Thesis for the Degree of Doctor of Philosophy

Simulated and observed change of precipitation and temperature in Europe with focus on the Greater Baltic Area

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Abstract

The regional climate of the Greater Baltic Area is complex and varies at a multitude of scales in space and time. This thesis contributes to increased understanding of climate change and climate variability in this area focusing on four significant research topics.

Droughts have a considerable ecological and socio-economic impact. The occurrence of rainfall is strongly controlled by large-scale atmospheric circulation. The observed summer North Atlantic Oscillation (SNAO) was correlated to a gridded dataset of the self-calibrating Palmer Drought Severity Index. A more positive circulation index is strongly linked to dry conditions over large parts of Southern Fennoscandia and northern Central Europe. Less distinct but still significant is the coupling to wetter conditions in the eastern Mediterranean. Using tree-ring based SNAO and precipitation reconstructions over 550 a, the relationship was investigated back in time in a multicentury perspective. Prior to the instrumental period the coupling is generally less pronounced but holds for distinct periods of drought.

A database of up to 121 daily more than century-long instrumental records of precipitation and temperature over Europe was analyzed for trends in climate extremes. Over the 20th century a clear increase of warm extremes and a decreasing trend in cold extremes could be detected. Precipitation extremes became slightly more frequent and precipitation amounts increased, especially during winter.

The ongoing warming resulted in a significantly extended thermal growing season in the Greater Baltic Area has extended significantly during the last century. An analysis of 48 long-term daily mean temperature records over this area revealed an overall lengthening of about one week between 1951-2000 mostly contributed by an earlier start in spring. The strongest change was observed at stations adjacent to the Baltic Sea in the South and the weakest in the North East. The 100-year records at Danish stations reveal a maximum shift in start (-22.8 d), end (12.6 d) and growing season length (33.5 d).

The sub-daily precipitation characteristics in the region are not very well understood yet. By studying hourly observations for 1996-2008 from 93 stations all over Sweden, a distinct summer season diurnal cycle with an afternoon peak mainly contributed by convective activities during summer was identified for inland stations. Along the East coast the influence of the Baltic Sea is evident showing a weaker cycle peaking in the early morning. The observed diurnal cycle was compared to simulations from the Rossby Centre regional climate model (RCA3) run at 50, 25, 12 and 6 km grid resolution. In general the model tends to simulate too frequent convective precipitation events of light intensity. The simulated peak timing is about 2-4 hours too early and the amplitude too high. The model performance varies depending on the spatial resolution. The 6-km simulation most realistically captures the peak timing and the diversity in the spatial pattern. With increasing model resolution the fraction of large-scale (convective) precipitation is increasing (decreasing). The results indicate the need for improvement of the convection parameterization scheme.

Keywords: observations, precipitation and temperature extremes, thermal growing season, drought, hourly precipitation, diurnal precipitation cycle, regional climate model, summer NAO, Greater Baltic Area

Für Emilia und Annalena

List of publications

This thesis consists of a summary (part I) and of five papers (part II) referred to with roman letters within the thesis.

I. Moberg, A., P.D. Jones, D. Lister, **A. Walther**, M. Brunet, J. Jacobeit, and co-authors, 2006: Indices for daily temperature and precipitation extremes in Europe analysed for the period 1901-2000, *Journal of Geophysical Research*,111, D22106.

A. Walther calculated climate extremes indices and contributed to build up and quality control the underlying database and did the analysis and parts of the writing for the subsequent report.

II. Linderholm, H.W., **Walther, A.** and Chen, D. 2008: Twentieth-century trends in the thermal growing season in the Greater Baltic Area. *Climatic Change*, 87: 405-419.

A. Walther contributed to writing the paper, analyzed the data and visualized the results.

III. Linderholm, H.W., Folland, C.K. and **Walther, A**., 2009: A multicentury perspective on the summer North Atlantic Oscillation (SNAO) and drought in the eastern Atlantic Region. *J. Quaternary Sci.*, Vol. 24 pp. 415-425.

A. Walther contributed with analysis and visualization of the spatial relationships between scPDSI and SNAO and discussing the results.

IV. Jeong J.-H., **Walther A.,** Nikulin G., Jones C., Chen D. 2011. Diurnal cycle of precipitation amount and frequency in Sweden: observation versus model simulation. *Tellus Series A: Dynamic Meteorology and Oceanography.* 63(4): 664-674.

A. Walther collected the data, conducted the analysis, visualized the results and contributed with writing.

V. **Walther, A**., Jeong, J.-H., Nikulin, G., Chen, D., Jones, C. Evaluation of the warm season diurnal cycle of precipitation over Sweden simulated by the Rossby Centre regional climate model RCA3. *Atmospheric Research*, (in press). doi: 10.1016/j.atmosres.2011.10.012

A. Walther initiated the paper, did the analysis, visualization of the results and most of the writing.

Publications not included in the thesis (reverse chronological order)

Burauskaite-Harju, A., A. Grimvall, C. Achberger, A. Walther and D. Chen (2012). Characterising and visualizing spatio-temporal patterns in hourly precipitation records. ***Theoretical and Applied Climatology***: 1-11.

Walther, A., J.-H. Jeong, G. Nikulin, D. Chen and C. Jones (2011). Potential future changes of the diurnal precipitation properties over Sweden. ***Geophys. Res. Abs.*** **13**(EGU2011-10793).

Westerberg, I., Walther, A., Guerrero, J.-L., Coello, Z., Halldin, S., Xu, C.-Y., Chen, D., Lundin, L.-C., 2010: Precipitation data in a mountainous catchment in Honduras: quality assessment and spatiotemporal characteristics. Theoretical and Applied Climatology, 101 (3-4), 381-396.

Song, Y., H. W. Linderholm, D. Chen and A. Walther (2010). Trends of the thermal growing season in China, 1951-2007. ***International Journal of Climatology*** **30**(1): 33-43.

