al. (2006), *F. sylvatica* is somewhat intolerant of towards heat stress. Generally, the number of serious pests is rather low (Felbermeier & Mosandl 2002).

The UK Forestry Commission (2015) classifies *F. sylvatica* as intolerant to drought. According to Roloff (2013a), adaptation to drought stress is likewise only moderate. Roloff & Grundmann (2008a) characterise slightly dry sites as suitable. Nevertheless, dry and very dry sites are only considered limitedly suitable. The main reason for the susceptibility to drought is the rather large leaf-area, a high risk of cavitation, and the fine root system that appears to be only limitedly adapted to drought. According to Leuschner (2009), young *F. sylvatica* trees are sensitive to both soil drought and dry surrounding air. In contrast to many studies that characterize *F. sylvatica* as drought sensitive (e.g. Aid 2014, Berry et al. 2012, Gillner 2012, Muck et al. 2009, Friedrichs 2008, Czajkowski et al. 2005, Felbermeier & Mosandl 2002, Aranda et al. 2000), other authors grant the European beech a higher tolerance to drought (Roloff & Grundmann 2008a, Dittmar & Elling 2007, Gallé & Feller 2007, Nahm et al. 2006, Dittmar et al. 2003). (Roloff & Grundmann 2008a) state that the potential for drought stress adaptation is often underrated because *F. sylvatica* can adapt to temporary drought conditions using reversible morphological changes, such as changes in root-shoot-ratio, as it possesses a wide genetic variability.

Besides these contradictory assumptions, there is evidence of the importance of provenances in the reaction to drought (Gillner 2012, Seifert 2011, Lendzion & Leuschner 2008). *F. sylvatica* has a wide genetic variety (Roloff & Grundmann 2008a, Sutmöller et al. 2008). Provenances from drier regions show higher water use efficiency and higher drought tolerance. The difference in drought sensitivity in different provenances is supported by a study by Fotelli et al. (2009), who report no drought-related limitations in Greece under similar conditions to those causing stress for Beech in Central European sites where droughts are less common. According to Seifert (2011), ecophysiological reactions of beech populations across Europe differ according to their location, even though stress conditions are similar. Even within Germany different ecotypes with varying drought sensitivity are reported by Peuke & Rennenberg (2004) and Burk (2006). García-Plazaola & Becerril (2000) describe differences in drought responses among different provenances, causing various levels of tolerance to drought depending on their degree of morphological adaptation. Southern beeches are better adapted to drought, photoinhibitory injury, and ozone damage than northern provenances. A high degree of plasticity of fine roots was found across a precipitation gradient (Seifert 2011, Meier & Leuschner 2008). According to these findings, it may be necessary to further distinguish between different provenances when analysing *F. sylvatica* for its drought tolerance. As more drought tolerant provenances produce seedlings with a higher tolerance (Seifert 2011), the use of seedlings from drier regions that cope better with drought may be considered for urban areas under climate change.

Concerning the required annual precipitation, different values can be found in literature, which again may be attributed to the described variety of drought sensitivity. Burk (2006) compares different studies that assume minimum annual precipitation sums ranging from 471 mm to 600-700 mm per year. Consequently, there is a disagreement on the needed amount of precipitation. Different precipitation requirements may arise from the varying requirement of the different provenances. In any case, Burk (2006) indicates the importance of other environmental factors, such as soil conditions. Sutmöller et al. (2008) point out that soil water availability is a limiting factor for the distribution. Climatic information alone is not sufficient to predict the ability of a species to adapt to future conditions. Yet, a study by van der Werf et al. (2007) identifies a relationship between growth of *F. sylvatica* and the temperature of the previous growing season as well as the June temperatures of the current year. While many studies focus on the effect of soil drought, Lendzion & Leuschner (2008) refer to the consequences of an increase in air water vapour saturation deficit, which may become more important under future climate change.

Irrespective of the threshold underneath which European Beech suffers from heat and drought stress, several signs of damage have been observed. Case studies during extremely dry years and the respective following years reveal the possible impacts of drought conditions. Reduced growth as a consequence of drought has been observed in various studies (Bolte et al. 2012, Michelot et al. 2012, Meinardus & Bräuning 2011, Scharnweber et al. 2011, Seifert 2011, Grundmann et al. 2008). Analysis of tree rings and pointer years revealed the effect of current year precipitation. Even more pronounced a positive relationship between radial growth and precipitation during the previous summer was found. This indicates that abundant precipitation during the previous summer fosters growth, while drought during previous summer inhibits growth (Michelot et al. 2012, Meinardus & Bräuning 2011, Grundmann et al. 2008, Geßler et al. 2006, Czajkowski et al. 2005). According to Bolte et al. (2012) the risk of vitality loss is expected to increase, if several years of unfavourable conditions occur subsequently without time for recovery.

A relationship between growth and temperature was found, too. Growth appears to be negatively correlated to maximum temperatures in previous August and current June and July, i.e. too high temperatures may limit growth (Michelot et al. 2012). According to Felbermeier & Mosandl (2002), high temperature above 47 °C is lethal to leaves of *F. sylvatica*. Sutmöller et al. (2008) identify continental conditions with July mean temperatures above 19 °C as one limiting factor to distribution. Yet, more of the investigated studies focus on the effect of drought.

Further reactions to drought, beside growth reductions, include early shedding of leaves during summer, cavitation, thickening of the cuticle, yellowing and curling of leaves, and degradation of chloroplasts (Burk 2006, Felbermeier & Mosandl 2002). According to Leuschner et al. (2001), different tree organs and processes show different sensitivity to soil drought, fine roots and stem being more sensitive than photosynthesis and leaf expansion. Felbermeier & Mosandl (2002) report beechnuts remaining sterile or falling off prematurely in dry summers. Moreover, pre-dawn leaf water potentials showed only low recovery during several days of drought (Gillner 2012). Accordingly, Köcher et al. (2009) report an inability of *F. sylvatica* to stabilize pre-dawn leaf water potential under soil drought conditions, which means the tree cannot adequately compensate for day time water loss during the night. Furthermore, unlike other tree species, *F. sylvatica* does not seem to have a good capacity for osmotic adjustment under drought conditions (Lendzion & Leuschner 2008).

At different German sites, crown defoliation was observed in 2004, following the 2003 summer drought (MELUR 2013, MLR Baden-Württemberg 2013, NW-FVA 2013a, BMELV 2012). Even though the situation improved, full recovery was not reached even after several years (BMELV 2012). Nonetheless, Bolte et al. (2012) remind that it is still uncertain whether defoliation is a damage to *F. sylvatica*, or a necessary form of adaptation. Additionally, NW-FVA (2013b) mentions an increase in strong fructification during the recent decades that is attributed to an accumulation of warm years, as intensive flowering and fructification is often caused by high temperatures in the previous year. In years with strong fructification, a larger amount of reserve substances is needed, wherefore fewer reserves are available for other processes (Sutmöller et al. 2008). For this reason, sparse foliage is not necessarily drought damage but may be a consequence of intensive fructification (MLR Baden-Württemberg 2013).

Several studies expect decreasing growth trends, vitality losses and/or decreasing fitness and species abundance in case of increasingly hot and dry conditions (Carón et al. 2015, Scharnweber et al. 2011, Leuschner 2009, Sutmöller et al. 2008, Geßler et al. 2006). According to Leuschner (2009), dry spells and heat waves will be the dominating influences in future with more severe impacts than other factors, e.g. ozone and soil contamination. Therefore, the author recommends refraining from planting *F. sylvatica* in areas with annual precipitation below 650 mm in the future as well as in regions where a precipitation decline during the growing season is expected. Roloff & Grundmann (2008a) assume that parts of Brandenburg and Saxony may partially become too dry for *F. sylvatica* in the future.

On the other hand, Scharnweber et al. (2011) advise to take the differences between provenances concerning drought tolerance into account and not to underestimate adaptation potential of Beech populations. Geßler et al. (2006) additionally point out that other environmental factors such as soil characteristics also influence the site-specific drought effect. As Gärtner et al. (2008) state, the future of *F. sylvatica* under climate change it is still under debate. Even though some studies expect an increase under warmer conditions, several others support the assumption that increasing drought and heat stress will negatively affect the species. There is only a consensus that severe water stress generally reduces growth. Yet, the question remains, if the future conditions in a specific location will be too severe or if *F. sylvatica* will be able to adapt.

4.2.7. Fraxinus excelsior

European Ash (*Fraxinus excelsior*; also: Common Ash) is distributed over large parts of Europe from Scotland and Southern Scandinavia to Northern Spain, Southern Italy, Western Russia, and the Caucasus (BWV 2006f, Stöhr 2003). Its core area is in lowlands to submontane areas with sub-Atlantic to Sub-Mediterranean climate (Aid 2014). While *F. excelsior* is tolerant to shade during youth, the species becomes more light demanding with older age (Clark 2013, Roloff & Pietzarka 1997). *F. excelsior* is characterised by a wide ecological amplitude that allows growth under a range of different climatic, soil and water conditions (Clark 2013, Tissier et al. 2004, Stöhr 2003, Marigo et al. 2000). It is found on moist, nutrient rich soils, to some extent even influenced by backwater, on floodplains, as well as on dry sites with temporary drought stress e.g. on hilltops with shallow soil (Kölling & Walentowski 2001, Roloff & Pietzarka 1997). *F. excelsior* is sensitive to frost and late frost and prefers warm sites (Breunig et al. 2002, Roloff & Pietzarka 1997). GALK (2015) describes it as heat tolerant. According to Roloff & Pietzarka (1997), *F. excelsior* has to cope with a number of pathogens, yet, none of them is currently threatening its existence. Due to its tolerance to drought, road salt, soil compaction, and pollution, its aesthetic value, and the lack of severe disease or pathogen problems, Percival et al. (2006) recommend it for urban areas. In urban areas it is frequently used as street tree or within green spaces (Roloff & Pietzarka 1997).

Several authors describe the European Ash as sensitive to drought and point out its high water demand (Aid 2014, Weber-Blaschke et al. 2008, BWV 2006f, Kölling & Walentowski 2001, Roloff & Pietzarka 1997). On the other hand, *F. excelsior* is described as drought-tolerant by other authors (e.g. Roloff 2013a, Scherrer et al. 2011, Lemoine et al. 2001). The UK Forestry Commission (2015) classifies it as intolerant to drought, implying it does not tolerate longer drought periods or severe soil drying. According to Roloff & Grundmann (2008a), *F. excelsior* is suitable for moderately dry sites but only limitedly suitable for dry to very dry sites. Thus, very dry sites are not recommendable as it suffers under prolonged drought conditions and reacts with early shedding of leaves (Roloff & Pietzarka 1997). According to the Bayerischer Waldbesitzerverband e.V. (2006b), the European Ash is generally tolerant with respect to different levels of soil moisture but sensitive towards drought. Roloff & Pietzarka (1997) and Weber-Blaschke et al. (2008) indicate a dependence on precipitation in May and June, irrespective of soil water reserves, as it requires a large amount of water during the time before budding. Generally, there is an agreement in literature that *F. excelsior* features an astonishing ability to respond to different environmental conditions due to its large ecological flexibility (Clark 2013, Stöhr & Lösch 2004, Stöhr 2003, Marigo et al. 2000, Roloff & Pietzarka 1997). Despite its very high transpiration rate (stomatal conductance 5-12 mmol m^{-2} s^{-1}) and a low water-use efficiency, *F. excelsior* appears to be well adapted to moderate drought stress (Roloff 2013a, Stöhr & Lösch 2004, Guicherd et al. 1997).

Under water stress *F. excelsior* adapts by osmotic adjustment and leaves that tolerate low water potentials, i.e. using an anisohydric rather than isohydric strategy (Lendzion & Leuschner 2008, Stöhr & Lösch 2004, Marigo et al. 2000, Guicherd et al. 1997) During a summer drought in 2006 sap flux density remained constant during the entire drought period, while *F. excelsior* developed and endured low leaf water potentials, preserving adequate leaf conductance and assimilating sufficient CO_2. Additionally, the fine root system remained vital. Compared to other species such as beech and sycamore, *F. excelsior* was able to cope best with prolonged drought conditions (Köcher et al. 2009). Scherrer et al. (2011) report that *F. excelsior* was not negatively affected by a 22-day drought, with no measured reduction in sap flow rates. Stöhr (2003), on the other hand, observed a decrease in sap flow over the day, yet leaf and stem water potentials were likewise low. Furthermore, a measured ongoing xylem sap flow during night-time was attributed to re-filling of the tree's water reserves.

Concerning future expectations, Bolte et al. (2012) suggest a slightly positive future for *F. excelsior* compared to other species that suffer more under warmer and drier conditions. According to Scherrer et al. (2011), its drought tolerance will be beneficial in the near future. Other studies concerning the future of *F. excelsior* in the UK are however more critical and expect future conditions to become more unsuitable for European Ash (Berry et al. 2012, Broadmeadow et al. 2005). Judging from the different scientific results that overall report very effective adaptation mechanisms to drought and indicate a decreasing suitability under very dry conditions, it may be assumed that *F. excelsior* – depending on the local conditions – will be able to cope better with drier and warmer future conditions than several other species. Nevertheless, it may be affected, too, if drought stress becomes too severe.

4.2.8. Populus nigra

Due to a large amount of hybrids and plantings of Black poplar (*Populus nigra*), its natural habitat is hard to define. Additionally, pure *P. nigra* individuals are rarely found in some regions due to the high degree of hybridisation. Today it is widely distributed within Europe, Northern Africa as well as Western and Central Asia and is found in lowlands to colline and submontane regions (Huber 2010, BWV 2006g, Weisgerber 1999). *P. nigra* prefers warm temperate or boreal climate with sufficient water supply and light availability. It demands high nutrient availability and good aeration of the soil (Roloff & Bonn 2008). Furthermore, as it is adapted to high soil moisture and temporary flooding for several weeks, Black poplar frequently colonises floodplains along rivers (Huber 2010, Weisgerber 1999). It does not only tolerate high moisture but even requires it as it belongs to the native tree species most sensitive to drought (Marron et al. 2006, Monclus et al. 2006, BWV 2006g). Compared to other native poplar species the Black Poplar is the most drought sensitive one (BWV 2006g). Typical of a pioneer species, *P. nigra* has very high growth rates, which is why it needs such large amounts of water. Furthermore, it shows high risk of cavitation (Durand et al. 2011, Fichot et al. 2010). One side effect of water deficits is the decreased resistance to diseases such as bark necrosis caused by the fungus *Cryptodiaporthe populea* (Weisgerber 1999). According to Roloff & Grundmann (2008a), *P. nigra* is not suitable for dry to very dry sites but suitable for moist to moderately dry sites. The UK Forestry Commission (2015) considers Black poplar intolerant of drought, implying it does not tolerate longer drought periods or severe soil drying. Likewise, it is classified as drought sensitive by (Roloff 2013a).

A study by Centritto et al. (2011) observed decrease in photosynthetic capacity as a reaction to drought stress, which was however restored approximately one week after re-watering. Elevated temperature at the same time enhanced light and dark respiration, causing an increase in the ratio of respiration to photosynthesis. As a consequence, *P. nigra* will strongly suffer under drier and warmer future climate conditions. Durand et al. (2011) found leaves to be affected by drought prior to cambium. *P. nigra* is a species that comprises a variety of hybrids and considerable genotypic variations (Fichot et al. 2010). Different genotypes and hybrids were investigated for their drought tolerance and water use efficiency by Monclus et al. (2005). The study concluded that *P. nigra* comprises a range of different drought tolerances. The same conclusion was drawn in a study by Regier et al. (2009), who compared a clone from a more arid region with a clone from a more humid region. The latter showed symptoms of drought stress while the former appeared to cope better with drought conditions. Thus, for plantation of *P. nigra* a type adequate to the local conditions should be used. Concerning future climatic changes, Monclus et al. (2005) considers a possible increase in drought events as problematic. Plantations thus have to focus on less drought sensitive hybrids with a better water use efficiency. Judging from the available literature, *P. nigra* appears to be one of the most drought sensitive of the selected trees. For this reason, the species does not appear to be the best choice in future in an urban context, which is already characterised by low water availability.

4.2.9. Quercus robur

Common Oak (*Quercus robur*; also: English Oak, Pedunculate Oak) is one of the most common and economically important forest trees in Central Europe. It is distributed over vast parts of Europe with northern limits in Scotland, Ireland, and Southern Scandinavia, eastern limits at the Ural Mountains and Southern limits in Southern France, Northern Spain, and Portugal (Aas 2002). The core distribution area is in low altitude regions with the temperate continental climate of Central Europe (Aid 2014). *Q. robur* prefers warm and not too dry summers and is demanding in terms of nutrient availability, light and soil moisture (Aid 2014, BWV 2006h, Aas 2002). According to GALK (2015) and Gurk & Hepp (2015) it likes warmth. It can also tolerate temporary flooding (Aas 2002). Although Common Oak can be found on sites with varying soil characteristics from wet, nutrient-rich, alkaline soils to dry, nutrient poor, acid soils, it has its growth optimum at medium conditions concerning nutrient and water availability (BWV 2006h, Aas 2002, Breunig et al. 2002). However, under natural conditions it is usually outcompeted in the most favourable sites by *F. sylvatica* due to the higher light demand. Thus, Common Oak is typically also found in slightly more extreme habitats (Aas 2002).

Q. robur is considered moderately tolerant to drought, implying it can withstand drought periods of up to one month with a decrease in soil moisture to a level around the permanent wilting point (UK Forestry Commission 2015). Roloff (2013a) classifies *Q. robur* as drought insensitive and ascribes the species a good drought stress adaptation. Accordingly, it is classified as suitable for dry to very dry sites by Roloff & Grundmann (2008a). *Q. robur* is commonly considered one of the more drought-sensitive oak species compared e.g. to the also common species *Q. petraea* and *Q. pubescens* (Aid 2014, Arend et al. 2011, Sergeant et al. 2011, Friedrichs et al. 2009, BWV 2006h, Dickson & Tomlinson 1996). Nevertheless, its drought tolerance is higher than that of European Beech (*F. sylvatica*), another economically important forest tree in Europe, due to its deeper rooting system and different hydraulic architecture (Bourtsoukidis et al. 2013, Berry et al. 2012, Scharnweber et al. 2011, Gallé & Feller 2007).

The effect of drought conditions was investigated in several studies. Reactions include the reduction of stomatal conductivity, the lowering of leaf water potentials, and the formation of fine roots. According to Thomas & Gausling (2000), the most important adaptation mechanism that occurs under mild as well as under severe drought stress is a shift in biomass ratio from leaves to fine roots. Osmotic adjustment, on the other hand, was only observed under mild drought but not under severe drought stress. Still, Aid (2014) advises against planting *Q. robur* on dry slopes and dry, nutrient poor sand. Furthermore, *Q.* robur avoids drought stress using stomatal control. Additionally, biochemical protection of leaves was described by Schwanz et al. (2001). Cavitation risk is rather low under normal summer conditions but increases under more severe drought stress and in case of reoccurring droughts (Gieger 2002, Epron & Dreyer 1993).

Koller et al. (2013) report an irreversible decrease in photosynthetic activity after a prolonged period of 50 days of drought stress. Furthermore, shedding of foliage can be the result of drought and heat stress. Crown thinning was observed in years following very dry and warm summers (Bolte et al. 2012). The defoliation is more severe than for other forest tree species, especially following the extreme summer drought in 2003 (MIL 2013). van der Werf et al. (2007), on the other hand, report only few effects of the 2003 summer drought on radial growth in the maritime climate of the Netherlands. They suggest negative impacts of drought are higher in extremely dry sites. This would point to a high tolerance towards moderate drought stress, but increasing sensitivity under severe conditions. Sergeant et al. (2011) come to a similar conclusion in their study on young *Q. robur* trees. While initially *Q. robur* is able to adjust to drought stress for some time at the cost of growth decline, more severe and prolonged drought conditions caused failure of adaptation mechanisms. Spieß et al. (2012), however, observed compensation growth upon re-watering, indicating the capability to recover from drought. Furthermore, their study concluded that mild drought stress during a long time period may even trigger adaptation to drought.

According to van der Werf et al. (2007), growth of *Q. robur* is influenced by precipitation and summer temperatures of the previous growing season. Low amounts of precipitation in the current and previous year affect *Q. robur* negatively (Sergeant et al. 2011, van der Werf et al. 2007). Sanders et al. (2014) identified a decline in growth below 247 mm of precipitation between May and September. Ragazzi et al. (2002) found a decline in northern Italy attributed to drought in March and April. According to the study, *Q. robur* needs precipitation of at least 100 mm per month during this period. Additionally, a fungal infestation in the following year worsened the observed decline. However, the sensitivity of an individual also depends on its provenance because drought tolerance has been shown to be provenance-specific (Arend et al. 2011, Gallé & Feller 2007). Besides limiting growth, drought can also make *Q. robur* more vulnerable to pests that are otherwise too weak to seriously affect the tree. One example is the disease Sudden Oak Death, caused by the pathogen *Phytophthora ramorum* (Sergeant et al. 2011).

Under climate change conditions, a slightly positive development is predicted for the future due to the higher heat and drought tolerance compared to other forest trees, such as the more drought sensitive *F. sylvatica* (Arend et al. 2011, Roloff & Grundmann 2008a). According to Roloff & Grundmann (2008a), this tree will benefit from an increase in dry sites that are too dry for *F. sylvatica*. This means that *Q. robur* can be a planting alternative in forestry. Arend et al. (2011) likewise estimate a lower risk of habitat loss for *Q. robur* than for *F. sylvatica*. Compared to *Q. petraea*, it will however suffer more under extremely dry conditions (Friedrichs et al. 2009). Scharnweber et al. (2011) observed growth depressions caused by drought stress and likewise conclude that *Q. robur* may be negatively affected by drier and warmer future growing seasons, although influence is assumed less pronounced than for *F. sylvatica*. Therefore, Scharnweber et al. (2011) still recommend *Q. robur* rather than *F. sylvatica* for future usage.