Brunet, M., P. D. Jones, J. Sigro, O. Saladie, E. Aguilar, A. Moberg, P. M. Della-Marta, D. Lister, A. Walther and D. Lopez (2007). Temporal and spatial temperature variability and change over Spain during 1850-2005. ***Journal of Geophysical Research-Atmospheres*** **112**(D12).

M. Brunet, J. Sigró, P. D. Jones, O. Saladié, E. Aguilar, A. Moberg, D. Lister and A. Walther (2007): Long-term changes in extreme temperatures and precipitation in Spain. ***Contributions to Science*** **3**(3): 333-344 (2007).

Brunet, M., O. Saladié, P. Jones, J. Sigró, E. Aguilar, A. Moberg, D. Lister, A. Walther, D. Lopez and C. Almarza (2006). The development of a new dataset of Spanish Daily Adjusted Temperature Series (SDATS) (1850-2003). ***International Journal of Climatology*** **26**(13): 1777-1802.

Walther, A. and H. W. Linderholm (2006). A comparison of growing season indices for the Greater Baltic Area. ***International Journal of Biometeorology*** **51**(2): 107-118.

Chen, D., A. Walther, A. Moberg, P. D. Jones, J. Jacobeit and D. Lister (2006). Trend Atlas of the EMULATE indices, Dept of Earth Sciences, University of Gothenburg, Sweden. **C73:** 798.

Linderholm, H. W., A. Walther and D. Chen (2005). Growing season trends in the Greater Baltic Area, Dept of Earth Sciences, University of Gothenburg, Sweden. **C69:** 92.

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Part I

Summary

1. Introduction

1.1. Climate extremes and society

Climate is commonly defined as long-term average of short-term atmospheric conditions – the weather – described by variables like pressure, temperature, humidity and precipitation. The climate system is built-up by 6 subsystems, namely the lithosphere, biosphere, atmosphere, cryosphere, hydrosphere and the anthroposphere. All of these interact with each other and have internal variability. Climate is fluctuating and changing on a wide range of temporal and spatial scales where not a single one could be pointed out as the most important. Human societies have been tightly connected to weather and climate since their rise. While short-term weather fluctuations mainly affect daily routines, the overarching climate conditions influence human's settlement behavior. Large-scale human crisis could be closely linked to climate change (Zhang et al. 2011). The authors showed that agrarian productivity, famine, epidemics, and population growth are clearly linked to the state of the climate during human history, especially during anomalously warmer or colder periods such as the medieval warm period or the little ice age. Climate and climate change can have direct and indirect psychological impacts affecting individual and community health, especially through more frequent and powerful extremes and landscape changes (Doherty and Clayton 2011).

The past 150 years are characterized by large-scale industrialization accompanied by a global population growth from 1,5 billion people to about seven billion at present. Through the anthroposphere humans are an important interlinked part of the climate system. In order to meet basic needs and to keep modern societies going, structures for the use and distribution of resources for the production of energy, construction material, clothing and food have been established. In this context many human activities have the potential to affect the climate system. One example is land-use changes altering the radiation balance by changed albedo and the release of greenhouse gases such as soil-bound carbon and methane. Another example is the direct release of carbon dioxide by burning fossil fuels. A growing population exerts more ecological pressure with potentially higher impacts also on climate. Due to the high complexity of natural systems with their intrinsic multi-scale variability, such as the climate system, it is often difficult to attribute causality to certain changes. Nevertheless, human activities were found to have been unequivocally affecting climate, especially during the last 150 years referred to as global warming (IPCC 2007a).

The vulnerability of societies by climate change and climate extremes depends on a number of factors such as the geographical settings and the socio-economic background (Lynn et al. 2012). Given an increasing population with relatively high socio-economic contrasts and concentrating in climatological risk zones, for example in the vicinity of low-lying coastal areas, increasing vulnerability is very likely. The increasing complexity of societies in terms of vulnerable infrastructure such as water and power supply also plays an important role. Natural disasters, anthropogenically influenced or not, are causing fatalities and enormous economic losses every year. While earthquakes and tsunamis usually stand for high fatalities, climate related extremes often account for the biggest economic damage to infrastructure and property (Munich-Reinsurance 2002).

Understanding present and past climate variability plays an important role for estimating potential future states of climate, applying the principle of uniformitarianism, which assumes that basic natural laws are invariant in time and space (Gould 1965). We can get a more or less confident idea of past climate variability with a certain statistical significance being aware of that present and future climate characteristics can be well outside the frame defined by observed and reconstructed past climate variability, and that not all processes and relationships in the climate systems may be of stationary nature. In order to study past climate variability long-term climatological records are needed, which can come from direct instrumental observations covering at most two centuries or reconstructions obtained from proxies such as tree rings (up to millennia), lake sediments or written historical documents. The longer the records the more climate variability can be investigated and the more robust signals can be obtained. Especially for the analysis of climate extremes long time-series are needed.

Climate extremes are challenging for a variety of scientific fields, namely statistics, ecology, medicine and last but not least climatology (Hegerl et al. 2011). Climate extremes are by definition relatively rare events with unusually high or low amplitude of a climate variable. They are an important part of weather and climate. For example this can be extremely high or low temperatures, record high precipitation amounts, droughts or extreme wind speeds. Often different factors combine, form instance, as in heatwaves, which are usually periods of anomalously high temperatures combined with little or no precipitation and bad air-quality (Beniston 2004). The ecological or societal impact is another important criterion for defining extremes. An extreme precipitation event in climatological sense can cause damage in a populated area whereas it could go unnoticed in a desert. Windstorms, floodings, droughts and heatwaves, and the accompanying effects such as landslides, wind damaged forests, bad harvests, wildfires, destroyed property and mortality are the most frequent and threatening climate related extremes affecting Europe as well as the Greater Baltic Area (e.g. Della-Marta et al. 2007).