4.2.10. Salix alba

White Willow (*S. alba)* is distributed all over Europe (except for the British Isles and Scandinavia), Northern Africa, Western, Southwestern and Central Asia as well as Western Siberia. It is mainly found under temperate, subcontinental climate conditions (BWV 2006i, Schirmer & Stimm 1999). As a pioneer species it is insensitive to salt and contamination in industrial sites (Schirmer & Stimm 1999). In terms of temperature requirements *S. alba* is a thermophile species and does not tolerate late frost because shoot and flowering occur rather early (BWV 2006i, Breunig et al. 2002, Türk 1999). As it naturally occupies sites along streams and rivers, it is very tolerant towards flooding and high groundwater levels and prefers moist or wet, deep soils (BWV 2006i, Schirmer & Stimm 1999, Türk 1999). Accordingly, *S. alba* is a very water-consuming species with a low effectiveness of water use. Large increment therefore only occurs under optimum water supply. The UK Forestry Commission (2015) classifies it as intolerant to drought, implying it does not tolerate longer drought periods or severe soil drying. Likewise, Roloff & Grundmann (2008a) consider very dry to dry sites as unsuitable and moist to moderately dry sites only as limitedly suitable.

Contrary to other authors, Roloff (2013a) describes the water demand of *S. alba* as low to moderate and attributes the White Willow a high drought stress adaptation. In case of drought stress, it sheds entire green branches to reduce transpiration losses. This is, however, undesirable in urban areas from an aesthetical point of view. The author argues that while the White Willow prefers wet habitats, it is also capable of coping with almost any other site. Yet, it does not frequently occur in drier sites as it is usually displaced by other more competitive species. Compared to the other investigated tree species, far fewer studies exist on the drought tolerance of *S. alba*. This may be due to the smaller economic interest compared to other species, or because currently it mainly occurs in sites such as river banks, where drought stress is not the most prominent problem. The Climate-Species-Matrix by Roloff et al. (2009), considers *S. alba* as problematic in urban areas in the future with regard to drought tolerance. As most other studies also indicate a rather high sensitivity to drought, the best future strategy appears to be to consider the use of *S. alba* in urban areas with caution, especially in sites that are prone to drought.

4.3. Comparison of tree species tolerances

4.3.1. Different stress coping mechanisms and factors influencing tolerance

Trees can adapt to drought in different ways, e.g. by improving water transport, reducing leaf area or expanding the root system to reach further water reservoirs (Burk 2006). Root systems were found to develop according to the predominant soil conditions, e.g. soil type, water supply, moisture content, and nutrient supply. Under good water supply, roots are in general mainly developed in the upper soil layers. With decreasing moisture availability, the root system is extended into deeper layers in order to extract further water reserves. This can be seen as a form of adaptation to soil drought (Burk 2006). Drought tolerance is generally higher in older individuals than in younger trees. During dry periods, those species which are especially tolerant to drought usually down-regulate transpiration by adjusting their stomatal conductance. A deeper or more extended root system furthermore allows for greater water uptake (Siewniak & Kusche 2009). Deep and extended roots can however pose difficulties in urban areas, e.g. if hydraulic lines or asphalt are damaged (Roloff 2013a).

Water transport within the plant is strongly dependent on the water potential gradient between soil and atmosphere. In case of increasing soil drought, the soil water potential falls to more negative values. Maintaining a high water conductance along the gradient involves the lowering of plant internal water potentials. Thus, to maintain water transport within the tree, it likewise has to decrease water potential within the roots, stem and leaves. Root water potentials of -2 to -4 MPa are considered the lowest measures values for Central Europe (Roloff 2013b, Burk 2006). The ability to tolerate low potentials is seen as a possible adaptation to drought stress, which can e.g. be seen in *F. excelsior* (Stöhr & Lösch 2004, Guicherd et al. 1997). In a study by Stöhr (2003), *F. excelsior* showed minimum water potentials of -3.1 MPa within the stem and -4.25 MPa within leaves, while for *A. pseudoplatanus* no further decrease beyond -2 MPa in both stem and leaves could be observed. A more recent study by Köcher et al. (2009) even reports leaf water potentials of up to -6 MPa for *F. excelsior*. Among the ten analysed studies species, it is therefore the one that can decrease leave water potentials to the lowest values.

Yet, if soil drought conditions last for a longer period of time, even the decrease in root water potential does not suffice to maintain the required water supply. As a consequence, the liquid phase continuum is disturbed and cavitation occurs (Bréda et al. 2006, Burk 2006). Sensitivity to cavitation differs between species. In some tree species vessels can be refilled after re-watering, i.e. the temporary cavitation is reversed, indicating an additional form of drought adaptation (Richter & Kikuta 2014). Other species that cannot cope with temporary cavitation experience serious damage caused by such drought conditions. High cavitation risk was found e.g. in *P. nigra,* as poplars belong to the tree species most vulnerable to cavitation (cavitation starts when xylem water potential reaches -1 to -1.2 MPa) (Durand et al. 2011, Fichot et al. 2010). Furthermore, *A. pseudoplatanus* (Lemoine et al. 2001) and *A. glutinosa* (highly vulnerable to xylem water potentials below -1.2 MPa) (Worrall et al. 2010) suffer considerably from cavitation. Vulnerability to cavitation can furthermore also vary within a plant. In *A. glutinosa* for example, roots are more vulnerable than branches (Hacke et al. 2014).

Physiological responses to drought vary considerably between different tree species (Ryan 2011). Two main strategies have been identified when facing drought conditions namely isohydric and anisohydric mechanisms with varying degrees of both forms in between (Ryan 2011, McDowell et al. 2008). Isohydric species generally possess effective mechanisms of stomatal regulation of transpiration. They decrease leaf stomatal conductance if soil water potential declines, thereby reducing water loss and preventing a decrease of leaf water potential (McDowell et al. 2008, Stöhr 2003). Furthermore, they often show extensive root systems, rather small leaves and a high leaf mass to area ratio (Aroca 2012). The downside of an isohydric response is the risk of carbon starvation as photosynthesis declines with the closing of the stomata but plant respiration still takes place (Allen et al. 2010). Thus, while withstanding short but intense droughts, isohydric species suffer particularly under prolonged drought conditions, when this mechanism may not be sufficient to preserve the tree from hydraulic failure (Gill et al. 2013).

Anisohydric species only have a limited capacity of stomatal control of transpiration, maintain higher leaf stomatal conductance, and thus face higher water losses and a decline in leaf water potential, especially around midday. As a response, they possess cavitation resistant vessels. Additionally, they can react with a decrease of osmotic potential due to their capacity of osmotic adjustment (McDowell et al. 2008, Stöhr 2003). The risk of carbon starvation is lower than for isohydric species, because stomata remain open. On the other hand, anisohydric species face a higher risk of cavitation, i.e. the formation of embolisms, for which reason many of these species have cavitation-resistant xylems (Allen et al. 2010).

Anisohydric cope better with prolonged droughts but are more likely suffer from hydraulic failure under short but especially intense droughts (Gill et al. 2013).

Typically, the daily amplitude of leaf water potential is much higher in anisohydric than in isohydric species. This amplitude is therefore taken as one indicator to classify a species as one or the other. Yet, no defined threshold exists for the classification of a species as isohydric or anisohydric. There is still a debate concerning some species that show a mixture of characteristics or where none of the strategies is particularly pronounced (McDowell et al. 2008, Stöhr 2003). Examples of species classified as isohydric include *A. pseudoplatanus* (Scherrer et al. 2011, Köcher et al. 2009, Stöhr 2003), *B. pendula* (Zapater et al. 2013, Sellin et al. 2009), *P. nigra* (Herrero et al. 2013, Cocozza et al. 2010) and *Q. robur* (Tulik 2014, Urli et al. 2014, Zapater et al. 2013). In comparison, *A. glutinosa* (Worrall et al. 2010), *F. excelsior* (Stöhr & Lösch 2004, Stöhr 2003), and *F. sylvatica* (Pretzsch et al. 2014, Rosner 2012) are considered anisohydric species.

Yet, an isohydric or anisohydric strategy alone does not give sufficient information on the drought tolerance of a tree species. Some species, such as *A. glutinosa* prefer moist or wet habitats, but are still described as anisohydric species. Leaves of *A. glutinosa* cannot effectively control transpiration, which is characteristic for a water-demanding species (Claessens et al. 2010). Its xylem is highly vulnerable to cavitation at water potentials below -1.2 MPa (Worrall et al. 2010). As *A. glutinosa* typically colonizes wet habitats and rarely has to cope with severe droughts and very low potentials, this strategy is still suitable in its preferred environment. Yet, it is not suitable for drought-prone sites. Due to their strategies, anisohydric species are found more often in drought-prone areas compared to isohydric species (McDowell et al. 2008).

4.3.2. Comparison of tolerance classification systems used in literature

It became apparent during the literature review that only very few studies exist that can actually be compared one-to-one. The reason for this is, that the case studies have different focusses, use different methodology, measure different parameters and were conducted at different sites and at different times. This is of course due to practical reasons and does not mean that the case studies do not give valuable information. It just means that these study-specific differences have to be kept in mind. Since many local factors strongly influence the effect of drought and heat on a species, a comparison of different studies is further complicated.

Moreover, the existing tolerance classification systems differ in their denomination and division of classes. Hence, **Tab. 7** gives an overview of the classifications and scales used in the respective studies. Higher drought tolerance, higher suitability for dry habitats, better adaptation to drought stress, and higher suitability as a street tree with limited water supply are seen as positive characteristics (coloured in dark and light green), as they are desirable when selecting species for urban areas under climate change. On the contrary, drought sensitivity, low suitability for dry habitats, low suitability as a street tree as well as insufficient drought adaptation are seen as negative characteristics (coloured in dark and light orange) because they are undesirable in urban trees under climate change. Some classifications included an intermediate category, which was depicted in yellow.

Tab. 7 Overview on different classifications assessing drought tolerance and related parameters(*= no classification in original sources, information was compiled from text and divided into classes).

	Source	Parameter	Classes	+ +	+	o	-	- -
A	Roloff et al. (2009)	**Drought tolerance** and the resultant **suitability for urban habitats** under **climate change**	1-4	1 very suitable	2 suitable		3 problematic	4 not suitable
B	Roloff & Grundmann (2008a)	**Applicability** for **dry to very dry sites** in respect to **climate change**	1-4	1 very suitable	2 suitable		3 limited suitable	4 not suitable
C	Niinemets & Valladares (2006), UK Forestry Commission (2015)	**Drought tolerance**	1-5	5 very tolerant	4 tolerant	3 moderately tolerant	2 intolerant	1 very intolerant
D	Roloff (2013a)	**Drought stress adaptation** *	+ / o / -		+	o	-	
E	Roloff (2013a)	**Drought stress sensitivity**	+ / -		+ not sensitive		- sensitive	
F	Bassuk et al. (2009)	**Suitable soil moisture conditions** (driest possible conditions of the suitable range are used for classification here)	1-12	10-12 prolonged periods of dry soil	7-9 occasional periods of dry soil		4-6 consistently moist, well drained soil	1-3 occasionally saturated or very wet soil
G	GALK (2015)	**Suitability as street tree**	+ / o / -		+ suitable	o limited suitable	- not suitable	
H	Other studies cited in section 4.2	**Drought tolerance** *	+ / o / -		+	o	-	
	Own assessment based on literature review	**Drought tolerance / Drought sensitivity**	1-4	**1 very tolerant**	**2 moderately tolerant**		**3 moderately sensitive**	**4 very sensitive**

Tab. 8 Comparison of tree species based on different classifications with regard to drought tolerance and related parameters. The description of classifications A-G as well as the respective parameters is displayed in **Tab. 7**. Source H summarizes further individual case studies. The overall assessment was deduced taking into account all available sources. Yet, due to different classification criteria and variations in experimental conditions of case studies, some sources may arrive at different conclusions compared to other assessments and compared to the overall rating.

Legend: suitable ++ | + | o | - | - - unsuitable | [n/a]

Species	Individual assessments of sources A-H [For detailed explanation of scales see Tab. 7]								Overall assessment
	A	B	C	D	E	F	G	H	
A. platanoides	+	++	o	+	+	++	o	+	moderately tolerant
A. pseudoplatanus	- -	+	o	o	-	++	-	-	moderately sensitive
A. hippocastanum	- -	[n/a]	o	o	-	[n/a]	o	-	moderately sensitive
A. glutinosa	- -	- -	-	o	-	+	-	-	very sensitive
B. pendula	+	++	-	+	+	[n/a]	o	+	very tolerant
F. sylvatica	-	-	-	o	-	[n/a]	[n/a]	o	moderately sensitive
F. excelsior	+	-	-	+	+	+	o	o	moderately tolerant
P. nigra	[n/a]	- -	-	[n/a]	-	[n/a]	[n/a]	-	very sensitive
Q. robur	-	+	o	+	+	++	+	+	moderately tolerant
S. alba	-	- -	-	+	+	[n/a]	-	-	very sensitive

Very few studies conducted analyses of the direct effect of heat on the tree species. Hence, much less information is currently available on heat impacts. Therefore, a similarly detailed table for heat tolerance is not given at this point. Subsequent to the overview of different classifications shown in **Tab. 7**, **Tab. 8** contains a comparison of the selected species according to these different classification systems of drought tolerance and related parameters. The studies rated slightly different parameters, all of them related to the species ability to cope with drought stress (e.g. drought tolerance or suitability for dry habitats).

Bassuk et al. (2009) describe soil moisture requirements of trees on a scale from 1 (occasionally saturated or very wet soil) to 12 (prolonged periods of dry soil), highlighting the respective range of conditions under which a species can survive reasonably well. The authors point out, that making absolute statements concerning the water requirements is highly difficult. They therefore work with a relative scale instead. Consequently, the overall assessment of drought and heat tolerance in this thesis also uses a relative scale instead of a quantitative classification (see **Tab. 7**, **Tab. 8** and **Tab. 9**). Four categories are included: '*very tolerant*', '*moderately tolerant*', '*moderately sensitive*', and '*very sensitive*'. Due to the mentioned lack of definite thresholds, no quantifiable criteria (such as a required minimum amount of precipitation or a threshold for temperature damage) are attached to these classes.

Tab. 9 Summary of drought and heat tolerance classifications of selected tree species. It gives a general indication of the species tolerance or sensitivity to drought and heat stress, respectively. Species are sorted alphabetically within each category; the order does not indicate a further grading.

	Drought stress	Heat stress
Very tolerant (++)	*B. pendula*	*B. pendula* *F. excelsior*
Moderately tolerant (+)	*A. platanoides* *F. excelsior* *Q. robur*	*A. hippocastanum* *A. platanoides* *Q. robur*
Moderately sensitive (–)	*A. hippocastanum* *A. pseudoplatanus* *F. sylvatica*	*A. pseudoplatanus* *F. sylvatica*
Very sensitive (– –)	*A. glutinosa* *P. nigra* *S. alba*	
Insufficient information		*A. glutinosa* *P. nigra* *S. alba*

The classification focuses primarily on Germany, i.e. species which are classified as tolerant are expected to be generally tolerant under the temperate climatic conditions of Central Europe. The species' tolerances in other regions (e.g. the drier and warmer Mediterranean area) are not regarded here. Species were deliberately merely sorted alphabetically within the categories without further grading. The overall assessment was deduced taking into account all cited sources. Yet, due to different classification criteria and variations in experimental conditions of case studies, some sources may arrive at different conclusions compared to other assessments and compared to the overall rating. The proposed classification shall provide an overview of the general consensus found in literature, even though in some cases the sources show rather ambiguous results. Given that the results of a case study furthermore strongly depend on local conditions and the experimental set-up, the sections 4.2.1 to 4.2.10 as well as the cited literature should be consulted if more detailed information on the individual species is required.

When comparing the different existing classifications schemes, one has to keep in mind what parameters are assessed. Drought tolerance can e.g. not be equated with suitability for dry habitats. Yet, it can be expected that tree species with a high drought tolerance, e.g. *B. pendula* or *F. excelsior*, are species which are generally more suitable species for dry habitats than those sensitive to drought, e.g. *A. glutinosa* or *P. nigra*. It may therefore be expected, that different assessed parameters complement each other and can be used combined to give an overall assessment. Based on currently available information it is not possible to classify three of the species (*A. glutinosa*, *P. nigra, S. alba*) concerning their heat tolerance. Furthermore, the current literature includes some contradicting case studies and not all results are completely in line for some species. As can be seen from **Tab. 8**, sources disagree in their assessment in several cases. As an example, *A. pseudoplatanus* is considered 'not suitable' for urban habitats under climate change by Roloff et al. (2009) according to its drought tolerance. It is, on the other hand, classified as suitable for dry and very dry sites according to Roloff & Grundmann (2008a). Likewise, *F. excelsior* is considered intolerant to drought by Niinemets & Valladares (2006), while it is not sensitive to drought according to Roloff (2013a). Possible explanations for these differences include the use of different thresholds of drought tolerance, different study focusses, different ages of observed individuals, different provenances or cultivars as well as differences in geographical location and climatic conditions.

For instance, source C (Niinemets & Valladares 2006) uses five different classes of drought tolerance. Yet, all species reviewed in this thesis fall into the categories 'moderately tolerant' or 'intolerant'. Source A (Roloff et al. 2009) on the other hand classifies species into four different classes, all of them being represented by at least one of the ten species reviewed here. While Niinemets & Valladares (2006) base their classification on threshold values of precipitation, tolerated duration of drought, and soil water potential, Roloff et al. (2009) combines existing classifications of preferred habitat as well as soil and climate factors into one evaluation. The use of different classification systems possibly has the effect that a species is considered tolerant according to one system but may be classified as intolerant in another system that has higher classification requirements. It is also possible that one study used a larger set of species, including a wider range of tolerances, compared to smaller species sets investigated by another study.

According to Leuschner (2009), contrasting assessments of a species' tolerance may also be caused by a still existing lack of understanding of physiological processes within trees under stressful conditions. Furthermore, results from studies that use artificial experimental design or laboratories often cannot be transferred directly to an open landscape or an urban green space. Additionally, differences in responses between young and old individuals of the same species complicate the transfer of results from studies on saplings to adult trees. Moreover, individual trees can show different sensitivities and tolerances according to their individual history. As in the case of *B. pendula*, individuals that are adapted to dry conditions from an early age, often cope better with drought than those that are used to a more abundant water supply (Roloff 2013a). Meanwhile, for some species, e.g. *F. sylvatica,* it was pointed out that provenances differ in their ability to tolerate environmental stresses (Gillner 2012, Seifert 2011, Fotelli et al. 2009, Lendzion & Leuschner 2008). The use of different provenances is reviewed in more detail in section 5.2.

The example of *A. platanoides* and *A. pseudoplatanus* clearly shows that different species within one genus can respond very differently to stress and can develop different tolerance levels. While *A. platanoides* was classified as 'moderately tolerant', *A. pseudoplatanus* on the other hand was considered 'moderately sensitive' concerning both drought and heat. Correspondingly, the Climate-Species-Matrix by Roloff et al. (2009), which classifies species according to their suitability for urban areas under climate change based on their drought tolerance, includes different species from the *Acer* genus. For instance, *Acer campestre* is classified as ‘very suitable’, while its relative *Acer pseudoplatanus* is considered ‘not suitable’. Hence, one must be careful with generalized statements on a whole genus. For this reason, only literature dealing with the respective species was used here.

It has to be mentioned that even though a species tolerates drought and / or heat, these are not necessarily its preferred conditions. A tree that shows best growing behaviour in moist soil and under abundant precipitation, might still tolerate drought stress if necessary. This assessment focuses on drought and heat tolerance, in the sense that trees species classified as tolerant are able to maintain fitness under stressful conditions. Thus, they do not necessarily have their optimum growing conditions in dry and hot sites, but suffer less than other species under the stress. At best, species that tolerate heat and drought also prefer these conditions. Yet this is not a prerequisite for being classified as ‘moderately tolerant’ or ‘very tolerant’. Furthermore, it has to be distinguished between the ability to simply survive drought stress and to thrive, grow, and reproduce under stressful conditions. As aesthetics are especially important in urban areas, visual signs of damage and shedding of leaves of branches are likewise undesired as limitations in growth or flowering (Roloff 2013a, Wittig 2008, Konijnendijk et al. 2005).

4.4. Current state of research

The literature review shows that the number of available studies differs substantially between single tree species. Commonly used forest species of greater economic interest, such as *F. sylvatica* and *Q. robur,* are more frequently studied for their climate-growth relationship and possible reactions to changing environmental conditions than species of lesser economic interest. Many studies focus on forestry because the interest in widely distributed forest trees is higher than the interest in ornamental species with wood of lower quality. The most commonly studied genera of forest tree in Germany are beech (*Fagus*), oak (*Quercus*), spruce (*Picea*) and pine (*Pinus*) (e.g. NW-FVA 2014 and BMELV 2012). Some species, such as *A. hippocastanum*, are not of economic interested from a silvicultural point of view. Yet, some of them are commonly used in urban areas and therefore of interest for urban planners and managers of urban green spaces. The respective studies also focus far more on aesthetics of trees and possible losses of visual quality than studies with a focus on forestry, where commercial aspects, tree growth rates and wood quality are of greater importance (Sjöman et al. 2012).

Two main topics are currently discussed in forestry with regard to future developments: Firstly, possible changes in community structures and species abundance in temperate forests due to climate change; secondly climate-adapted conversion of forests towards a species mixture that is suitable for future climatic conditions (Carón et al. 2015, Kölling et al. 2009b). Local governments such as the state government of Bavaria have decided upon actions plans to replace tree species that are vulnerable to future climate change impacts by more adapted species. On this account, research studies (e.g. Kölling et al. 2009b) focus on determining which species are the most suitable for a region, and which can be considered problematic and should hence be avoided in the future.

The results from studies focussing on forestry can be transferred to other sectors, if the original context is kept in mind. Drought and heat conditions are more severe in urban areas than in woodlands, thus, trees are also exposed to more severe stress (Roloff 2013a). Gillner (2012) concluded that the effects of additional factors affecting growth in urban areas are very hard to distinguish. For this reason, dendrochronological studies so far mainly focused on forest trees and more natural areas. Nevertheless, changing climatic conditions similarly influence urban trees as well as forest trees. Some lack of knowledge remains when transferring findings to another context, as it cannot be guaranteed that species, which cope well with drought and heat inside a forest ecosystem, do equally well in an urban area. On the other hand, findings from urban areas can also help to assess the future suitability of tree species for forestry under changing climatic conditions because urban trees already experience conditions that forest trees may have to cope with in the future (Schmidt 2014).

In Germany just eight different genera make up the majority of all urban trees (Bauer 2012). This may be a reason for the research focus on some particular species or genera. *Acer*, *Quercus*, *Fraxinus* and *Aesculus*, four genera of which individual species are included in this analysis, are among these most frequently planted genera. The actual species composition of the urban tree population may in fact depend on several factors, including costs, availability, and suitability to urban areas as well as less quantifiable aspects like experiences from gardeners or creative decisions (Wittig 2008). Until now the urban tree population in German cities is mainly made up by native species and only some individual introduced species like the very popular *A. hippocastanum* (Schmidt 2014). The amount of available information is naturally highest for the species that are most commonly used today despite some knowledge gaps that also exist for relatively well studies species. Certainly, considering climate change, a demand for additional information on species suitability under future conditions emerges.

In addition to long-term studies on climate growth relationships, many studies focus on the extreme heat wave and drought period in 2003 or on experimentally simulated drought conditions. Studies conducted during 2003 and the following years give a good opportunity to study the effect of extreme climatic conditions on trees since they were affected by heat and drought simultaneously (Saccone et al. 2009, Friedrichs 2008, Bréda et al. 2006). Nonetheless, it has to be considered that the drought and heat wave were regionally diverse (Beck 2011). To give a few examples, Saccone et al. (2009) observed negative influences of the 2003 heat wave on seedling survival of *F. excelsior* and *A. pseudoplatanus*. Likewise, growth decreases in *F. sylvatica* caused by water stress were reported in the year following the drought by Czajkowski et al. (2005). Furthermore, several studies observed a decrease in forest foliation and forest tree increment as well as an increase in forest dieback in Germany in 2003 and the years following the drought (e.g. MELUR 2013, MKULNV 2013, NW-FVA 2013a, Burk 2006). A study on *B. pendula,* on the other hand, reported Silber Birch was able to cope well with the drought conditions by adjusting transpiration and efficiently extracting water from soil (Gartner et al. 2009). Other examples originate from research in urban areas, e.g. reports of increased mortality of newly transplanted and non-watered *A. hippocastanum* (Percival & Noviss 2008). Percival & Noviss (2008) consequently recommended artificial enhancement of drought tolerance, especially during the time of new root establishment, as trees that are not sufficiently drought-tolerant need additional irrigation to prevent such an increase in mortality. Such findings underline the classification (**Tab. 9**) of *F. sylvatica* and *A. hippocastanum* as ‘moderately drought-sensitive’ and of *B. pendula* as ‘very drought-tolerant’.

Establishing climate-growth relationships is a method used by several studies to derive effects of climatic factors on growth and vitality of individual tree species. These studies investigate the relationship between climate and growth of trees, taking both internal factors (e.g. age) and external factors (e.g. climatic factors or management practices) into account (Gillner et al. 2014). The climate-growth-relationships depend on region, tree species and the respective local conditions (Beck 2011). Gillner et al. (2014) point out, that singular extreme events can have as strong an influence as long-term changes in average climatic conditions. Lindner et al. (2010) even suggest extreme events, such as prolonged drought periods, have more dramatic consequences for trees than steady but small changes. It is therefore important to consider climatic variability.

The study of so-called pointer years is a frequently used method to identify climate-growth relationships. Pointer years of significantly reduced growth can be caused by different environmental factors and external influences, such as climatic factors but also by pest outbreaks or human disturbances such as construction works in cities (Gillner et al. 2014). Beck (2011) found that negative pointer years in common German forest tree species such as oak and beech in the 1970s were mainly associated with winter coldness. In the last 20 years, however, more growth depressions were caused by hot and dry summers instead. Other studies (e.g. Scharnweber et al. 2011) were able to establish relationships between annual climate patterns (precipitation and temperature) and tree growth. For *F. sylvatica* and *Q. robur* the results indicate that growth depends on water availability during early summer month. Furthermore, drought was identified as the key driver for growth depressions.

In addition to scientific studies, some knowledge from practitioners is also available, e.g. the GALK list of street trees (GALK 2015), which incorporates experiences of urban gardeners. Generally, literature tends to focus more on the effects of drought stress than on heat stress. Heat stress can directly influence tree growth, metabolism and processes but can moreover cause secondary effects (see also sections 2.3.2 and 2.3.3). If temperature increases while precipitation stays constant, drought stress can be induced or intensified due to increased evaporation and a subsequent decrease in water availability. Thermophile trees thrive under warmer temperatures, yet, if they are sensitive to drought, they may actually suffer under warmer and drier conditions (Ryan 2011). A study focus on drought stress is therefore certainly justified, as drought stress can also be linked to heat. Nevertheless, the direct consequences of heat stress should not be ignored and need further investigation for several of the species. Finally, no conclusion on heat tolerance was possible for *A. glutinosa, P. nigra*, and *S. alba*. Even though individual studies reported on heat tolerance of the remaining species, the assessment had to be based on fewer reports compared to the assessment of drought tolerance because of the limited literature availability.

5. Analysis and discussion

5.1. Considerations for urban tree species selection

The importance of adequate species selection has been recognized not only for urban vegetation, but also in the context of forestry and forest ecosystem management (Reif et al. 2010). For the selection of forest trees the BWV (2009) recommends the following parameters for the assessment: annual precipitation sum, annual mean temperature, soil type and soil moisture. In contrast, according to Burk (2006), forest stands depend stronger on amount of precipitation during growing season than on the annual precipitation amount. Thus, instead of annual precipitation, precipitation during growing season is likely to be a better indicator. In general, selection within forestry mainly concentrates on fast-growing genotypes with well utilizable wood that show a high resistance against diseases and pests (Sjöman et al. 2012).

Regardless, the evaluation of suitability of tree species is complicated in urban areas due to altered natural climatic and environmental conditions. This means, that selection criteria recommended for forest trees do not suffice for urban trees and additional factors have to be considered. Physical stability, road safety, and tree longevity determined by stress tolerance are of foremost importance. Furthermore, mass-propagation, ease of cultivation as well as design qualities are furthermore important in urban areas (Duhme & Pauleit 2000).

Practical guidelines for tree selections in urban areas are provided for instance by Bassuk et al. (2009), GALK (2008), Gilman & Sadowski (2007), and Pauleit (2003). Further literature recommended for consultation are the Climate-Species-Matrix by Roloff et al. (2009) for future tree species suitability in urban areas according to drought tolerance and winter hardiness as well as the GALK list (GALK 2015) that focuses on street trees. The relatively new "CITREE" database emerged from a research project at the TU Dresden and provides decision support for urban tree species selection (TU Dresden 2016). Moreover, some general remarks on the environmental requirements of some of the selected species can be found in Ellenberg & Leuschner (2010), while Roloff (2013a) summarizes the suitability of several species specifically for urban areas. Finally, for the UK the 'Right Tree for a Changing Climate' database (UK Forestry Commission 2015) provides information and guidance on selecting suitable species that are adapted to expected changes in climatic conditions.

Depending on the location, a higher level of uniformity of trees may be desirable in practice, especially for street trees. Using specific clones and reducing the variation in planted cultivars can meet this demand. Consequently, commercial interests can be in conflict with ecological interests of creating a higher diversity within urban green spaces. Sæbø et al. (2005) therefore suggest selecting untraditional species to promote a higher level of biodiversity. Moreover, crown shapes and sizes, growth rates, and potential life spans should be taken into account during the selection process. More diversity is particularly desirable for parks that benefit from a larger visual variety of trees of different age, structure and size. A larger diversity of trees makes the whole of urban trees more resistant against pests than monocultures (MKULNV 2013, GALK 2011). For this reason, the planting of urban trees according to the 10-20-30 formula (maximum 10 % of a single tree species, maximum 20 % of a tree genus, maximum 30 % of a tree family) is suggested to be less prone to pest infestation (Li et al. 2011). However, in practise, trees are often selected according to availability, traditions, horticultural experience as well as trends, causing a low variety within Northern Europe cities (Sjöman et al. 2012). On average only eight tree genera are make up the majority of trees within a city, which is why the number of different tree species in urban areas should be increased (Duhme & Pauleit 2000).

5.2. Native vs. non-native species and new provenances

Today it is impossible to give precise predictions of the future climate, as all climate projections comprise certain bandwidths of possible future developments. For this reason large genetic diversity and large phenotypic plasticity are desirable features in urban trees to be able to cope with a range of possible changes. The greater their ability to physiologically adjust to changing or stressful conditions is, the better (MKULNV 2013, Aspelmeier & Leuschner 2005). Ideally, trees can cope with a broad range of different climatic conditions.

As different species are diversely affected by the same drought conditions, the selection should focus on those species that are adapted best and show the highest tolerance to drought and heat. Species originating from drier climates may not suffer from drought, while species from more humid climates are already drought stressed under the same conditions (Ryan 2011). The fact that – in theory – the most suitable species are not necessarily native species, fuels another debate on the use of native versus non-native species. GALK (2011) distinguishes between the selection process for more natural landscapes or rural areas and the one hand and for urban areas on the other hand. While native species are preferred for non-built-up areas for reasons of nature conservation, cultivars and non-native species from semi-arid regions may represent alternatives to the less drought resistant native trees in cities. These trees may be better adapted to stressful urban conditions and increase the level of diversity that is desired (MKULNV 2013, GALK 2011).

Pauleit (2003) supports the testing of new, non-native tree species to find suitable alternatives for future climates. Hemery (2007) likewise suggests the plantation of non-native species as suitable alternatives, provided site conditions match the requirements of the trees. Furthermore, he advises against using trees with a narrow genetic range. Likewise, Reif et al. (2010) argue that non-native species can be appropriate for the environmental conditions of a location. Nonetheless, the authors remind that the use of non-native species is seen critical among nature conservation experts. Among the conservation community the use of native species is often a central criterion. In practise, planting alternatives from other regions may therefore not find acceptance among the local community and conservationists. With this in mind, Roloff & Grundmann (2008a) suggest utilizing non-native species only for severe sites where native species are no longer an option. In any case, thorough testing of new tree species is highly recommended before planting new species on a large scale.

Trees not only need to be drought and heat tolerant, but also need to resist other occurring stresses throughout the year. These may be less pronounced or absent in their original habitat for instance frost or late frost. Roloff & Grundmann (2008b) recommend the observation of the effect of new tree species on the new habitat, e.g. on soil, flora and fauna. According to Sjöman et al. (2012), further knowledge and more extensive experience are needed concerning site adaptation of tree species.

Instead of using completely new, non-native species, another option is the use of different provenances of species that are also native to Germany. Many tree species that are widely distributed over climatically differentiated regions have developed provenances over time. These are adapted to the respective local conditions to which they are exposed. Even though they belong to the same tree species, they comprise different genetically defined characteristics (Reif et al. 2010). Thus, depending on their origin, provenances are differently well adapted to stresses. Provenances in drier regions are for example better adapted to drought than provenances from more humid regions. Thus, similar climatic conditions can cause different stress levels in different provenances, as shown by a study on *F. sylvatica* during the summer drought 2003 (Fotelli et al. 2009).

A high degree of different provenances was especially reported for the two widely distributed forest trees *F. sylvatica* (Seifert 2011, Lendzion & Leuschner 2008, Peuke & Rennenberg 2004, García-Plazaola & Becerril 2000) and *Q. robur* (Arend et al. 2011, Scharnweber et al. 2011). Possibly, provenances from warmer and drier regions that have proven to be more drought tolerant can serve as alternatives for the local provenances under climate change (MKULNV 2013). Broadmeadow et al. (2005) suggests selecting provenances from origins, where the current climatic conditions resemble the projected future conditions of the target site. Furthermore, GALK (2011) recommends the use of different provenances in order to reach a higher genetic variety. Yet, some uncertainties remain, such as the acceptance of non-native provenances by conservationists and the tolerance to different stresses that are less pronounced in the provenances origin (e.g. frost) (Reif et al. 2010).

Unlike in natural areas, plantings in urban areas often comprise a variety of different cultivars that are optimised according to the demands placed upon the tree. Thus, in addition to naturally occurring provenances, cultivation provides potential for creating tree varieties suitable for future conditions e.g. by promoting more heat and drought tolerant cultivars. A high degree of genetic variation and the potential to create hybrids are advantages in this context (Bauer 2012, Roloff & Bonn 2008). Additionally, as mass production of native tree seeds can be difficult, problems of availability of native varieties may arise in practice (GALK 2011).

5.3. Estimating species suitability with bioclimatic envelopes

A commonly used approach to determine future species suitability, especially in forestry research, is the use of bioclimatic envelope modelling. To some extent, different bioclimatic envelope models, also known as species distribution or ecological niche models, differ in their methodology (Araújo & Peterson 2012, Pearson & Dawson 2003). Many bioclimatic envelope models follow the ecological niche theory and are based on the assumption that climatic conditions – among other factors – mainly determine the natural distribution range of a species. Consequently, changes in climatic conditions are thought to cause a geographical shift in species distribution (Araújo & Peterson 2012, Pearson & Dawson 2003). While matching the current potential species distribution with the respective climatic conditions in the populated areas, bioclimatic envelopes (i.e. climatic niches) are deduced (Vasconcelos et al. 2013, Pearson & Dawson 2003). In order to assess the future suitability of a species and possible shifts in the potential species distribution, these envelopes are then combined with projected climatic changes in the regions of interest (Vasconcelos et al. 2013).

A study by Vasconcelos et al. (2013) creates bioclimatic envelopes for the most important forest tree genera in Rhineland-Palatinate, taking mean annual temperature, growing season and summer temperatures as well as annual precipitation, precipitation during growing season and during summer into account. By analysing areas where the tree species exists and their respective frequencies of occurrence, the authors estimate climatic comfort conditions for each species. Thereby, a climate matrix is generated for each species, displaying temperature and precipitation ranges and the suitability of the tree species under different conditions. The results reveal a general decrease in suitability for all observed genera (beech, oak and spruce) and regions within Rhineland-Palatinate. Yet, regional differences occur, e.g. stronger losses are expected for hillsides in river valleys or lowlands, while conditions may become more favourable in higher altitudes. A comparison of species reveals that the highest risk of future unsuitability is expected for spruce. A lower but still considerable risk is expected for beech, while only slight changes are projected for oak. These findings are generally in line with the drought tolerance assumed in this thesis for the ‘moderately sensitive’ European Beech and the ‘moderately tolerant’ Common Oak. This approach used gives a good first indication of general climatic requirements of a species based on its large-scale distribution.

As Falk & Hempelmann (2013) point out, climate variables primarily determine species distribution on a continental scale., while terrain and soil gain increasing influence on smaller scales. Overall the bioclimatic envelope approach is rather useful for forestry and estimation of a general suitability of a tree in a certain climate instead of providing information on local suitability. It could for example be useful to estimate the general suitability of new provenances or non-native species to the large-scale climate of a region. As this approach works with comfort ranges of climate parameters, it also considers opposite extremes of certain factors, e.g. high and low temperatures. The bioclimatic envelopes can e.g. also help to estimate suitability under particularly low temperatures or frost, which is important for non-native, drought tolerant species, as they also have to cope with all other prevailing environmental stresses that may differ from stresses in their natural distribution area. Still, a further analysis is required in the end in order to estimate a species’ suitability in urban areas.

Another study by Kölling (2007) presents climatic envelopes for 27 forest tree species in order to estimate their future suitability for forestry in Germany. The author uses two-dimensional frequency distributions of annual precipitation sums and annual mean temperatures to compare current and projected future climatic conditions with species requirements according to their current potential distribution. It is assumed that suitability increases with better correspondence of the requirements and the prevailing current or future conditions. This approach provides the opportunity, to compare species requirements derived from their natural distribution to the climatic conditions within Germany. It thereby works with similar assumptions as the previously discussed approach by Vasconcelos et al.

(2013). Yet, since the study works with annually averaged climate data, a potential temporal shift of precipitation from summer to winter may be neglected by this approach. Regional climate data offer additional information to refine such climatic envelopes.

On the other hand, different studies criticise the rather static approach of bioclimatic envelope models because other influencing factors such as biotic interactions, soil conditions, extreme sites, evolutionary change, dispersal ability, and adaptation potential of tree species to more extreme conditions are not considered (Araújo & Peterson 2012, Sutmöller et al. 2008, Pearson & Dawson 2003). Furthermore, Europe's original landscape has been altered in many ways, wherefore the current distribution of a species is not equal to its natural distribution. Causes include e.g. replacements by settlements, logging of trees, and artificial plantings in other places. Therefore, there is a difference between the potential and actual distribution, i.e. between the fundamental and realized niche, due to different non-climatic constraints. For this reason there is a risk of drawing the wrong conclusions by matching the current distribution of a species with the respective climatic conditions (Falk & Hempelmann 2013, Araújo & Peterson 2012, Pearson & Dawson 2003). Another cause of concern is the data quality because inaccurate or incomplete species presence data can cause a false picture of the bioclimatic envelope (Araújo & Peterson 2012).

Despite all criticism, Pearson & Dawson (2003) consider bioclimatic envelope models valuable for a first assessment of suitable areas under climate change, provided the mentioned limitations are kept in mind. Furthermore, the authors emphasize the importance of an adequate spatial scale. On a continental-scale, climate appears to be the main influence. Therefore, several models were rather successful in simulating the distribution of higher plant species. Yet, results were of different accuracy for different species. Moreover, finer details of distributions were often not captured. On a local scale, other factors, e.g. soil type and biotic interactions, gain influence and can become more dominant compared to climate (Pearson & Dawson 2003). This is of particular importance in the context of urban trees, as the urban microclimatic conditions can differ considerably from the conditions of the surrounding.

In addition to that, transferring information from a larger to a smaller scale is challenging as it entails additional sources of error. It is possible that a species is suitable according to the large-scale climate conditions, but local factors or extreme sites prevent good growth. Additional information, which is currently not provided by bioclimatic envelopes, is necessary in the context of urban green to address the challenging urban conditions and additional stresses. One would therefore need comfort conditions of a species specific to the urban environment, including e.g. a range of tolerances to pollution, salt or the more extreme climatic conditions. Such an approach would however need a different methodology, as the required information cannot be extracted from large-scale distributions in the same way. To sum it up, it appears that bioclimatic envelope models can give a good first indication concerning the species suitability in a larger region. However, they cannot give a reliable assessment for highly variable urban areas due to the additional influence of many local factors that are not sufficiently considered in many models. Bioclimatic envelope models rather have the power to estimate the suitability according to larger-scale climatic conditions.

5.4. Recommendations for achieving the best benefits for urban areas

As trees are planted not only for a few years but are intended to thrive and provide their benefits over several decades, a number of considerations are necessary to achieve the highest possible benefit. First of all, appropriate species have to be chosen according to current and expected future climatic conditions. Secondly, the individual tree needs to be appropriate for the specific local site conditions. Therefore, a comprehensive site assessment ideally precedes planting of a tree (Sjöman et al. 2012, Bassuk et al. 2009, Gilman & Sadowski 2007). Improving site conditions to facilitate a successful tree establishment are likewise recommended (Duhme & Pauleit 2000). The approach to consider tree characteristics as well as sites conditions is called 'right tree in the right place' (Benedikz et al. 2005). This is especially crucial to avoid higher costs for additional maintenance or necessary replacement of damaged or dead trees later on (Doick & Hutchings 2013, Bassuk et al. 2009, Gilman & Sadowski 2007). Further factors include tree quality, adequate planting and management, the creation and preservation of a suitable surrounding (e.g. no sealing of surfaces later on) as well as acquisition and management costs (Danielzik + Leuchter Landschaftsarchitekten 2012, Benedikz et al. 2005, Sæbø et al. 2005).

Another important point is that urban green spaces and street trees require regular maintenance. Adequate arboriculture is necessary to maintain health and aesthetical value, but also to ensure safety in urban environments, since wind fall and damages due to snow load pose a danger to the residents (Siewniak & Kusche 2009). Poor soil quality and unfavourable site conditions can partly be compensated by the use of adequate plant substrate. Furthermore, the promotion of mycorrhizal fungi may increase water and nutrient uptake (Böll et al. 2014). Percival & Noviss (2008) point out that container-grown trees are especially vulnerable to drought stress within the first month after transplanting them into their final location. Drought stress is therefore observed particularly often in young, newly planted urban trees. The authors suggest an increase of drought tolerance e.g. by applying chemicals. Generally, attention should be paid to adequate watering, at least during the first months after planting to ensure successful tree establishment. Bassuk et al. (2009) similarly recommend irrigating newly planted trees during the first years to guarantee the acclimation to their surroundings.

Konijnendijk et al. (2005) published a reference book on urban forests and trees, which provides more detailed information for practitioners, e.g. on planning and design of green spaces, detailed information on plant selection, management techniques as well as case studies from different cities. In Germany, technical and legal requirements regarding tree care are also laid down in different official regulations (Siewniak & Kusche 2009). Moreover, a short practical guide on site assessment and species selection was published by Gilman & Sadowski (2007) and a more general practical guide on urban climate and adaptation options for practitioners by MUNVL (2010).

5.5. Discussion of research questions and future outlook

To round off the analysis and discussion of this study, the four research questions raised in the introduction will be discussed below.

1. *What climate change impacts are projected for the selected case study regions in Germany for the 2050s (2036-2065)?*

EURO-CORDEX ensemble projections were evaluated for three case study regions (East, Northwest and Southwest) that exemplify different climatic conditions for Germany. The focus was on the frequency and duration of heat waves and dry spells in the 2050s. An increase in the number of hot days and heat waves during the growing season is projected for all regions. The strongest increase in the number of hot days is expected in the Southwest, the region which according to E-OBS observational data already experiences more hot days than the other regions today. Furthermore, an increase in the number and duration of dry spells is projected for the Southwest. The East is projected to see an increase in summer precipitation sum, yet, no distinct signal exists concerning dry spell number and duration, i.e. no information on the temporal distribution of precipitation is given. The projections are quite ambiguous with partially broad bandwidth of possible developments for some of explored climate indices. No distinct trend is visible for precipitation, dry spells, and the duration of heat waves during the growing season in one or more of the regions. Even though there are no distinct signals for some indices, the projected increases in dry hot days and heat waves could potentially cause drier conditions in all regions due to increased evaporation under higher temperatures.