During the 20th century the mean temperature over Europe has increased by 0.8°C. In addition to those slow long-term changes and their impacts, Europe was found to be climatologically most sensitive to extreme seasons (hot and dry summers and mild winters), short-duration events (windstorms and heavy rains) according to IPCC (2007b). In a changing climate the characteristics of extremes are likely to change alongside the mean conditions (Hegerl et al. 2006). In fact, many of those changes have been observed over Europe already during the recent few decades, and are expected to intensify in the future. More frequent heat waves and, in the context of an intensifying hydrological cycle, higher precipitation extremes in many areas can be expected (Rummukainen 2012). Another important aspect is the spatial patterns of change. The continental mean temperature change does not tell anything about the spatial variability of warming. In general, the higher latitudes warm more rapidly than the western Mediterranean. Rainfall changes are spatially highly variable. Furthermore, the impact of changes can be very different. Warming may increase the potential for crops in one place, but may limit growth in already hot areas by water limitation. Thus for many applications it is not enough to know how the large-scale climate patterns look like, detailed knowledge is needed to be put together to the bigger picture.

1.2. Aims and objectives

Our understanding of regional climate is still limited in a variety of significant fields hampering the possibility to draw more robust conclusions about past and present climate processes, and asking for contributions supporting the development of knowledge and tools to reliably support decision making and planning. Better understand past and present climate in order to predict the future. In this context the overall aim of this thesis is to contribute to the assessment and increased understanding of climate variability in Europe, especially the Greater Baltic Area (GBA). Many temporal and spatial scales are important and interlinked in the regional climate, which was considered in the selection of articles. The detailed objectives are

- To study long-term changes of daily precipitation and temperature extremes during the last century.
- To characterize the properties of the thermal growing season and its variability during the past century
- To identify the role of large-scale atmospheric circulation on drought conditions over an extended period of time
- To explore the spatio-temporal characteristics of sub-daily precipitation and to investigate how well those patterns can be simulated by a regional climate model

The studies focused on relatively diverse climatological topics related to the research area using a wide range of data. Scientific contributions are made in the following fields: relationship between large-scale atmospheric circulation and regional climate conditions, long-term changes of daily precipitation and temperature extremes, changes of the thermal growing season, and observed and simulated properties of sub-daily precipitation characteristics over Sweden.

The cited papers are the result of teamwork where I contributed to a different extent. This summary, which is a product by myself highlights the main findings and to put them into a bigger context. Methods, results and the discussion presented here are less comprehensive than in the papers and their selection is of subjective nature.

In Paper I the long-term linear trends of daily temperature and precipitation extremes in Europe utilizing more than century-long observational records were analyzed. A set of extremes indices was developed to define extremes.

Paper II investigated parameters of the thermal growing season such as start, end and length over the Greater Baltic Area and their change during the 20th century.

Paper III shows an analysis of the relationship between large-scale atmospheric circulation in terms of the summer North Atlantic Oscillation (SNAO), and drought conditions in the adjacent continents in the eastern Atlantic region on a multicentury perspective utilizing tree-ring based SNAO reconstructions.

Sub-daily precipitation characteristics over Sweden are investigated in Papers IV and V. In Paper IV the spatial patterns of the observed cycle of precipitation amount and frequency was investigated for summer and winter seasons and initially compared to one model simulation.

In Paper V a set of regional climate model simulations of the summer season diurnal precipitation cycle over Sweden were evaluated and compared to observations.

2. Background

2.1. Research Area

Thus the Greater Baltic area (GBA) is located in the transition zone between temperate and subarctic climates in latitudinal direction, and between maritime and continental climate from west to east. The area is home to more than 100 million people. It is covering countries in the wider vicinity of the Baltic Sea, namely Finland, Sweden, Denmark, Norway, Estonia, Lithuania, Latvia and the western parts of Russia (Fig. 1). For paper I a larger area was covered. Europe as a whole and the GBA in particular are very heterogeneous areas in climatological sense.

The geographical characteristics have a significant influence on the regional climate. The latitudinal extent is ranging from the subtropical high-pressure belt in the south, via the mid-latitudes to sub-polar and polar area influenced by the polar vortex in the north. The Mediterranean region is alternately under the influence of the subtropical high-pressure cells during summer, and the westerlies expanding southward during winter. This leads to a pronounced dry season in summer and precipitation maximum during winter. Most parts of central and northern Europe are under direct influence of dynamic pressure systems linked to the westerlies basically year-round. The latitudinal contrast in terms of incoming solar radiation and hence temperature between lower and higher latitudes is greatest during the winter season. This results in more frequent passage of low-pressure systems in winter whereas they are much less frequent during summer and more common in higher latitudes. Longitudinally the influence of the maritime air originating over the Atlantic is decreasing eastward where the climate is becoming more continental. The Scandinavian mountains along the border between Sweden and Norway is a very effective barrier for maritime air from the west leading to quickly decreasing precipitation totals within a relatively short distance.