Reasons for the lack of ensemble agreement for some indices include the difficulty to model precipitation, which is influenced by numerous processes on different scales. Furthermore, certain assumptions have to be made when modelling climate, either due to an incomplete understanding of natural processes, the unpredictability of socio-economic developments or because models need to simplify reality. The ambiguous results may furthermore be attributed to the choice of location, as Germany belongs to the transition zone between regions with more distinct trends in Northern and Southern Europe. While projections agreed to a greater extent on the changes in Northern and Southern Europe, larger bandwidth and opposing projections exist for Germany especially concerning the precipitation-based indices.

It is in any case important to note that the ensemble members' lack of agreement on a trend for some indices does not imply that there will be no change. On the contrary, for some indices the future development remained unclear and larger changes into any direction as well as a constant development are equally possible. This results in a need for further development of the regional climate models on the one hand, but also for preparedness to a larger range of possible changes on the other hand. The former is addressed by the ongoing development of regional climate models. Models are improved continuously and the ensemble is further expanded (EURO-CORDEX initiative 2015). The latter has to be addressed through adequate climate change adaptation, focusing on a bandwidth of possible changes instead of focusing on only one alternative or even refraining from action altogether.

In future investigation, the simultaneous occurrence of dry spells and heat waves should be considered. Furthermore, additional indices which focus more specifically on actual water availability may provide further insights into the future situation of urban trees. On the other hand, as the literature review has shown, not many quantitative thresholds to define tree species requirements (e.g. minimum amount of precipitation needed during growing season) exist. Since many local conditions including soil factors and also the tree's individual history influence tree vitality, such general values can only be found rarely. Moreover, they are more relevant for the large-scale distribution of species and less relevant for site-specific suitability as long as they are not complemented by additional information. Towards smaller scales, many local influences come into play and gain an increasing importance. This complexity persists even if additional indices were calculated from the EURO-CORDEX data. It can therefore not be expected, that the outcome of this work would have been fundamentally different if other indices had been chosen.

2. *How will the ten selected tree species be generally affected from dry spells and heat waves and what do these results mean with respect to climate change impacts in the case study regions?*

After discussing the projected climate change impacts, ten broadleaf tree species were selected based on a vegetation survey in an urban park in Friesoythe, Lower Saxony, which were then classified according to their respective heat and drought tolerances. Different classification systems with varying numbers of classes exist for drought tolerance or related parameters. Most publications tend to focus on relative statements instead of naming specific thresholds of species requirements, e.g. for the required minimum amount of precipitation (see **Tab. 7**). The existing classification systems were compared and combined (see **Tab. 7**, **Tab. 8**). **Tab. 9** provides an overview on the concluding assessment of the ten species' heat and drought tolerances. The analysis on this thesis has shown that much fewer information is currently available regarding the species' heat tolerances than regarding their drought tolerances. Therefore, the assessment of heat tolerance is based on fewer studies compared to the analysis of drought tolerance. Furthermore, the level of detail of information on both tolerances varies strongly between different species. Knowledge gaps exist particularly for the less intensively studied ones with lower economic value.

After careful consideration, it became evident that a simple comparison of projected climatic conditions and tree species tolerances cannot lead to a profound conclusion on the future suitability of a species. Due to the high variability in projections accompanied by a flexible, site-specific behaviour of trees, a simple matching of both data is currently not possible. Considering the large number of local impacts within the city and the variety of factors that determine the effect of stress factors (e.g. timing and duration of heat or drought, predisposition etc.), it also seems unlikely that an overall assessment of future suitability will become much easier in the future. Even if the bandwidths of projected changes were smaller and trends were more distinct for all indices, local factors often overwrite the regional situation and have to be considered likewise. Instead, the more general assessment of drought and heat tolerance of the selected species offers a first step towards decision-making in tree species selection. Since the ensemble results are ambiguous for some indices, particularly for the development of dry spells, adaptation to a bandwidth of changes is necessary. Trees should be selected accordingly.

Nevertheless, broad variations in projected changes, a lack of knowledge on climate change or on species suitability should not prevent any action from being taken. Even though definite recommendations either for or against certain trees in the three case study regions are currently not possible, general differences in drought and heat tolerance can be identified with some exceptions (see section 4) and should be attended to when selecting tree species for urban areas. It is therefore advisable to favour ‘very tolerant’ and ‘moderately tolerant’ tree species.

By focusing on the *no regret* approach, i.e. choosing primarily drought and heat tolerant tree species for urban areas, adaptation measures can be useful already today and decrease the risk of highly susceptible urban green spaces in the future. As urban green provides numerous benefits to the city and its inhabitants, planting adequate urban trees has an immediate positive effect – a *win-win* situation. Since trees possess very long life spans under good growing conditions, today’s decisions should be made carefully. They affect the respective green spaces for several decades and costly substitutions of carelessly planted unsuitable species should be avoided. At best, trees can cope with the entire bandwidth of projected climatic conditions, thereby increasing the likelihood of survival under future climatic conditions. In order to include in particular those projections towards drier and warmer conditions, a general focus on ‘very tolerant’ or ‘moderately tolerant’ species is advisable. With regard to urban development, it is recommended to support the implementation with a long-term monitoring process.

However, the role of regional climate modelling data should not be underrated, even though regarding some indices it is still afflicted with a lack of agreement of the ensemble members on a trend. It is furthermore important to choose the modelled indices according to the research question. For instance, annual values of precipitation are often less relevant for tree growth than precipitation during the growing season or even during individual months (van der Werf et al. 2007, Burk 2006). Accordingly, the indices used here refer to the growing season (May– September). Moreover, the precipitation sum alone – whether it is an annual, seasonal or monthly value – does not determine water availability. Soil factors and evaporation contribute strongly to the amount of water that is finally available for the tree. Furthermore, the precipitation sum does not consider different temporal distributions of rainfall. The same sum can come off regular, moderate rainfall or few heavy precipitation events. Various local factors determine whether a tree can cope with environmental stress or not and natural conditions are altered anyhow in urban areas. To determine absolute threshold values such as a minimum amount of precipitation is therefore questionable. Instead, it appears to be more promising to focus on qualitative assessments of the tolerances of a tree that are as comprehensive as possible. Qualitative information can help to find suitable species, even if some knowledge gaps exist and no threshold values can be given.

A critical point for functioning adaptation is the transfer of scientific knowledge into practise. While several guidelines and recommendations already exist, it appears that this area could also need some further improvement or an improved synthesis of information. Comprehensive concepts for sustainable urban tree plantings, further knowledge of the suitability of specific species, and tree quality standards are urgently needed. Moreover, according to Pauleit (2003), funding for urban tree plantations is often restricted and shortcomings in qualified staff with the necessary knowledge can complicate sustainable implementation and management of urban green spaces. To put this goal into practice, cooperation between urban planners, landscape architects, biologist, climate adaptation experts, and civil engineers is important throughout the whole planning and implementation process. Climate services, such as the Climate Service Center Germany (GERICS), can provide specialist expertise on projected climate change impacts and possible adaptation options tailored to a specific case study. They play a particular important role in providing adaptation expertise, building networks, consolidating and translating scientific knowledge as well as giving advice on specific case studies.

3. *Future outlook: in the face of climate change, is there a need to replace all the popular tree species which currently characterise our cityscape?*

Trees, as an important part of the cityscape, can considerably increase the inhabitants' life quality by improving microclimatic conditions, enhancing urban biodiversity, and providing ornamental value and shade. They are also a sound measure of adaptation to climate change impacts. Yet, these benefits strongly depend on the trees' health, which may be threatened in the future by climate change and the expected increase in heat and drought stress during summer. Drought and heat tolerance of tree species in urban areas is gaining increasing importance under the impacts of climate change (Leuzinger et al. 2010). As can be seen from various case studies, several of the investigated species are sensitive to drought and / or heat, which might make them unsuitable for future conditions.

The analysis of climate projections and tree species tolerances' has shown that currently there is no immediate need to replace all of the well-known and popular tree species. At least some of them were classified as 'moderately tolerant' or even 'very tolerant' to heat and drought. It can therefore be assumed that they will also withstand the possibly increasing stresses in the near future. Yet, as counterexamples showed, other species might actually become unsuitable in the future or could only be able to thrive well, if additional measures (e.g. irrigation) are taken. Such additional measures are however not desirable due to monetary constraints, higher efforts, and the possibility that the measures may not even counteract all negative stresses. Instead, the focus should rather be on species that only require a minimum amount of maintenance or can ideally even cope well on their own apart e.g. from pruning. To ensure planting success it is thereby essential to consider local conditions. The use of non-native species or provenances is broadly discussed in research. It might well be that new species will add to the existing ones and thereby alter the current cityscape in the future. Careful consideration of tolerance towards other stresses (e.g. frost), concerns raised by nature conservationists as well as overall suitability for the urban context, is recommended before transferring new species on a large scale.

6. Conclusion

One aim of this thesis is the analysis of expected changes regarding heat waves and dry spells in three case study regions in Germany in the 2050s using regional climate projections of the EURO-CORDEX ensemble. While an increase in the number of hot days and heat waves during the growing season is projected for all regions, the projections are quite ambiguous for other explored climate indices. Therefore, no distinct trend is visible for precipitation, dry spells, and the duration of heat waves during the growing season. One possible reason for the ambiguous results is Germany's location in a transition zone between Northern and Southern Europe, for which opposing future developments are projected.

Nevertheless, the projected bandwidth of climatic changes show the need to think about adaptation options to avoid undesirable damages to trees and the increase of maintenance costs. Based on a literature review, general drought and heat tolerances were assessed for ten selected tree species. The species were classified according to drought tolerance or sensitivity, respectively, in an overall assessment using the four classes 'very tolerant' (*B. pendula*), 'moderately tolerant' (*A. platanoides*, *F. excelsior, Q. robur*), 'moderately sensitive' (*A. hippocastanum, A. pseudoplatanus*, *F. sylvatica*), and 'very sensitive' (*A. glutinosa*, *P. nigra, S. alba*). Concerning heat stress, the same classification was compiled with the following results: 'very tolerant (*B. pendula*, *F. excelsior*), 'moderately tolerant' (*A. hippocastanum*, *A. platanoides, Q. robur*), and 'moderately sensitive' (*A. pseudoplatanus, F. sylvatica*). Because of insufficient information, no assessment of heat tolerance was possible for *A. glutinosa*, *P. nigra*, and *S. alba*. Typically, the more drought-tolerant species also seem to be more tolerant to heat, while those rather sensitive to drought similarly tend to be more heat-sensitive. Yet, since tree growth and vitality depend on many local factors, processes, and interactions, research on climate-growth relationships and on understanding the effect of heat and drought in more detail is still needed. Definite recommendations for or against the selected species in the specific case study regions are currently not possible. Nevertheless, a focus on the 'very tolerant' or at least 'moderately tolerant' species is advisable. Future tree plantings should therefore avoid selecting species that are classified as 'moderately sensitive' or even 'very sensitive' to heat and / or drought.

The analysis of climate projections and tree species tolerances' has shown that currently there is no immediate need to replace all tree species, since at least some of them were classified as 'moderately tolerant' or even 'very tolerant' to heat and drought. It can therefore be assumed that they will also withstand the possibly increasing stresses in the near future. Yet, as counterexamples showed, other species might actually become unsuitable in the future or could only be able to thrive well, if additional measures (e.g. irrigation) are taken. Such measures are however not desirable due to monetary constraints, higher efforts, and the possibility that the measures may not even counteract all negative stresses. Instead, the focus should be on species that only require a minimum amount of maintenance or can ideally even cope well on their own apart e.g. from pruning. By focusing on *no regret* measures, i.e. choosing primarily drought and heat tolerant tree species for urban areas, adaptation measures can be useful already today and decrease the risk of highly susceptible urban green spaces in the future. With regard to urban development, it is recommended to support tree implementation with a long-term monitoring process to ensure success of future plantings. The use of non-native species or provenances is currently under discussion..

However, careful consideration of tolerance towards other stress, concerns raised by nature conservationists as well as overall suitability for the urban context, is recommended before transferring new species on a large scale.

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Appendix A – EURO-CORDEX time series

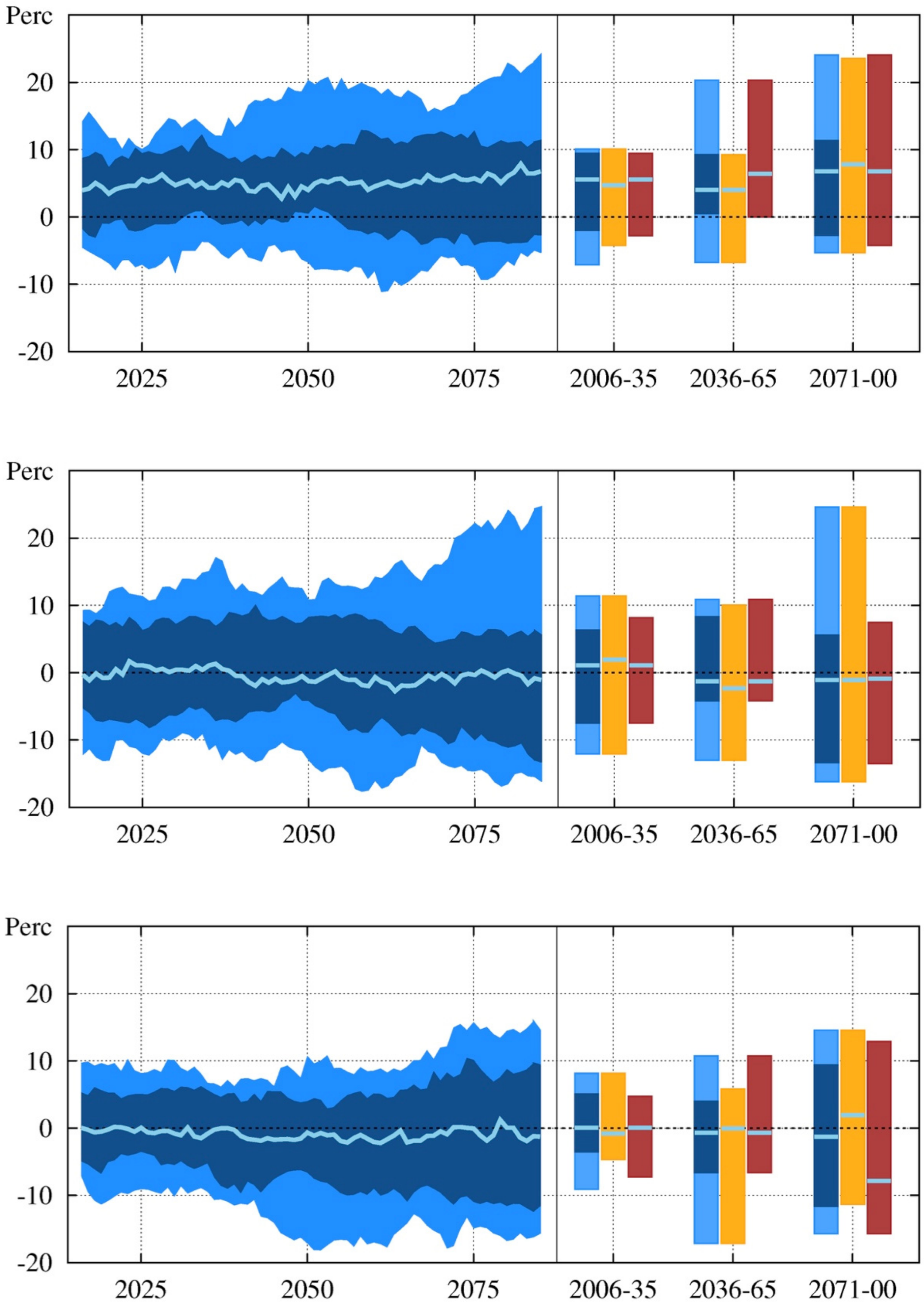


Fig. A1 Projected changes in mean precipitation sum (time series of the ensemble range) during the growing season (in %) for regions E (top), NW (middle), and SW (bottom). Statistical values are averaged over a 30-year period referenced to 1971-2000. Time axis values represent the mid-year of the 30-year periods. The time series includes the ensemble median (light blue line), the likely range (dark blue shaded area), and the ensemble range (light blue shaded area). The box to the right shows specific 30-year periods of the time series itemized to the ensemble mean (blue), RCP4.5 (yellow), and RCP8.5 (red) ensemble members.

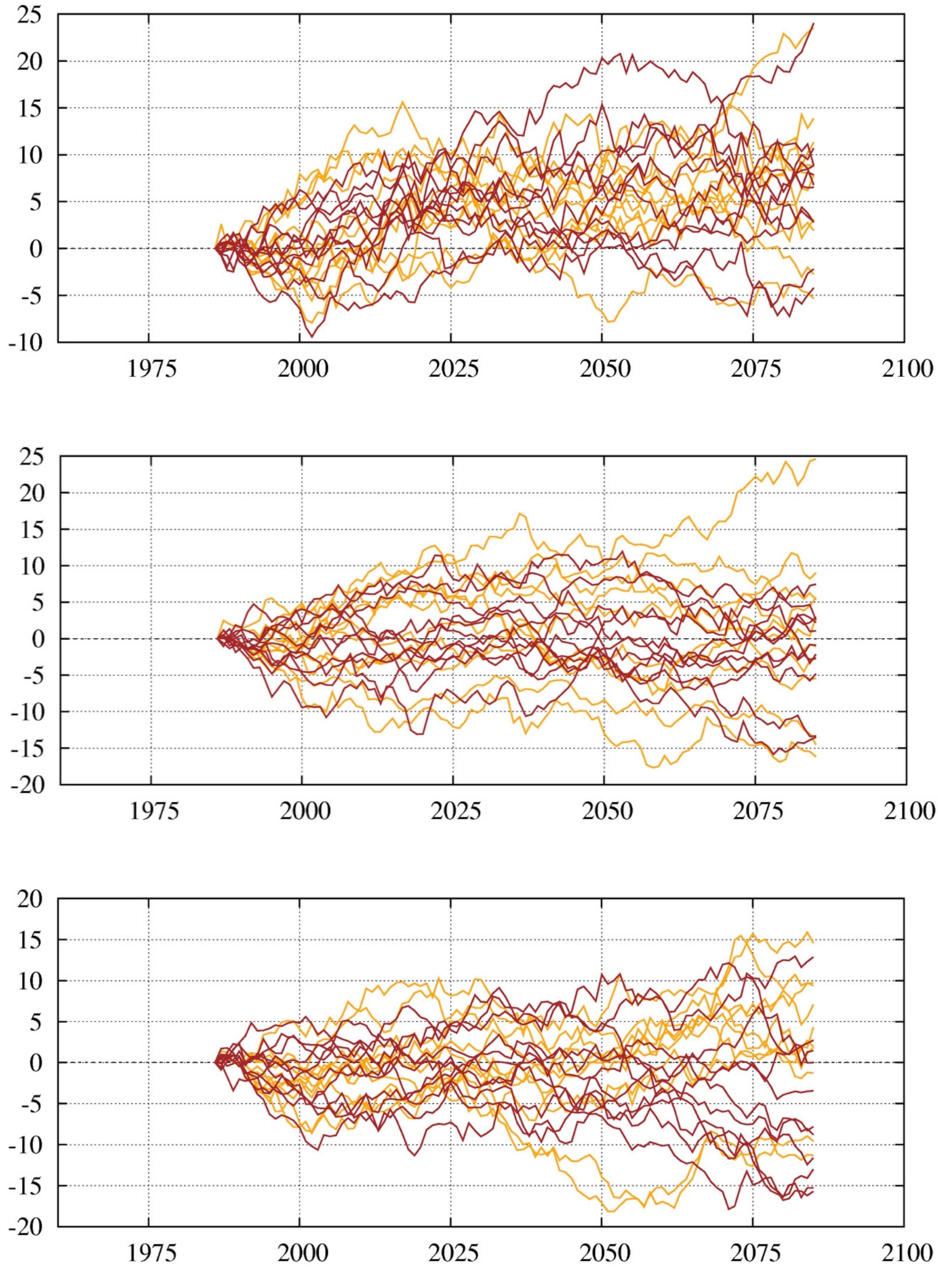


Fig. A2 Projected changes in mean precipitation sum (time series of individual simulations) during the growing season (in %) for regions E (top), NW (middle), and SW (bottom). Shown are all individual model simulations contributing to the ensemble (RCP4.5 in yellow, RCP 8.5 in red) smoothed by a 30-year running mean referenced to the period 1971-2000. Time axis values represent the mid-year of a 30-year period.