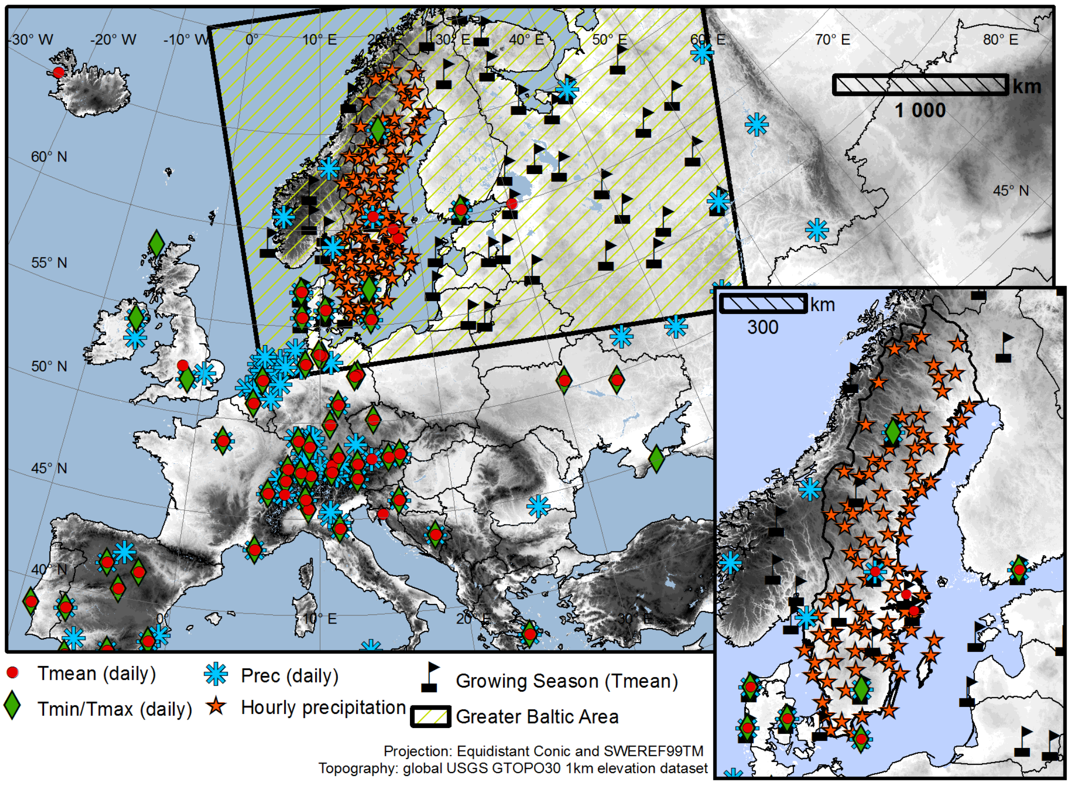

Figure 1. Research Area and locations of the meteorological stations. Daily Tmean, Tmin/Tmax and precipitation data was used for Paper I. An extended set of Tmean stations for growing season analysis was used for Paper II. Hourly precipitation observations were used in Papers IV and V.

The location of the Baltic Sea has an important influence on the transition from maritime to continental climates. The water body functions as a moisture source supporting low-pressure systems and in this way extending their penetration over the continent. It also has significant impact on meso-scale climatology such as seabreeze circulation along the coast.

2.2. Synoptic climatology

Weather and climate processes take place on a wide range of spatial and temporal scales all from seconds to seasons and from small-scale random turbulences to planetary waves. Dynamic climatology is focusing on the global climate system in terms of its origin and maintenance (Barry and Carleton 2001). The relationship of regional and local climate conditions to the large-scale atmospheric circulation is studied within synoptic climatology. The process of linking together variables representing a larger space and a smaller space respectively can be referred to as downscaling (Benestad et al. 2008), which can be done in two ways – statistically or dynamically. An example for dynamical downscaling, also referred to as nesting, is to run a high resolution RCM boundary-forced within a low-resolution GCM producing more detailed regional climate parameters (Rummukainen 2010). On the other hand, the approach of weather typing is frequently used to statistically downscale large-scale climate properties. In this case the atmospheric airflow is classified into a number of characteristic circulation types. One example is the Lamb classification originally developed for classifying airflow patterns over the British Isles (Lamb 1972). Based on sea level pressure 26 classes of cyclonic, anti-cyclonic and directional types are obtained and can then be linked to regional precipitation or temperature climate as done for the Iberian peninsula (Lorenzo et al. 2008) or Scandinavia (Chen 2000; Hellström 2005).

The climate of Europe is largely influenced by synoptic-scale atmospheric patterns called the North Atlantic Oscillation index (NAO), which is a leading large-scale pattern of weather and climate variability in the Northern Hemisphere (Hurrell and Deser 2009). The NAO index is based on the pressure difference between the Icelandic low-pressure and the Azores high-pressure indicating the redistribution of atmospheric mass between the Arctic and the Subtropics. The index swings between its positive and negative phases effecting temperatures, winds and precipitation over the Atlantic and adjacent regions. During positive NAO periods there are stronger-than-normal westerlies leading to more intense weather systems over the North Atlantic, as well as milder and wetter conditions over Western Europe. On the contrary, during negative NAO periods there are weaker westerlies allowing for stronger zonal circulation patterns leading to, for example, strong and cold winters over large parts of Northern and Central Europe like in 2010/11. The NAO has, in addition to significant inter-annual and intra-seasonal variability, a pronounced low-frequency variability on decadal time-scales (Hurrell 1995). Phases of consecutive years with positive or negative NAO index take turns comprising natural variability. A strong negative phase during 1950-1970 was followed by a long phase with positive NAO index during 1970-2000s. Scaife et al. (2008) found large changes of low temperature and high precipitation extremes during winter linked to observed NAO change between 1960-1990. The authors conclude that natural variability could account for as much change in extremes, as the anthropogenic forcing over the 20th century would imply.

In numerous studies the coupling between NAO and winter climate conditions was studied. It has been widely reported that the NAO has an influence on mean climate (Hurrell and Deser 2009), climate extremes (López-Moreno and Vicente-Serrano 2008; Scaife et al. 2008), as well as on specific regions such as the Iberian peninsula (Lorenzo et al. 2008) or NW Europe (Alexandersson et al. 1998). The latitudinal pressure difference becomes smaller during summer when the high latitudes become significantly warmer due to increased input of solar energy. Parallel to the well-known relatively strong wintertime NAO, distinct large-scale pressure patterns are evident over the extratropical North Atlantic also in summer, referred to as summer NAO (Folland et al. 2009). Compared to the NAO its position is shifted northeastward and the spatial extent is smaller. Connected to changes in the position of the North Atlantic stormtrack, above all temperature and precipitation, both mean climate and extremes, over Northern Europe are affected by the SNAO. Long-term assessment of NAO and SNAO variability beyond the instrumental period is important in order to put the observed decadal to multidecadal variability throughout the 20th century with a pronounced phase of positive SNAO between 1970-95 in a longer context. Folland et al. (2009) found no counterpart to that during the past three centuries, which may be an indication for anthropogenic influence on the North Atlantic pressure swing through global warming. On the other hand the strong natural NAO variability on decadal time-scales may relativize the warming attributed to human activities. A longer perspective is important to further investigate.