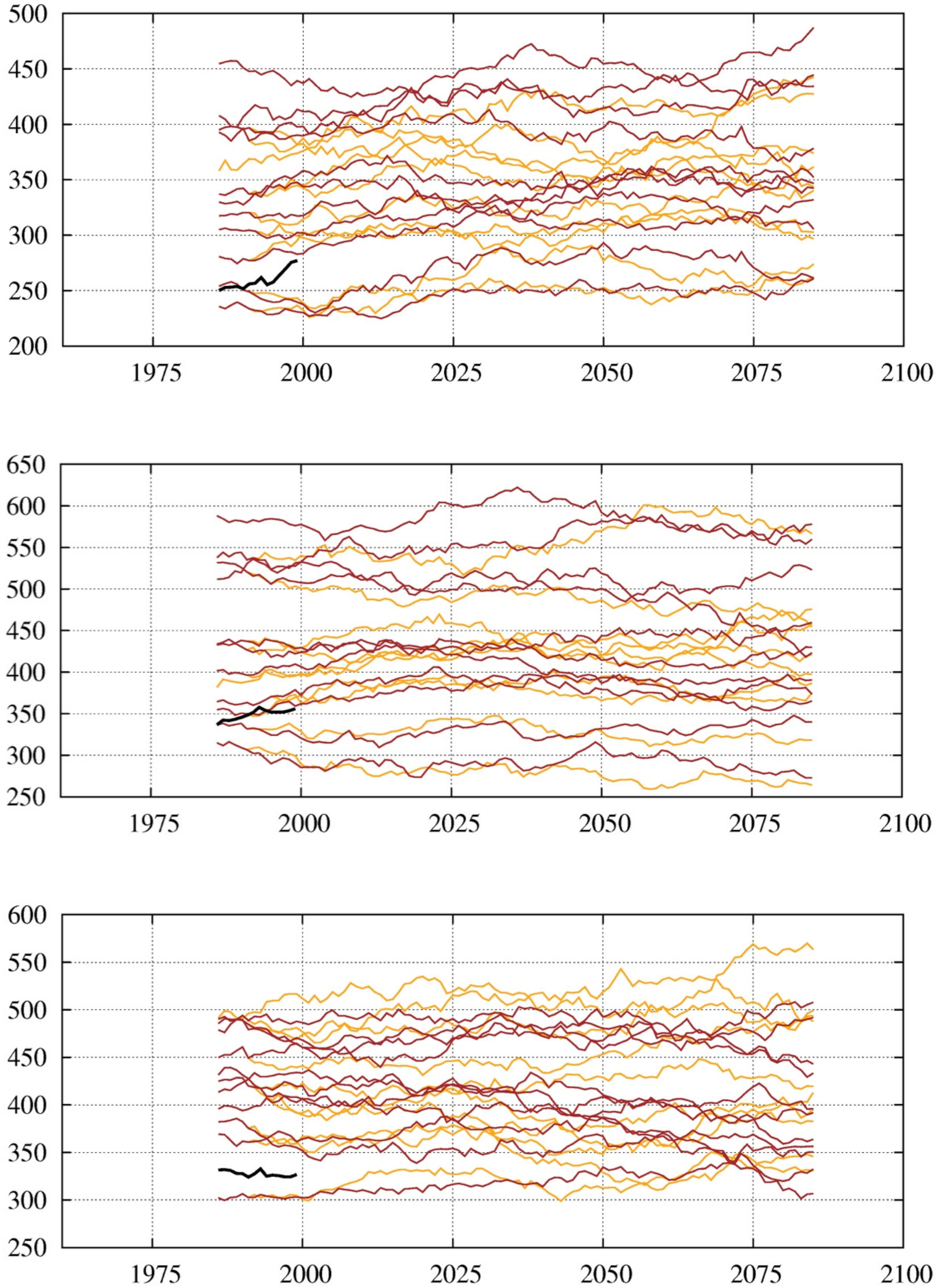


Fig. A3 Projected mean precipitation sum (time series of individual simulations) during the growing season (in mm) for regions E (top), NW (middle), and SW (bottom). Shown are all individual model simulations contributing to the ensemble (RCP4.5 in yellow, RCP 8.5 in red) smoothed by a 30-year running mean referenced to the period 1971-2000. Time axis values represent the mid-year of a 30-year period. The black line shows observational E-OBS data, likewise averaged over a 30-year period.

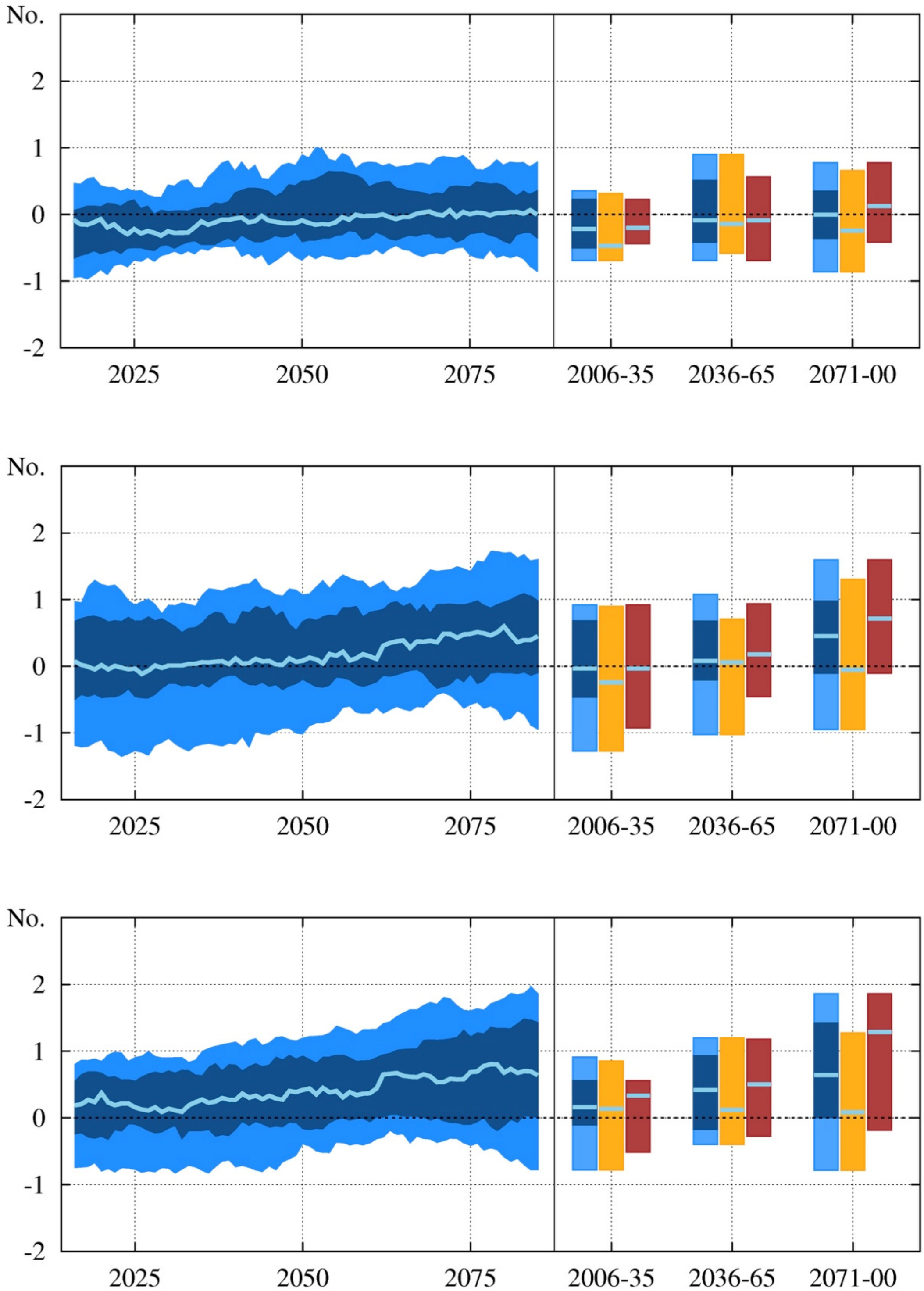


Fig. A4 Projected changes in mean number of dry spells (time series of the ensemble range) during the growing season (in number of dry spells) for regions E (top), NW (middle), and SW (bottom). Statistical values are averaged over a 30-year period referenced to 1971-2000. Time axis values represent the mid-year of the 30-year periods. The time series includes the ensemble median (light blue line), the likely range (dark blue shaded area), and the ensemble range (light blue shaded area). The box to the right shows specific 30-year periods of the time series itemized to the ensemble mean (blue), RCP4.5 (yellow), and RCP8.5 (red) ensemble members.

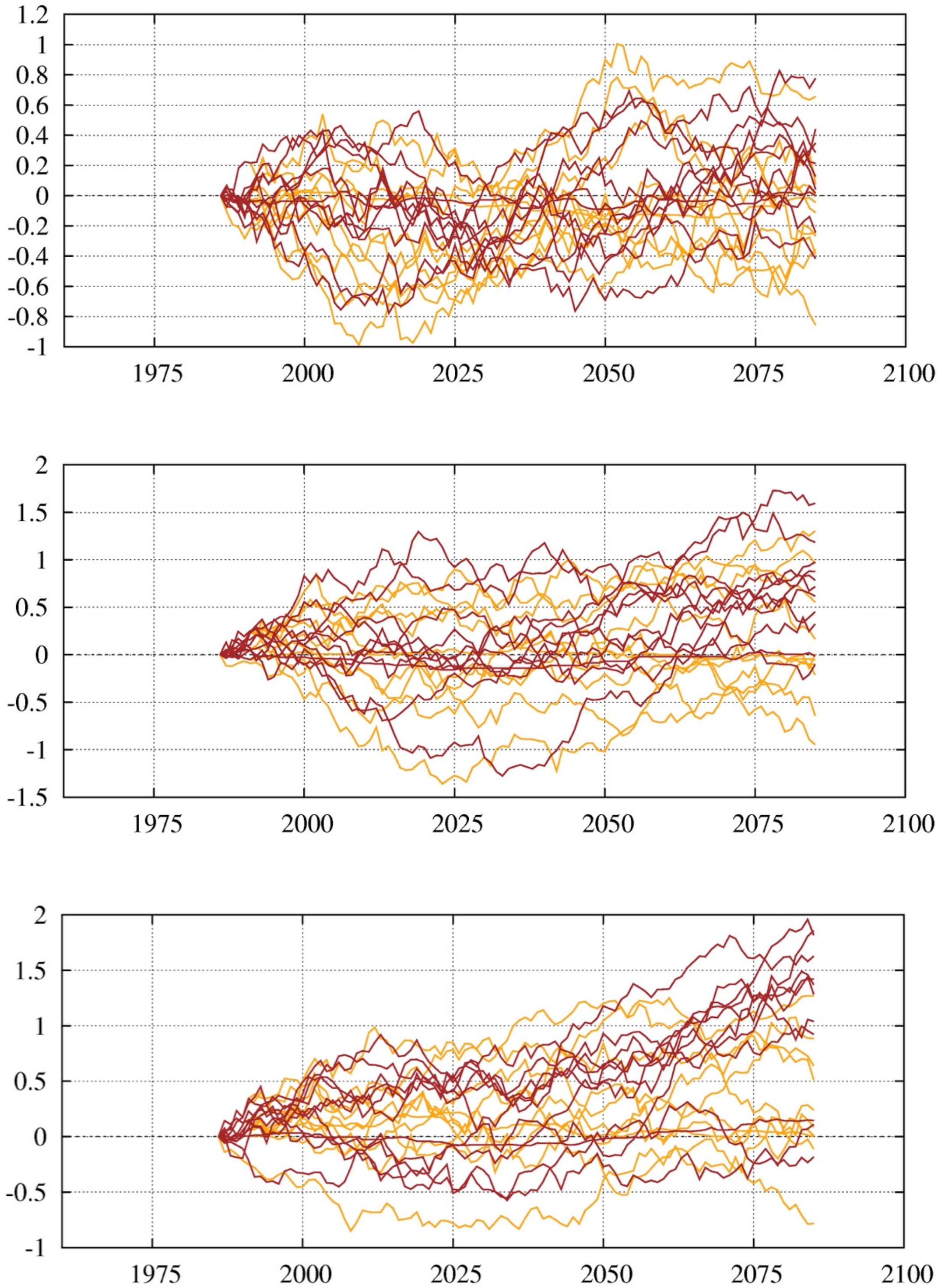


Fig. A5 Projected changes in mean number of dry spells (time series of individual simulations) during the growing season (in number of dry spells) for regions E (top), NW (middle), and SW (bottom). Shown are all individual model simulations contributing to the ensemble (RCP4.5 in yellow, RCP 8.5 in red) smoothed by a 30-year running mean referenced to the period 1971-2000. Time axis values represent the mid-year of a 30-year period.

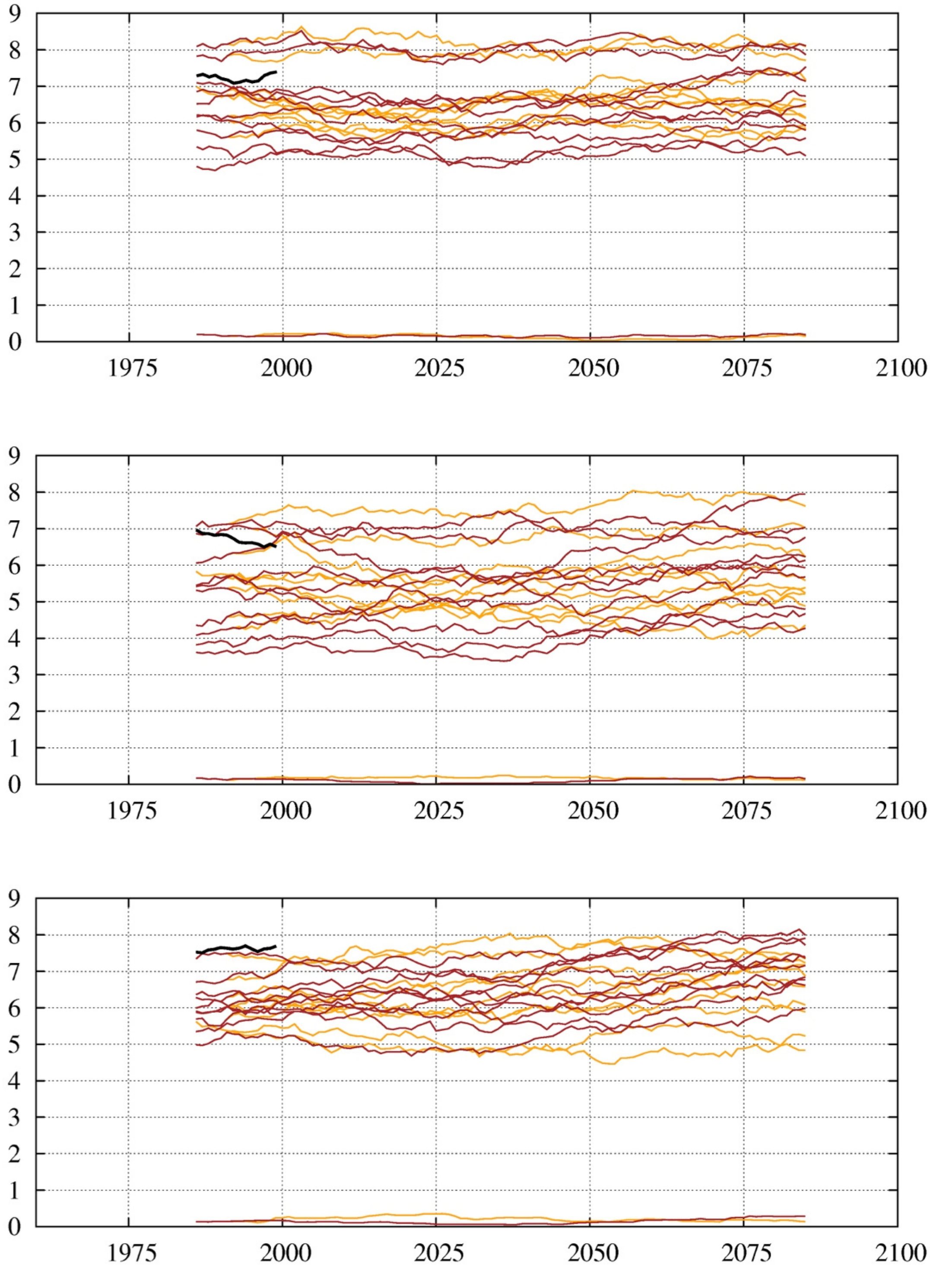


Fig. A6 Projected mean number of dry spells (time series of individual simulations) during the growing season (in number of dry spells) for regions E (top), NW (middle), and SW (bottom). Shown are all individual model simulations contributing to the ensemble (RCP4.5 in yellow, RCP 8.5 in red) smoothed by a 30-year running mean referenced to the period 1971-2000. Time axis values represent the mid-year of a 30-year period. The black line shows observational E-OBS data, likewise averaged over a 30-year period.

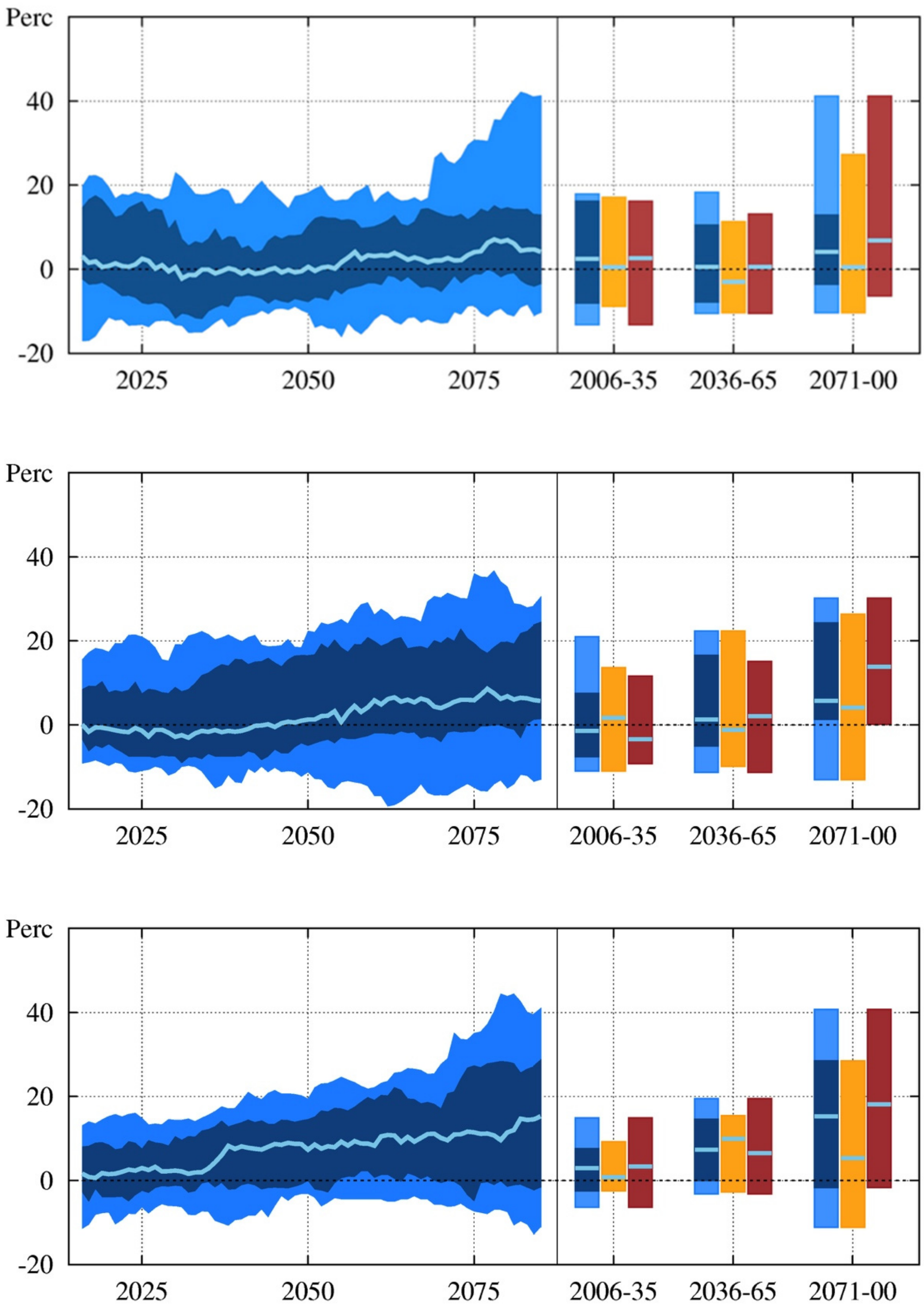


Fig. A7 Projected changes in mean maximum duration of dry spells (time series of the ensemble range) during the growing season (in %) for regions E (top), NW (middle), and SW (bottom). Statistical values are averaged over a 30-year period referenced to 1971-2000. Time axis values represent the mid-year of the 30-year periods. The time series includes the ensemble median (light blue line), the likely range (dark blue shaded area) and the ensemble range (light blue shaded area). The box to the right shows specific 30-year periods of the time series itemized to the ensemble mean (blue), RCP4.5 (yellow), and RCP8.5 (red) ensemble members.

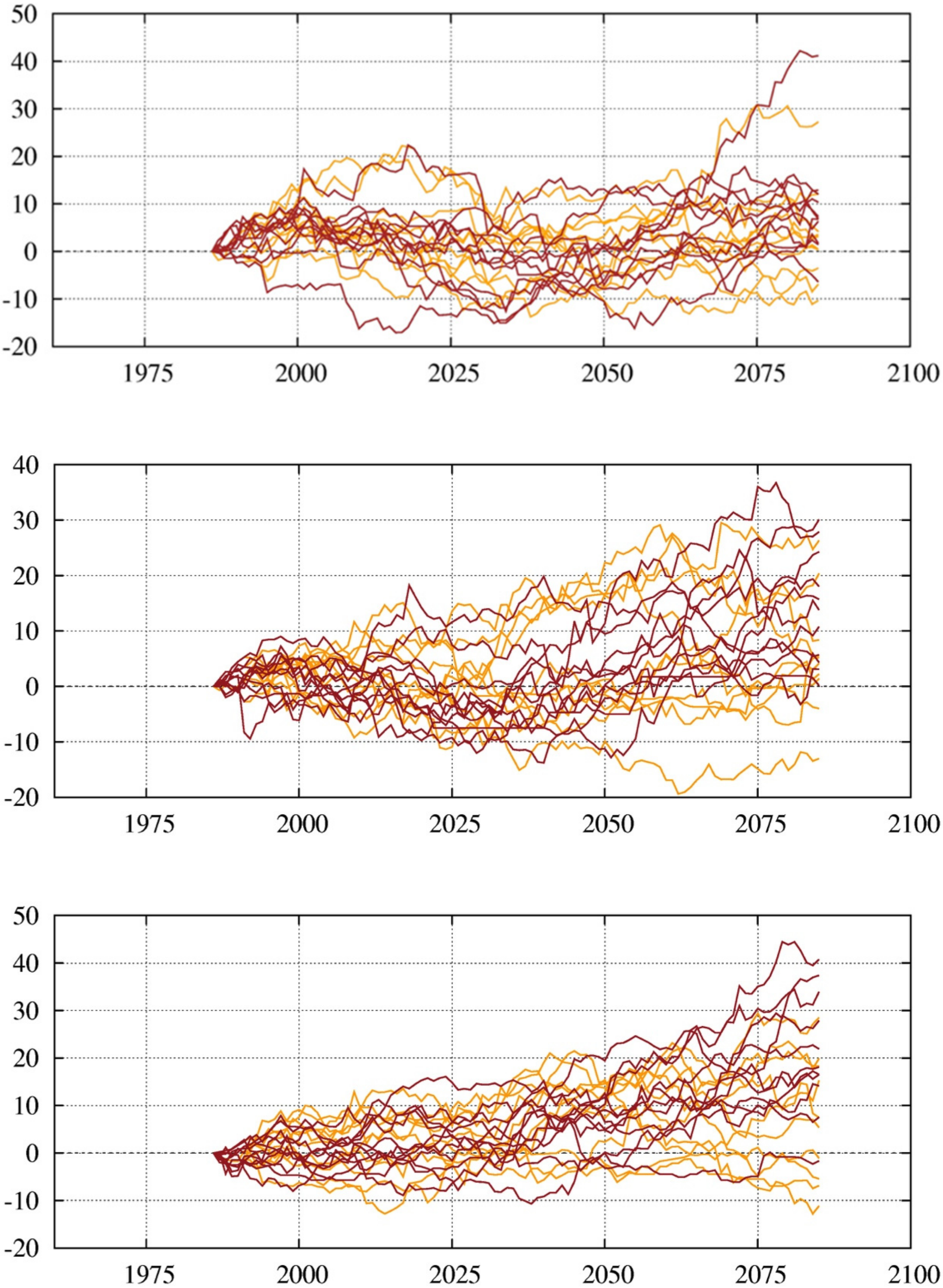


Fig. A8 Projected changes in mean maximum duration of dry spells (time series of individual simulations) during the growing season (in %) for regions E (top), NW (middle), and SW (bottom). Shown are all individual model simulations contributing to the ensemble (RCP4.5 in yellow, RCP 8.5 in red) smoothed by a 30-year running mean referenced to the period 1971-2000. Time axis values represent the mid-year of a 30-year period.