2.3. Meteorological observations

Long-term instrumental records are of great importance in the process of detection and attribution of recent climate change, and to assess and calibrate numerical climate models, satellite data and radar measurements (Brunet and Jones 2011). Ground-based observations are still the most important source for reliable in-situ measurements of climatic variables such as pressure, humidity, temperature and precipitation and for their long-term analysis. In Europe we find the oldest network where readings following standardized procedures have been carried out for more than a century in many places. In Uppsala (Sweden), daily measurements of temperature and later on also precipitation reach back to 1722. Parts of the available long-term daily records are meanwhile well catalogued due to projects focusing on data rescue (DARE) like the European Climate Assessment and Dataset (ECA&D) database (Klein-Tank et al. 2002) and EMULATE (Moberg et al. 2006). Nevertheless, Brunet and Jones (2011) estimated that not more than 20% of the climate data is available to the scientific community with the majority of the past climate data still being undigitized, not available or not accessible, and in this way hampering the ability to obtain more robust assessments of the past climate properties.

Higher temporal resolution combined with so far relatively short observation periods of up to a few decades characterize automated hourly to minute-wise measurements, which are increasingly available and form the base for the assessment of sub-daily climatological characteristics, such as the diurnal precipitation cycle. Especially for hydrological modeling and urban planning detailed knowledge about short-term precipitation variability is important. Studies looking at the sub-daily climate characteristics in higher latitudes are still limited. Dai (2001) studied 15,000 3-hourly observations over the whole globe with data between 1975-1997 and established a number of distinct pattern related to different climate zones. This means an average station density of 1 station per 10000 km^2. Longer observations are available for single sites. Twardosz (2007) presented the analysis of an outstanding long-term hourly record of 117 years in Krakow/Poland. With the increased availability of denser sub-daily measurements more studies can focus on regional scale sub-daily precipitation variability. The Swedish database of 93 stations with an average density of at least 1 station per 4800 km^2 is a valuable resource in this context also considering the coverage period of meanwhile 17 years of data.

All measurement techniques and observational methods are subject to a variety of errors and uncertainties. When it comes to instrumental records a major source of uncertainty is data inhomogeneity. Station relocation, change of instruments, changed reading practices and environmental changes in the station surroundings can, if not considered and corrected, give rise to biased climate estimates. Being aware of the uncertainties, they can be taken into account even if not corrected in many cases. For example, the 250+ a records from Stockholm and Uppsala were intensively checked and corrected for homogeneity issues (Moberg and Bergström 1997), which was possible due to sufficient metadata and motivated by the length and outstanding usefulness of these long-term records. There is a set of well-established methods for homogenizing time-series on a monthly and annual basis, whereas the homogenization of daily data is still challenging (Della-Marta and Wanner 2006). Without proper metadata it is difficult to distinguish abnormal but reasonable values such as extremes from erroneous values, especially in daily and sub-daily data. Another source of uncertainty is the spatial representativeness of the measurements. With rain gauge point measurements the spatial variability in complicated terrain with pronounced local-scale climate features, such as mountains or coastal zones, may not be represented in a sufficient way.

Remote sensing techniques such as radar and satellite-based instruments are playing a rapidly increasing role for measuring a wide range of climate variables. Ground-based radar networks are used for qualitative measurements of precipitation intensity without giving exact quantities but classes such as weak or heavy precipitation (Rubel and Brugger 2009). The reflectivity of clouds and water particles is used as a proxy. In this way precipitation systems can be tracked in real-time and with continuous spatial coverage. The Tropical Rainfall Measuring Mission (TRMM) is using satellite-mounted rainfall radar to measure precipitation but is spatially confined to latitudes between 48N-48S (Theon 1994). This data is meanwhile widely used for investigating precipitation characteristics in lower latitudes but the limitation in spatial extent is restricting its use for Northern Europe.

2.4. Thermal growing season

During the growing season terrestrial biomass is produced through photosynthesis utilizing carbon dioxide. This process is an important element of the global carbon cycle. A huge amount of the annually produced biomass goes into field crops. Climate-related growing season parameters such as start, end and length and the climate conditions during the growing season are important factors affecting plant growth and productivity. The growing season can be defined in different ways.

Phenologically the growing season can be determined through the observation of parameters like flowering time, leaf unfolding or leaf coloring of certain species, which are measured in phenological station networks. Because of direct in-situ measurement all relevant climatological processes and landscape factors are integrated (Menzel 2003). Karlsen et al. (2009) utilize satellite-derived normalized difference vegetation indices (NDVI), a measure of greenness of the vegetative earth surface, to determine growing season parameters. By using this type of data spatially continuous and at the same very detailed maps can be derived.

Another approach is the widely used concept of the thermal growing reason using mean temperature measurements as a proxy for conditions supporting plant growth. Growing season start and end are then defined by a combination of temperature thresholds to be exceeded or fallen below for a number of consecutive days (Walther and Linderholm 2006). If not combined with other methods this approach does not consider other factors than temperature, which can lead to misleading results in some areas. However, the estimate is easy to calculate and, compared to the phenological station network, a relatively large number of stations with long time-series is available.

The effects of climate change on the growing season and the climate conditions therein can be manifold. In many places a prolongation was observed (e.g. Song et al. 2010; Qian et al. 2011). A longer growing season may favor increased plant growth as found for Finland by (Peltonen-Sainio et al. 2009). On the other hand increased carbon uptake may be counteracted by other factors such as increased respiration as shown by (Parmentier et al. 2011), who found that the highest carbon uptake happened during the coldest and shortest growing season. Also changes in the mean and extreme climate parameters within the growing season (Menzel et al. 2011) as well as the climate conditions prior to the growing season can affect plant growth (Shen et al. 2011).

2.5. Climate model simulations

Global climate models (GCM) and regional climate models (RCM) are used to numerically simulate the global climate system based on dynamics and physics represented by the so-called primitive equations describing the conservation of mass, momentum and energy. GCMs operate on the scale of the global climate system and have still relatively course spatial resolution, typically several hundred km^2 per grid-cell. Regional climate models operate nowadays with spatial resolutions down to a few km^2. The general structure is similar to GCMs. Because RCMs are typically run for continental domains they are forced with data from global climate models at their boundaries. Increasing the resolution is not solely a computational issue. If climate processes and variability of sub-grid scale (i.e. less than the model resolution) are not fully understood, those processes cannot be modeled satisfactorily even if the resolution is increased computationally. Instead, sub-grid scale phenomena, i.e. climate processes taking place at finer than the model's temporal and spatial scale, need to be parameterized. One example are local to meso-scale convective precipitation systems, which usually develop starting from very local scales and can thus not be modeled explicitly with grid resolutions much larger than the cloudresolving scale. Consequently they have to be parameterized. Testing the performance and validating climate models is not straightforward because there is no single best metric to compare simulations and reality. Climate model intercomparison projects (CMIP) are conducted where CMIP-1 contains model from the mid-90s and CMIP-3 covers the state-of-the-art models at the time of IPCC AR4. Focusing on temperature variables Reichler and Kim (2008a) found that CMIP-3 models much more realistically simulate mean climate then their predecessors due to better parameterization, less flux corrections and increased computer power, which allows for more testing and higher spatial resolutions. Reichler and Kim (2008b) found, that the mean state of some quantities is reproduced better by the models than by reanalysis data showing that care has to be taken when validating model output. However, even if improved significantly, current models are not perfect and still have major deficiencies when it comes to simulating precipitation characteristics at various scales and cloud dynamics as well as higher moments of climate such as temporal variability and extremes. Especially the representation of sub-daily precipitation in RCMs in general is still poor and needs further investigations to improve simulations (Maraun et al. 2010).

3. Data and methodology

3.1. Data

Table 1. Overview over data used in the publications. Observations (obs), simulation (sim), reconstruction (rec).

Type	**Variable**	**Temporal resolution**	**Period**	**Area**		**Publication**
obs	T_{min}, T_{max}, T_{mean}, Prec	daily	<1900-2000	Europe		I, Chen et al. (2006)
obs	T_{mean}	daily	1901-2000	Greater Baltic Area		II
obs	SNAO, SC-PDSI	monthly	1901-2002	Europe, North Atlantic		III
rec	SNAO, SPI	annual	1500-1995	North Atlantic, Sweden		III
obs	prec	hourly	1996-2008	Sweden		IV
sim	prec, $prec_{conv}$, $prec_{large\text{-}scale}$	hourly	1996-2008	Sweden	50, 25, 12, 6 km	IV, V
sim	prec	hourly	2086-2098	Sweden	50 km	Walther et al. (2011)

3.1.1. Instrumental precipitation and temperature records

For papers I, II and in Chen et al. (2006) different types of daily temperature and precipitation measurements were used as shown in Table 1 and Fig. 1. In paper I a database with daily records of minimum (T_{min}), maximum (T_{max}), mean temperature (T_{mean}) and precipitation (prec) over Europe was compiled which was comprehensively analyzed in paper I and Chen et al. (2006). Parts of it, namely T_{mean} measurements were used in paper II. Due to the relatively low station density of century-long daily records in the Greater Baltic Area, additional stations from the ECA&D database were included (Klein-Tank et al. 2002). In this way 48 stations were available for the analysis with a common data period 1951-2000.

A precipitation database for Sweden with hourly measurements from 93 stations for 1996-2008, which is relatively outstanding in terms of data-quality, and spatial and temporal coverage is available from the Swedish Meteorological and Hydrological Institute (SMHI). Because of the high temporal resolution this dataset is very useful for hydrological applications, such as small-scale hydrological modeling, because for example daily data does not reveal the high diurnal variability when it comes to runoff.

3.1.2. Climate simulations

For papers IV and V and in Walther et al. (2011), 1-hourly output from simulations done with the Rossby Centre Regional Climate model version 3 (RCA3) for 1996-2008 were utilized to validate simulated sub-daily precipitation characteristics. A series of parallel long-term simulations of present climate were used with spatial resolutions of 50, 25, 12 and 6 km. All simulations were done with identical physics and dynamics packages, especially the convective parameterization scheme remained unaltered. The model was forced with the ERA40 re-analysis dataset, which can be considered a quasi-observational dataset (Uppala et al. 2005). Besides the change in resolution there are two more differences between the simulations, one of which is that the 1-km topographical base data is interpolated to the different resolution implying a different smoothing, which can affect precipitation characteristics. Furthermore higher spatial resolutions require shorter computation time-steps. Otherwise, simply spoken, mass and energy fluxes would pass a grid-cell without being considered when the parameters for this particular cell.

The use of these model data has the advantage that different precipitation types can be obtained. In addition to the total precipitation we extracted convective and large-scale precipitation separately from each simulation. Large-scale precipitation is explicitly modeled on the model grid scale, whereas convective precipitation is output from the convection scheme and in way a parameterized sub-grid scale phenomenon. The distinction between these types turned out to be very helpful for evaluating the model performance at different resolutions.

Future hourly precipitation simulated with the same model were used in Walther et al. (2011). The ensemble of future simulations consists of runs with different properties in terms of forcing GCMs and emission scenarios. All simulations are available with 50 km grid resolution for the continuous period 1961-2098. According to the available observational data 1996-2008 was selected as present (control) climate, and 2086-2098 as future climate incorporating climate change conditions from different emission scenarios. Seven simulations are run under A1B (balanced emissions), one simulation under A2 (high emission) and one under B1 (low emission)

SRES emission conditions. The forcing GCMs used were BCM (Bjerknes Centre for Climate Research, Norway), CCSM3 (NCAR, USA), CNRM (Met-Office, France), IPSL (Institut Pierre Simon Laplace, France), ECHAM5 (Max-Planck-Institute for Meteorology, Germany) (2 runs with different initial conditions) and HadCM3 (Hadley Centre, UK). The simulations were processed separately and then averaged into a multimodel mean.