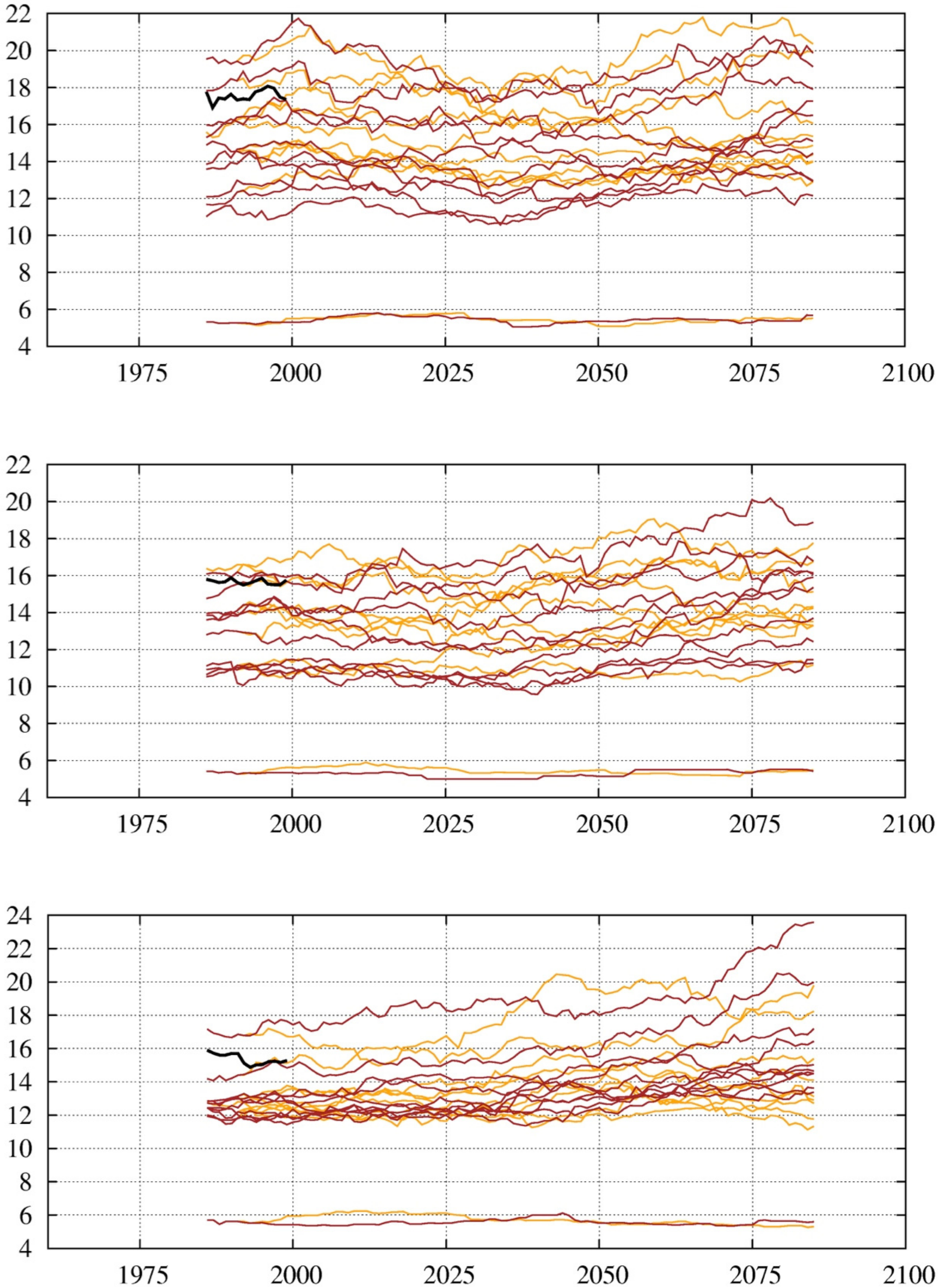


Fig. A9 Projected mean maximum duration of dry spells (time series of individual simulations) during the growing season (in days) for regions E (top), NW (middle), and SW (bottom). Shown are all individual model simulations contributing to the ensemble (RCP4.5 in yellow, RCP 8.5 in red) smoothed by a 30-year running mean referenced to the period 1971-2000. Time axis values represent the mid-year of a 30-year period. The black line shows observational E-OBS data, likewise averaged over a 30-year period.

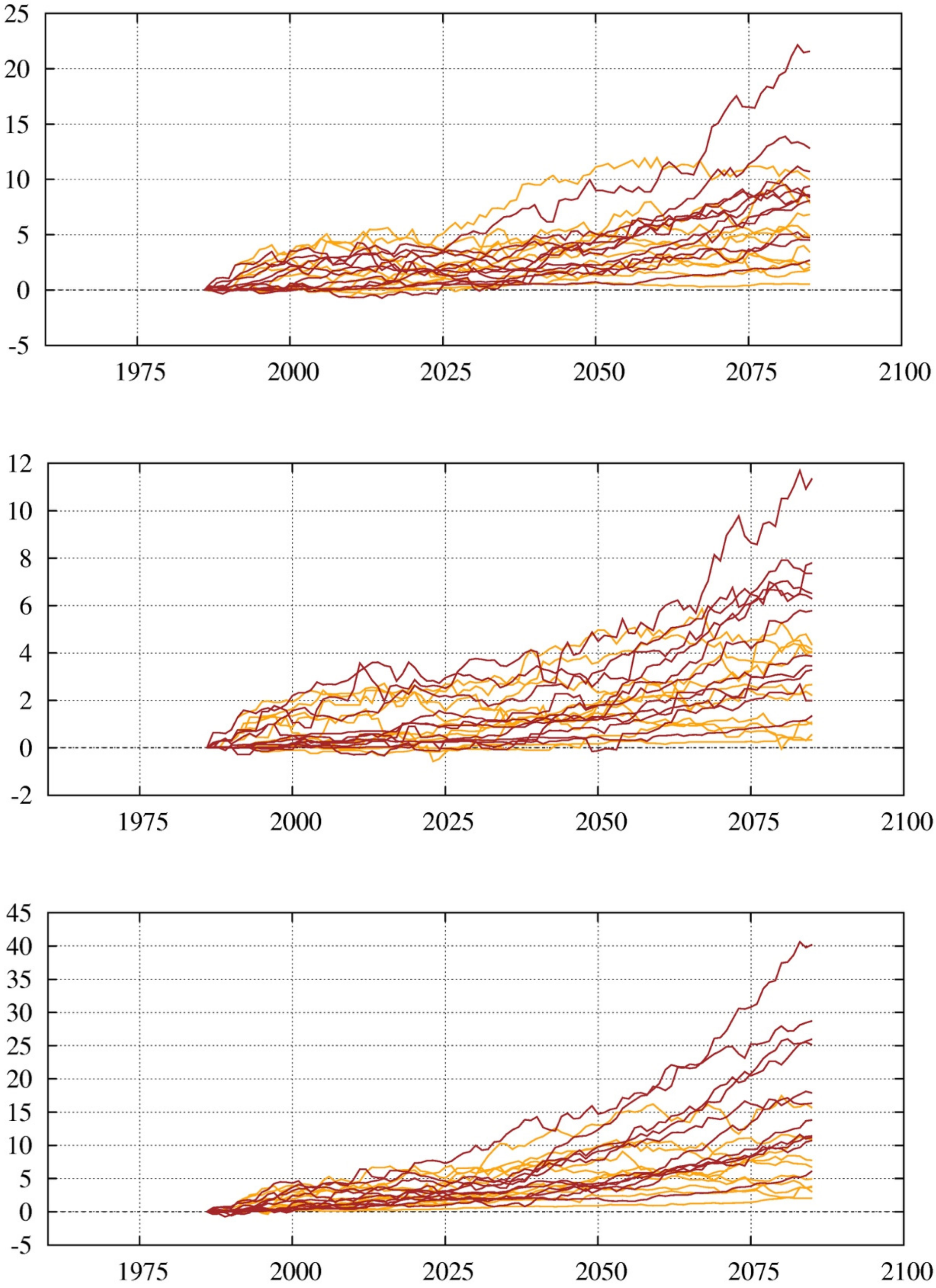
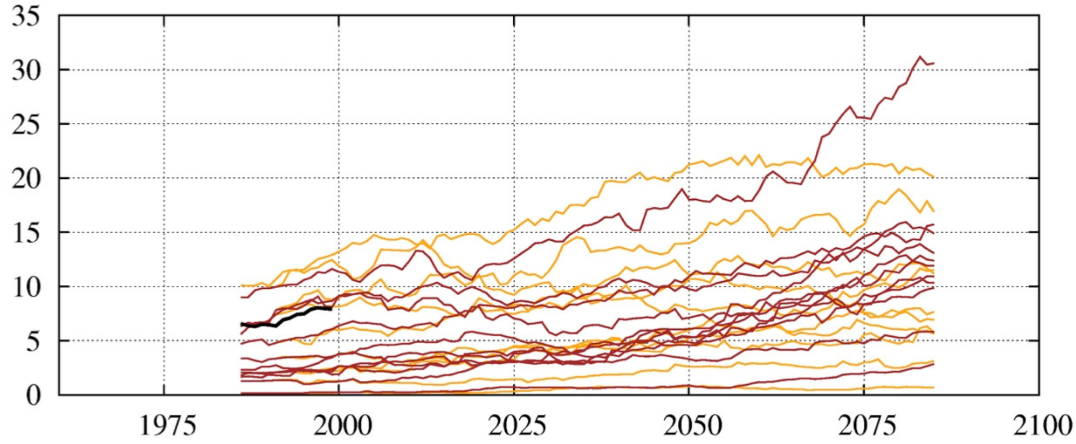
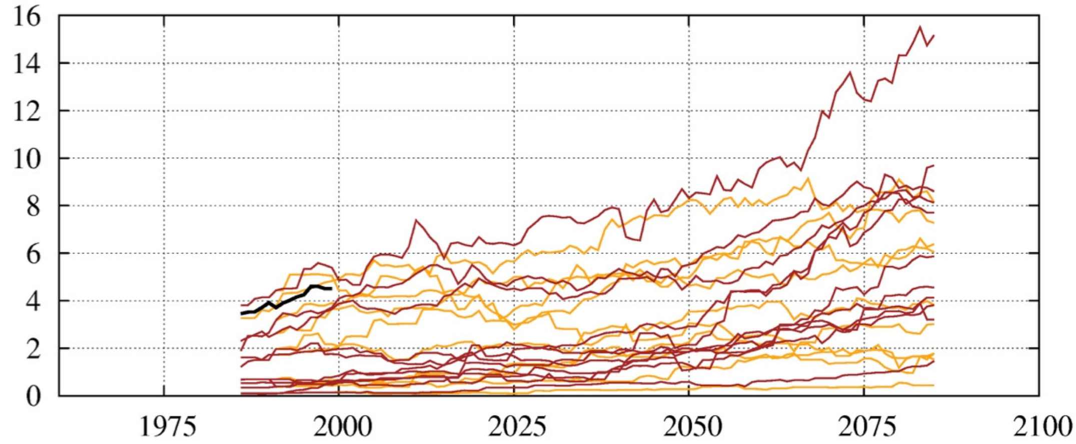


Fig. A10 Projected changes in mean number of hot days (time series of individual simulations) during the growing season (in days) for regions E (top), NW (middle), and SW (bottom). Shown are all individual model simulations contributing to the ensemble (RCP4.5 in yellow, RCP 8.5 in red) smoothed by a 30-year running mean referenced to the period 1971-2000. Time axis values represent the mid-year of a 30-year period.





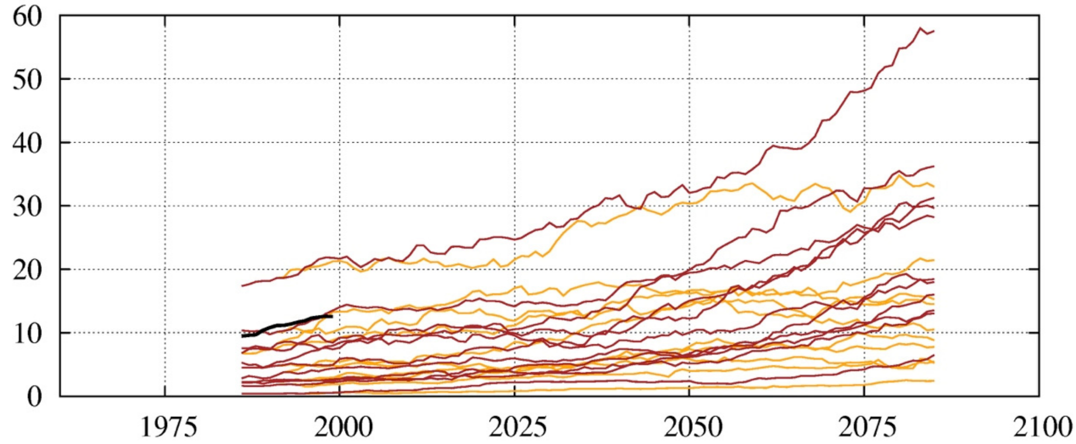


Fig. A11 Projected mean number of hot days (time series of individual simulations) during the growing season (in days) for regions E (top), NW (middle), and SW (bottom). Shown are all individual model simulations contributing to the ensemble (RCP4.5 in yellow, RCP 8.5 in red) smoothed by a 30-year running mean referenced to the period 1971-2000. Time axis values represent the mid-year of a 30-year period. The black line shows observational E-OBS data, likewise averaged over a 30-year period.

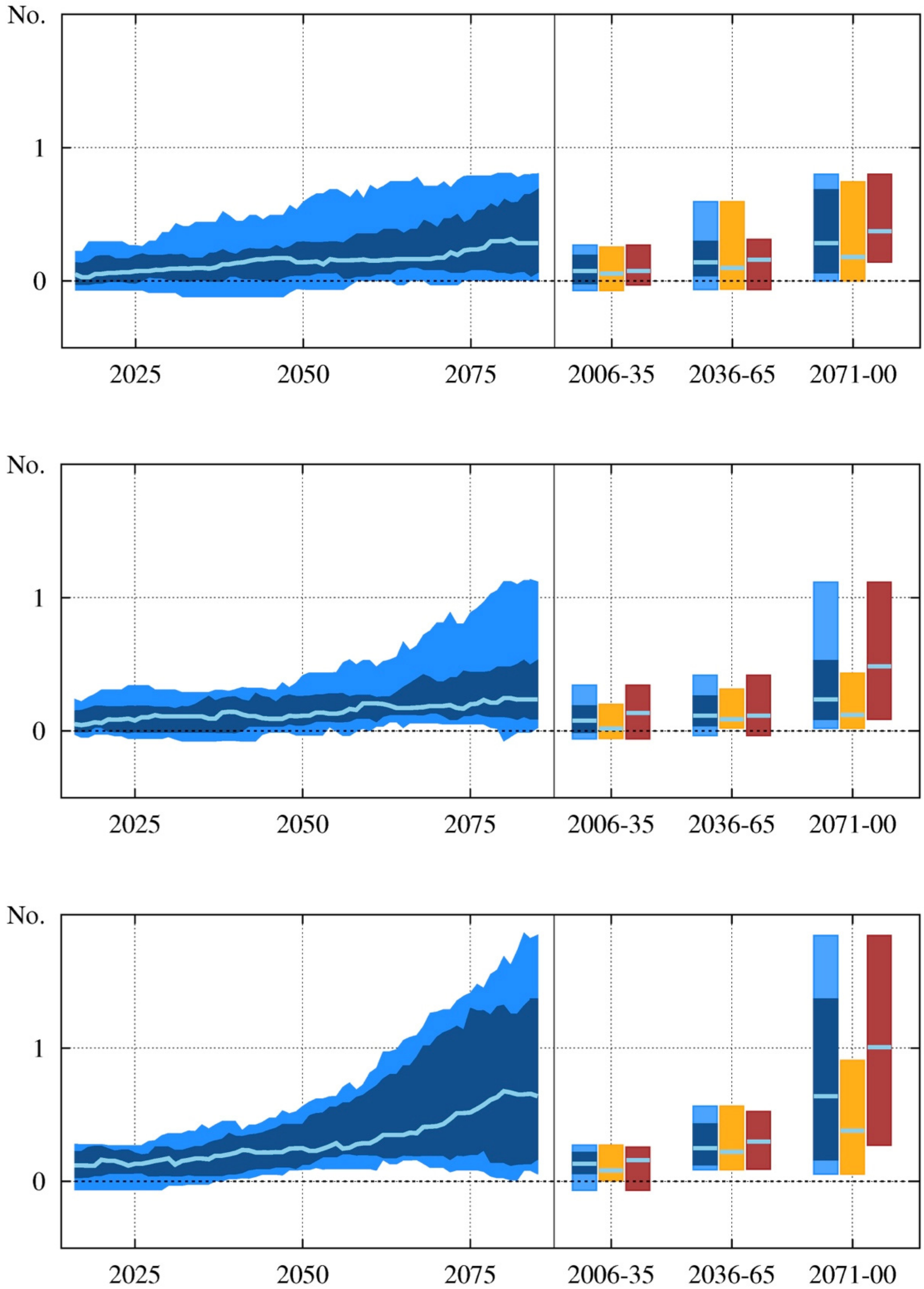


Fig. A12 Projected changes in mean number of heat waves per year (time series of the ensemble range) during the growing season (in number of heat waves) for regions E (top), NW (middle), and SW (bottom). Statistical values are averaged over a 30-year period referenced to 1971-2000. Time axis values represent the mid-year of the 30-year periods. The time series includes the ensemble median (light blue line), the likely range (dark blue shaded area) and the ensemble range (light blue shaded area). The box to the right shows specific 30-year periods of the time series itemized to the ensemble mean (blue), RCP4.5 (yellow), and RCP8.5 (red) ensemble members.

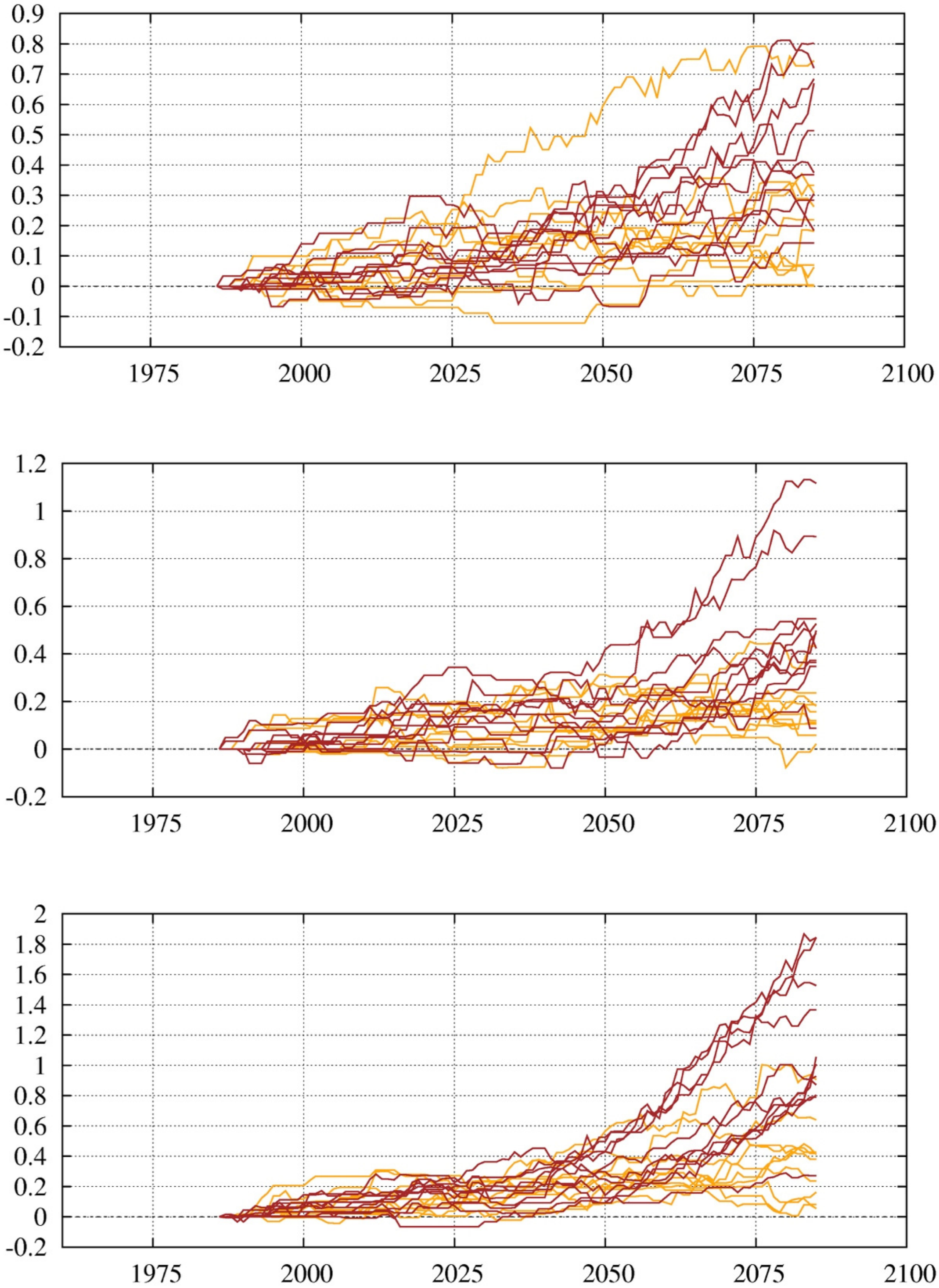


Fig. A13 Projected changes in mean number of heat waves (time series of individual simulations) during the growing season (in in absolute numbers) for regions E (top), NW (middle), and SW (bottom). Shown are all individual model simulations contributing to the ensemble (RCP4.5 in yellow, RCP 8.5 in red) smoothed by a 30-year running mean referenced to the period 1971-2000. Time axis values represent the mid-year of a 30-year period.