3.1.3. SNAO, reconstructions and drought index

In general, tree growth is linked to climate conditions during the growing season in summer. In this context a tree-ring based reconstruction of the summer NAO was used in paper III to extend the analysis period of previous studies back in time and span a multicentury period. The reconstruction was mainly based on long tree-ring records around the North Atlantic sector yielding a 550-year long time-series with annual temporal resolution.

Because a lack of regional tree-ring based drought reconstructions in Northern Europe, a reconstruction of the Standardized Precipitation Index (SPI) in east-central Sweden reaching back until 1700 was used serving as an indicator for June-August drought. SPI is built on rainfall probabilities. Larger values correspond to wetter conditions, which is similar to the following drought index.

For the evaluation of the relationship between observed SNAO and drought over the 20th century, the self-calibrating Palmer Drought Severity Index (scPDSI) was used (obtained from http://www.cru.uea.ac.uk/cru/data/drought/). In order to account for the heterogeneous research area with different climate regimes this index is more appropriate compared to the original PDSI. For the index calculation both, precipitation, temperature and description of the soil characteristics are considered.

3.2. Statistical methods

3.2.1. Climate indices

Precipitation and temperature extremes can be defined in different ways. Here we used a set of climate indices based on daily minimum, maximum and mean temperature and on daily precipitation totals (Paper I; Chen et al. 2006). Commonly different thresholds for daily extremes are used depending on the purpose of the study and the area in focus. The catalogue used here covers a broad range of climate and extremes indices consisting of mean values, percentiles, percentile-based indices and indices using absolute thresholds. In this way a comprehensive picture of extreme climate characteristics can be obtained. In total 64 indices were calculated not all of which being used in paper I. An analysis of all indices for al possible periods, stations and regions was done in Chen et al. (2006), which is also available online under http://rcg.gvc.gu.se/data/TrdAtlas. Table 1 (paper I) shows the main groups of indices used to define extremes based on the daily instrumental records.

The thermal growing season parameters (start, end, and length) were determined by calculating indices based on the T_{mean} observations. GS start is defined by the first period in spring with 5 days above 5°C after the last frost (Tmean<0°C). GS ends when the 10-day running mean in autumn falls below 5°C. The GS length is the period in between start and end.

3.2.2. Linear trend analysis and correlation

Linear trend analysis was used to study past changes of extremes (Paper I; Chen et al. 2006) and growing season parameters (Paper II; Linderholm et al. 2005; Song et al. 2010). As estimator for linear trends the ordinary least squares (OLS) method was used. Serial autocorrelation was taken into account by decreasing the degrees of freedom when testing the trends for significance (5% level) using a two-tailed t-test. For paper II the significance of the trend was tested using a non-parametric trend test, the Mann-Kendall test (Yue et al. 2002).

Correlation and regression were used to investigate the relationship between the variables used in paper III, namely the SNAO, SPI and scPDSI.

3.2.3. Diurnal precipitation cycle and comparison of modeled vs observed data

The diurnal precipitation cycle of both modeled and observed data was obtained applying the harmonic analysis technique as used by Angelis et al. (2004). Here the first (24h) and second (12h) part of the harmonics was defined as mean smoothed diurnal cycle representing the observed raw cycle sufficiently and enabling comparability with other studies. The procedure is explained in detail in section 2.3. in paper IV.

Observations such as precipitation and temperature measurements are usually point samples whereas output from climate models comes as areal averages for each grid-cell at the respective model resolution. In practice this could for example mean that a number individual meteorological stations are located within a model grid-cell and should be compared to the model output, i.e. one value for the whole cell. There is no single best solution to do this. In fact, the climate model is not supposed to simulate climate parameters on very small, i.e. station scale. One way would be to calculate a spatial average over the stations within the grid cell. In this way the scales are more easily comparable. For papers IV and V we decided to compare observations with the nearest grid-cell for several reason. Firstly the much localized precipitation characteristics are preserved in this way. Secondly, with 93 stations distributed over whole Sweden the station density is relatively low and in most cases there is only one station per grid-cell anyway. Areal diurnal cycle averages for the South, the North and the East Coast were calculated from the individual diurnal cycle from each station and closest grid-cell, respectively.

4. Results and discussion

4.1. Large-scale atmospheric circulation and drought in Europe

As presented in Fig. 2 (paper III) the mode of the summer North Atlantic Oscillation shows significant negative correlations to the SC-PDSI during 1901-2002. Positive (negative) PDSI values indicate wet (dry) conditions. That means the positive SNAO phase is coupled to dry conditions in a corridor covering the UK, the Northern parts of Central Europe and France, the southern parts of Fennoscandia, the Baltic countries and parts of Russia. Significant positive correlations are found for northernmost Fennoscandia and the eastern Mediterranean meaning that a positive SNAO phase is coupled to relatively wet conditions in these areas. However, the positive correlation signal is weaker than the linkage to drought.

Looking at a longer perspective using reconstructed SNAO we find that the decadal observed variability is captured quite well. In general the reconstruction performs best on temporal scales longer than 10a, that means from decadal to multi-decadal and centennial timescales. The explained variance increases from 46% on interannual timescales to 86% on longer than 10a scales. In Fig. 1 (paper III) the reconstructed SNAO variability over the past 550a is shown. A consecutive period with relatively low SNAO index is between 1650-1750 coinciding with the Maunder Minimum, a period with relatively low solar activity. This gives a hint on the reasonable connection between large-scale circulation and solar input. However, the reconstruction does not provide the possibility to investigate this in detail. The highest values are found in the end of the period, around 1980 being part of a relatively strong increasing trend towards more positive SNAO during the last century.