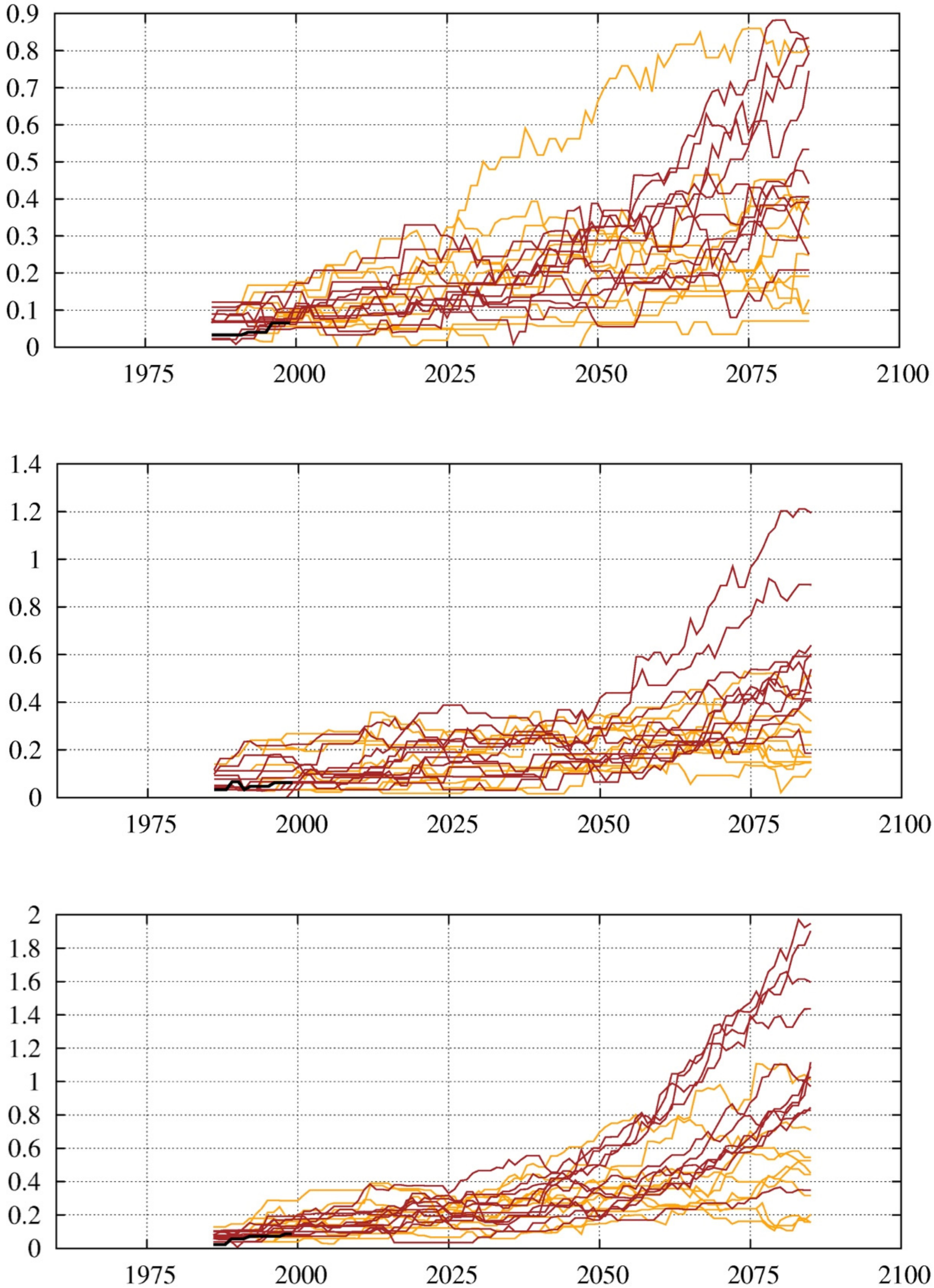


Fig. A14 Projected mean number of heat waves (time series of individual simulations) during the growing season (in number of heat waves) for regions E (top), NW (middle), and SW (bottom). Shown are all individual model simulations contributing to the ensemble (RCP4.5 in yellow, RCP 8.5 in red) smoothed by a 30-year running mean referenced to the period 1971-2000. Time axis values represent the mid-year of a 30-year period. The black line shows observational E-OBS data, likewise averaged over a 30-year period.

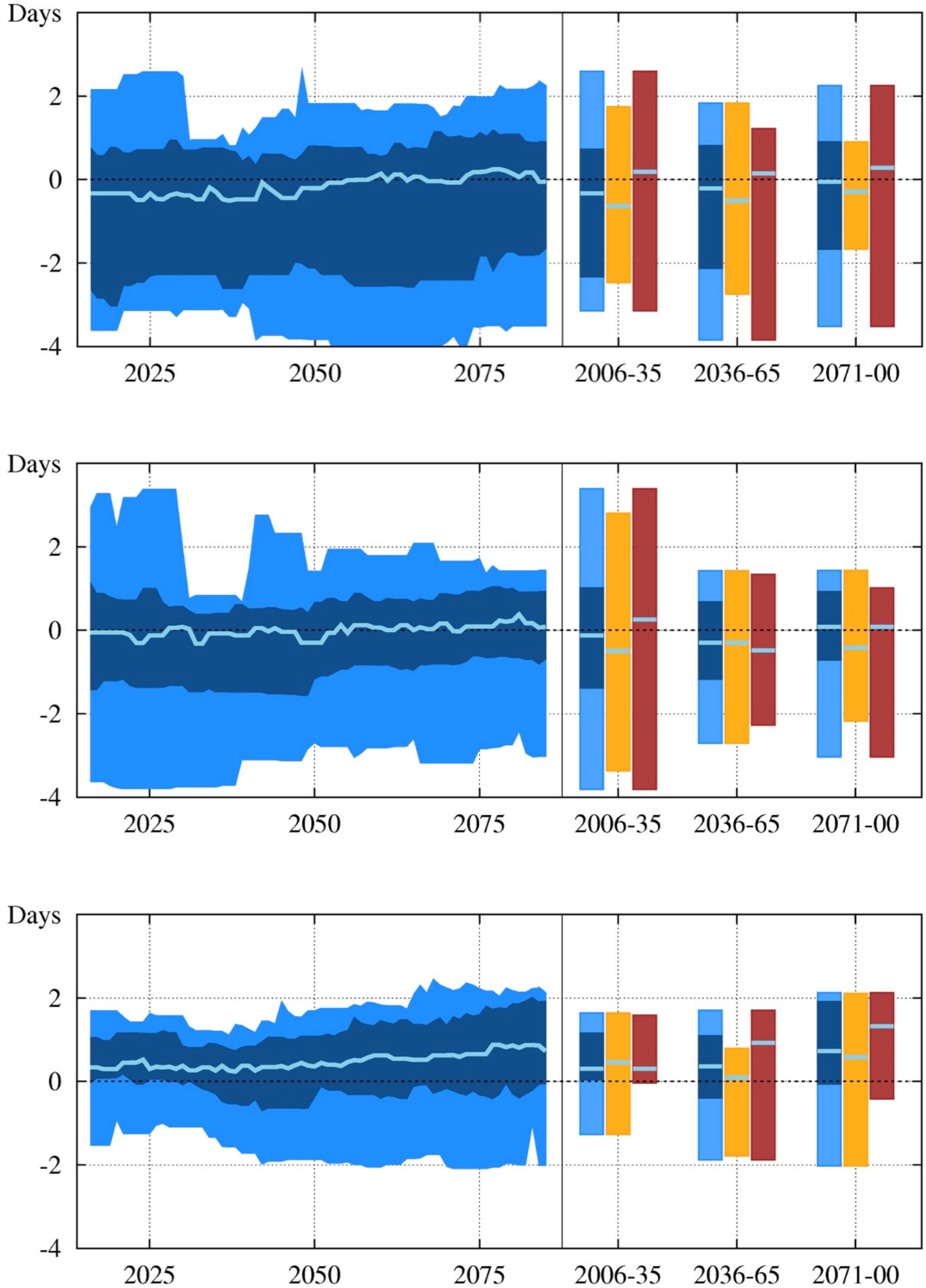


Fig. A15 Projected changes in mean average duration of heat waves (time series of the ensemble range) during the growing season (in days) for regions E (top), NW (middle), and SW (bottom). Statistical values are averaged over a 30-year period referenced to 1971-2000. Time axis values represent the mid-year of the 30-year periods. The time series includes the ensemble median (light blue line), the likely range (dark blue shaded area) and the ensemble range (light blue shaded area). The box to the right shows specific 30-year periods of the time series itemized to the ensemble mean (blue), RCP4.5 (yellow) and RCP8.5 (red) ensemble members.

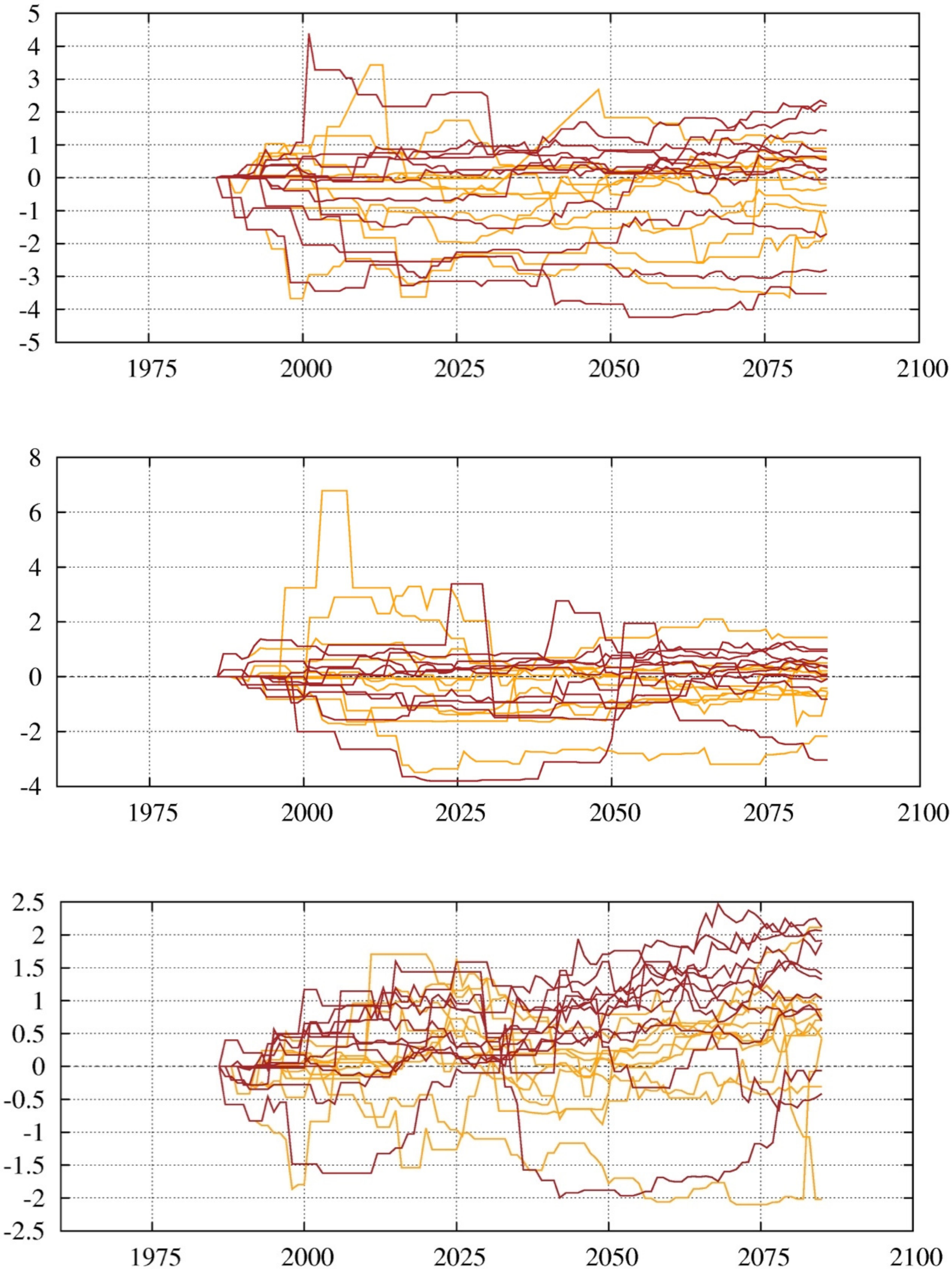


Fig. A16 Projected changes in mean average duration of heat waves (time series of individual simulations) during the growing season (in days) for regions E (top), NW (middle), and SW (bottom). Shown are all individual model simulations contributing to the ensemble (RCP4.5 in yellow, RCP 8.5 in red) smoothed by a 30-year running mean referenced to the period 1971-2000. Time axis values represent the mid-year of a 30-year period.

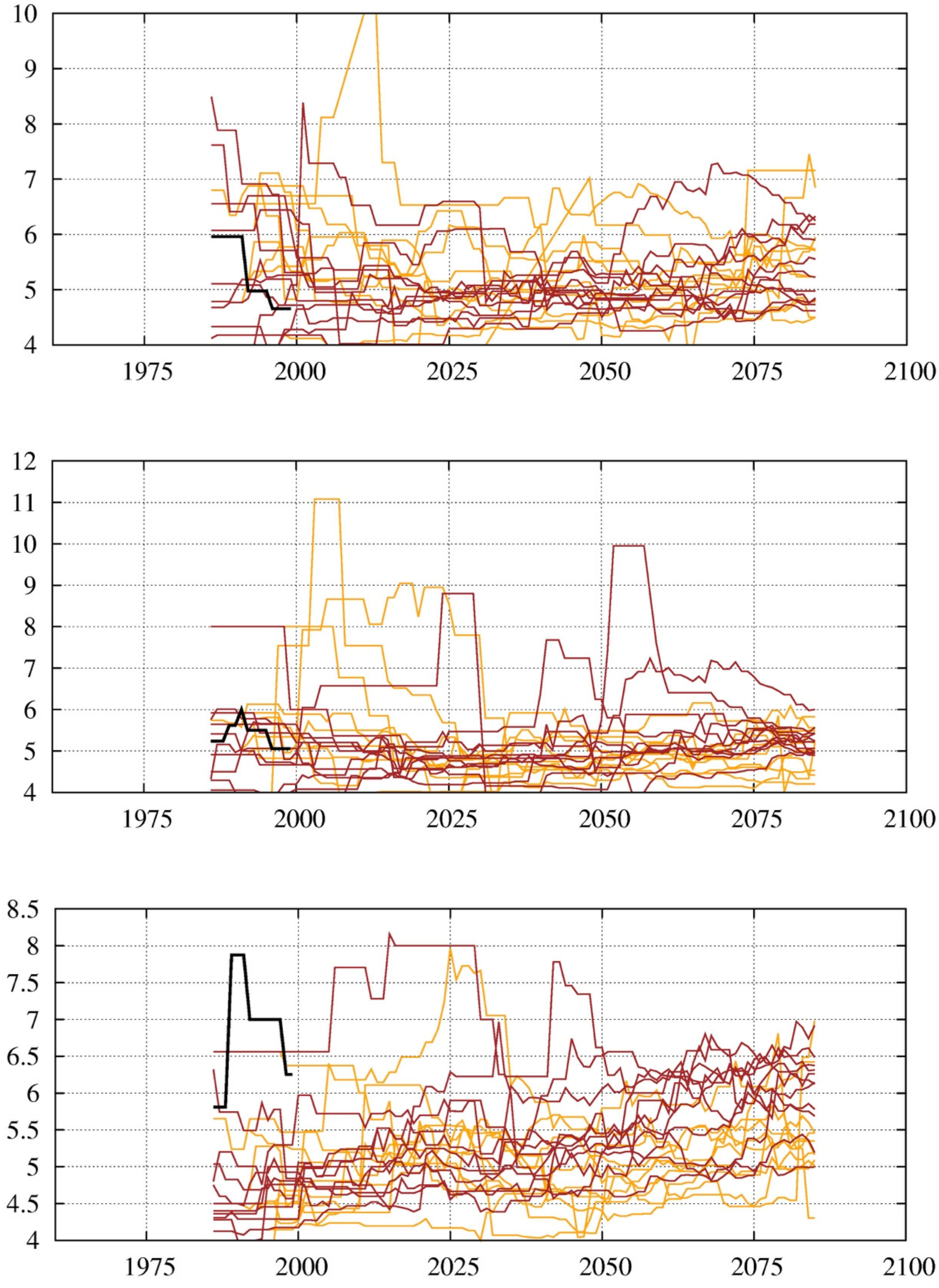


Fig. A17 Projected mean average duration of heat waves (time series of individual simulations) during the growing season (in days) for regions E (top), NW (middle), and SW (bottom). Shown are all individual model simulations contributing to the ensemble (RCP4.5 in yellow, RCP 8.5 in red) smoothed by a 30-year running mean referenced to the period 1971-2000. Time axis values represent the mid-year of a 30-year period. The black line shows observational E-OBS data, likewise averaged over a 30-year period.

Appendix B – EURO-CORDEX map plots

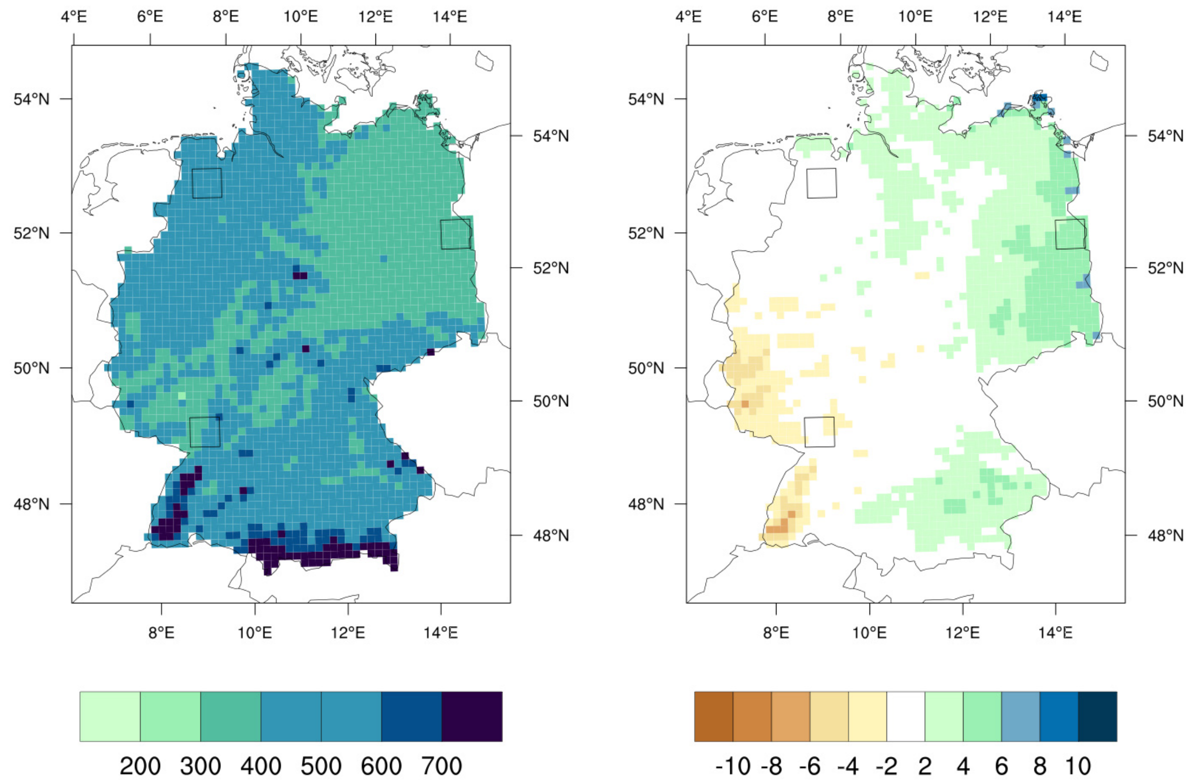


Fig. B1 Map of projected mean precipitation sum (MJJAS) in Germany in the 2050s (in mm) (left) and map of projected changes in mean precipitation sum (MJJAS) in Germany in the 2050s compared to the reference period 2071-2100 (in %) (right).

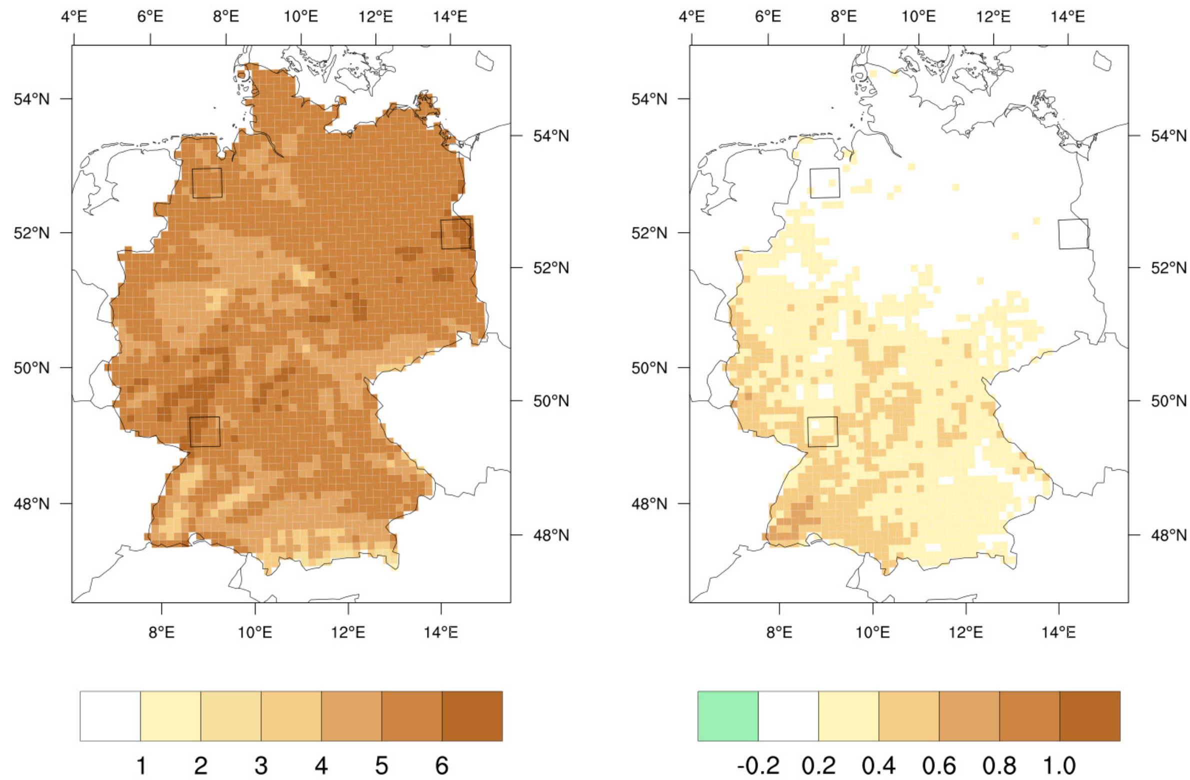


Fig. B2 Map of projected mean number of dry spells (MJJAS) in Germany in the 2050s (in absolute numbers) (left) and map of projected changes in the mean number of dry spells (MJJAS) in Germany in the 2050s compared to the reference period 2071-2100 (in absolute numbers) (right).

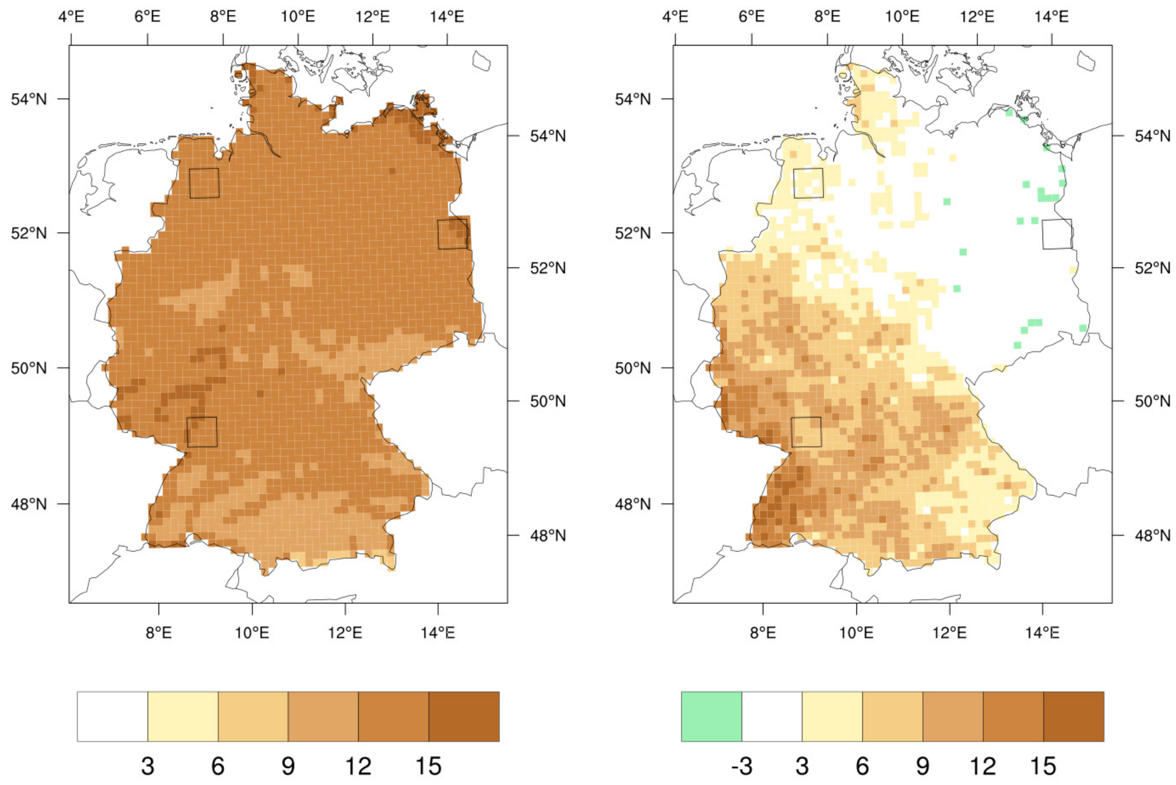


Fig. B3 Map of projected mean maximum duration of dry spells (MJJAS) in Germany in the 2050s (in days) (left) and map of projected changes in mean maximum duration of dry spells in Germany during the growing season in the 2050s compared to the reference period 2071-2100 (in %) (right).

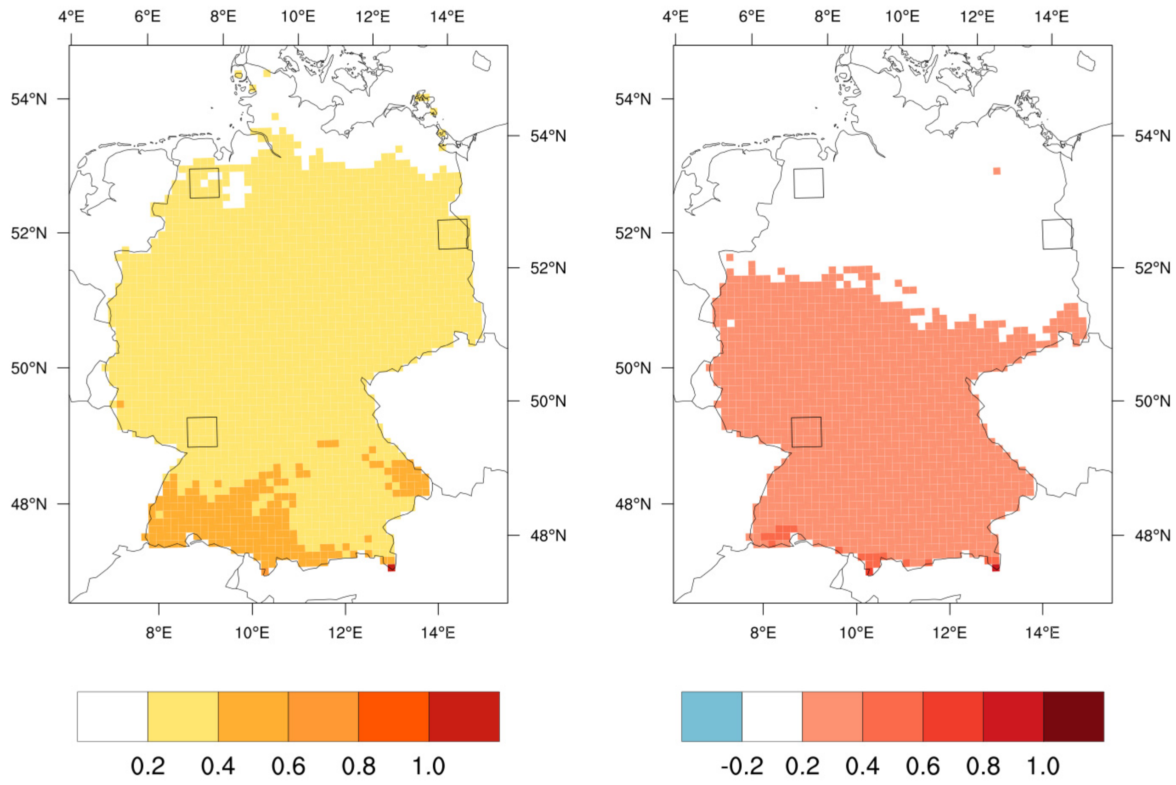


Fig. B4 Map of projected mean number of heat waves per growing season (MJJAS) in Germany in the 2050s (in absolute numbers) (left) and map of projected changes in mean number of heat waves (MJJAS) in the 2050s compared to the reference period 2071-2100 (in absolute numbers) (right).

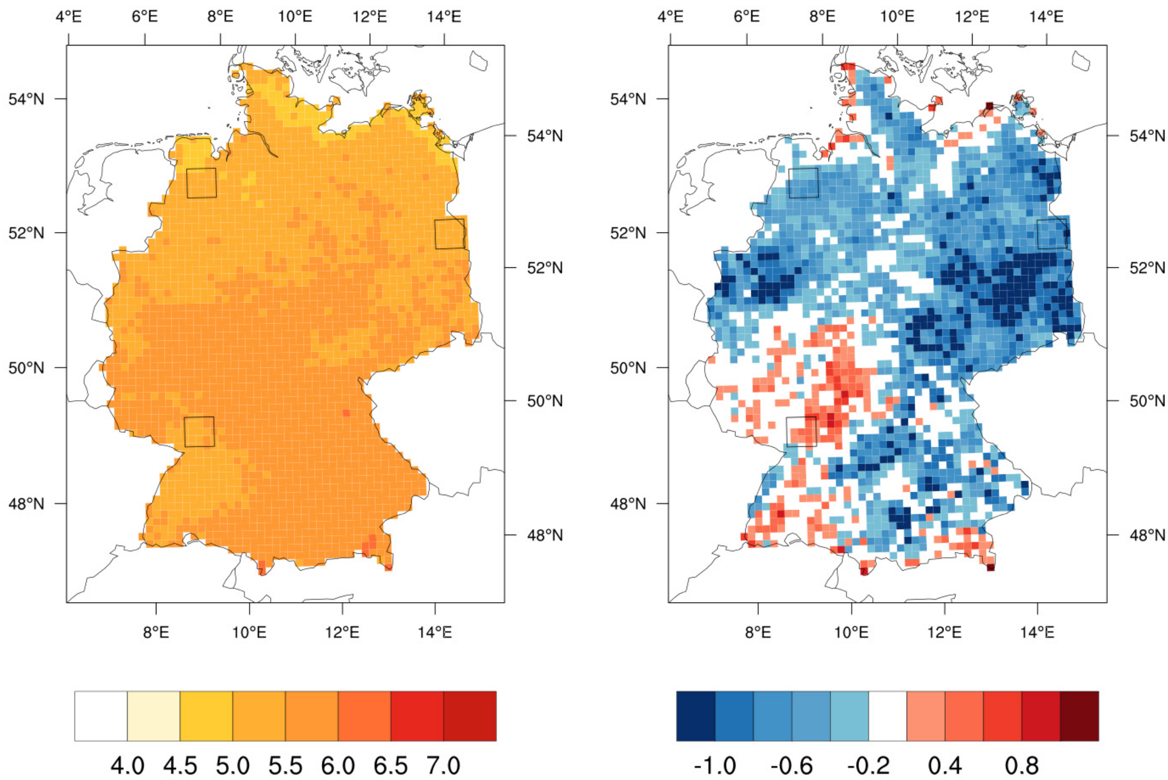
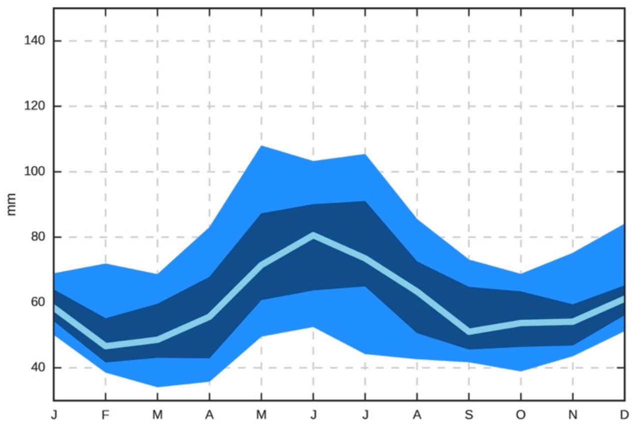
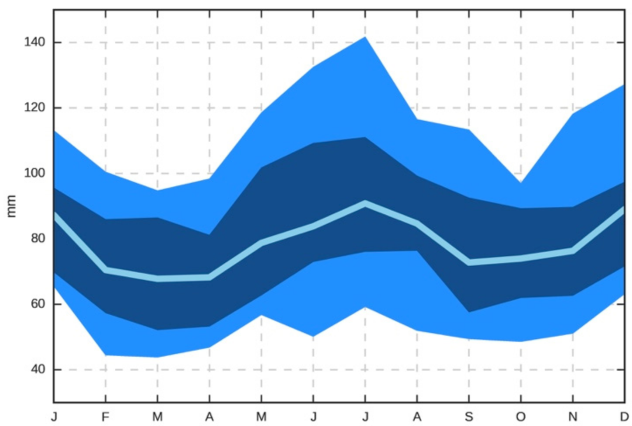


Fig. B5 Maps of projected mean average duration of heat waves (MJJAS) in Germany in the 2050s (in days) (left) and map of projected changes in mean average duration of heat waves (MJJAS) in Germany in the 2050s compared to the reference period 2071-2100 (in %) (right).

Appendix C – EURO-CORDEX intra-annual precipitation patterns





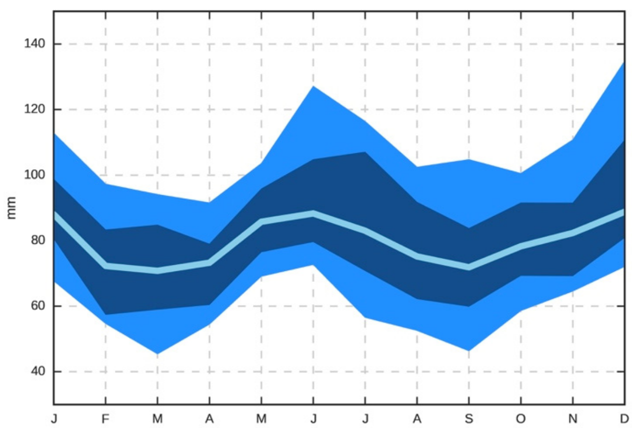


Fig. C1 Projected mean monthly precipitation sums in the 2050s (ensemble) (in mm) for regions E (top), NW (middle) and SW (bottom). Displayed are the ensemble median (light blue line), the likely range (dark blue shaded area), and the ensemble range (light blue shaded area).

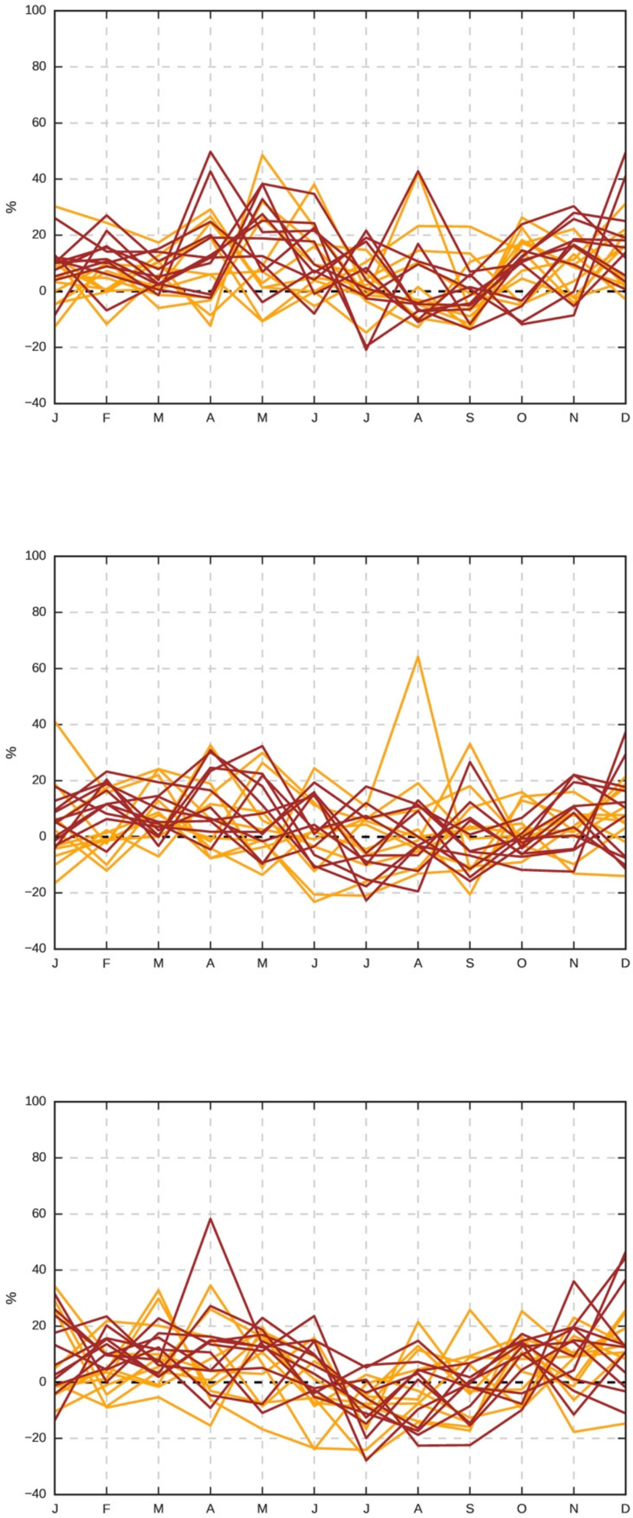


Fig. C2 Projected changes in mean monthly precipitation sums in the 2050s (individual simulations) compared to 1971-2000 (%) for regions E (top), NW (middle) and SW (bottom). Displayed are the individual projections of all ensemble members (yellow: RCP4.5; red: RCP8.5).

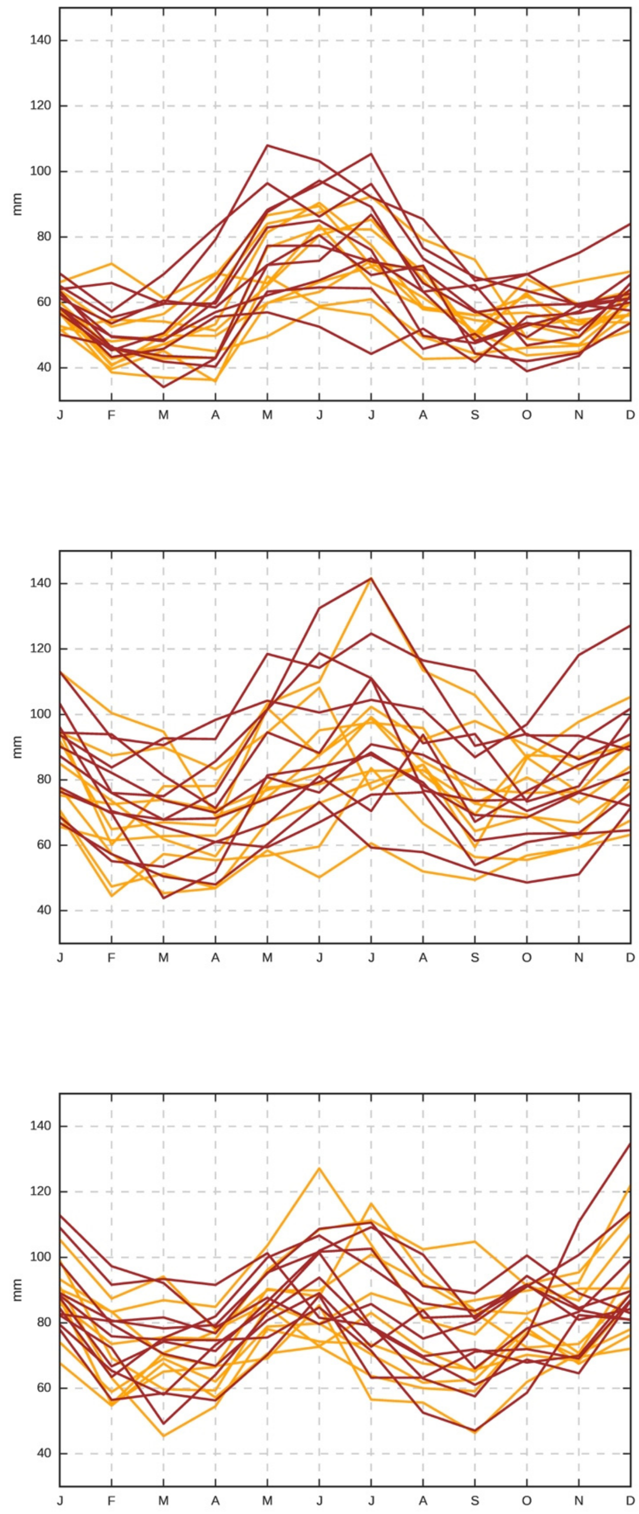


Fig. C3 Projected mean monthly precipitation sums in the 2050s (individual simulations) (in mm) for regions E (top), NW (middle) and SW (bottom). Displayed are the individual projections of all ensemble members (yellow: RCP4.5; red: RCP8.5).

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