The linkage between drought and SNAO prior to the 20th century is less obvious according to our analysis. A reconstructed drought index over Northern Europe, the period where the strongest link was found for the 20th century, is not available. The Standardized Precipitation Index (SPI) for a local site reconstructed using tree ring records (differing from those used for the SNAO reconstruction) and a summer (JJA) precipitation reconstruction were used instead (Fig. 3 and 4, paper III). The general correlation between the respective series is relatively low showing the best agreement during the 20th century. The SPI correlates well with positive SNAO during periods of knowingly drought conditions obtained from a farmer's diary. Otherwise correlation is decreasing back in time. The significantly weaker relationship can be due to the quality of the reconstruction and the variables used. Prior to the instrumental period the information about droughts over Northern Europe is insufficient and differs from the indices available for the 20th century. Also the number of available proxies for the reconstruction of precipitation is dropping significantly before 1850, which is widening the confidence interval of the reconstruction significantly. A more detailed study of past droughts in Northern Europe would be beneficial for better assessment of the long-term SNAO/drought relationship.

4.2. Long-term changes in precipitation and temperature extremes

More frequent warm extremes, less frequent cold extremes and in general increased precipitation and precipitation extremes – this is the relatively clear signal obtained from analyzing the long-term daily observations over the 20th century and beyond. The extended analysis covering periods beyond 1900 (Chen et al. 2006) shows a similar picture for the 1801-2000 and 1851-2000 periods even if the number of stations available is very limited. For the 150-year period only 9 stations are available with Tmin/Tmax data, 13 stations with Tmean and 9 stations with precipitation. The picture becomes more diverse when focusing on changes in different seasons and regions. Over Europe, the strongest trends for warming and increase in precipitation totals and extremes were observed for the winter season.

Table 2. Fraction of stations in [%] with positive (pos) and negative (neg) seasonal trends for 1901-2000 for extremes related to daily minimum (T_{min}, TN) and maximum temperature (T_{max}, TX). The shaded areas mark the majority. The indices are devided into percentiles, warm and cold extremes for easier interpretation (examples: TX95P T_{max} 95th percentile; TX95N exceedance of T_{max} 95th percentile; etc). Significant trends (5% level) are marked with *. Annual index (FD, number of frost days) ** For further idex details see Table 1 in paper I.

		MAM				JJA				SON				DJF			
		pos	pos*	neg	neg*	pos	pos*	neg	neg*	pos	pos*	neg	neg*	pos	pos*	neg	neg*
	MEANTN	84.2	61.4	15.8	1.8	91.2	68.4	8.8	3.5	93.0	66.7	7.0	0.0	87.7	35.1	12.3	0.0
	MEANTX	91.2	50.9	8.8	3.5	87.7	56.1	12.3	3.5	93.0	66.7	7.0	3.5	96.5	49.1	3.5	0.0
Percentiles	TN2P	78.9	22.8	21.1	0.0	68.4	31.6	31.6	7.0	77.2	24.6	22.8	0.0	75.4	26.3	24.6	1.8
	TN5P	75.4	22.8	24.6	0.0	71.9	43.9	28.1	7.0	86.0	26.3	14.0	0.0	71.9	26.3	28.1	1.8
	TN10P	77.2	29.8	22.8	0.0	82.5	50.9	17.5	7.0	93.0	35.1	7.0	0.0	75.4	26.3	24.6	0.0
	TN90P	77.2	31.6	22.8	3.5	93.0	63.2	7.0	0.0	87.7	45.6	12.3	0.0	98.2	42.1	1.8	0.0
	TN95P	66.7	19.3	33.3	10.5	91.2	61.4	8.8	0.0	86.0	40.4	14.0	0.0	96.5	47.4	3.5	0.0
	TN98P	63.2	14.0	36.8	12.3	87.7	54.4	12.3	0.0	80.7	36.8	19.3	1.8	96.5	54.4	3.5	0.0
	TX2P	93.0	26.3	7.0	0.0	70.2	24.6	29.8	7.0	98.2	22.8	1.8	0.0	78.9	12.3	21.1	0.0
	TX5P	93.0	28.1	7.0	0.0	64.9	33.3	35.1	7.0	94.7	26.3	5.3	0.0	91.2	19.3	8.8	0.0
	TX10P	91.2	26.3	8.8	0.0	70.2	33.3	29.8	3.5	94.7	33.3	5.3	0.0	89.5	19.3	10.5	0.0
	TX90P	61.4	35.1	38.6	5.3	86.0	50.9	14.0	3.5	82.5	33.3	17.5	3.5	94.7	68.4	5.3	0.0
	TX95P	63.2	22.8	36.8	3.5	84.2	42.1	15.8	5.3	66.7	21.1	33.3	3.5	96.5	80.7	3.5	0.0
	TX98P	54.4	15.8	45.6	7.0	84.2	40.4	15.8	5.3	68.4	24.6	31.6	7.0	94.7	80.7	5.3	0.0
Cold	TN2N	17.5	3.5	82.5	38.6	26.3	7.0	73.7	40.4	21.1	1.8	78.9	42.1	31.6	0.0	68.4	8.8
	TN5N	21.1	3.5	78.9	45.6	19.3	7.0	80.7	47.4	17.5	3.5	82.5	43.9	28.1	0.0	71.9	19.3
	TN10N	19.3	5.3	80.7	43.9	15.8	7.0	84.2	50.9	15.8	1.8	84.2	49.1	29.8	0.0	70.2	21.1
Warm	TN90N	86.0	64.9	14.0	0.0	91.2	59.6	8.8	0.0	93.0	70.2	7.0	0.0	94.7	54.4	5.3	0.0
	TN95N	86.0	59.6	14.0	0.0	96.5	59.6	3.5	0.0	89.5	64.9	10.5	0.0	96.5	64.9	3.5	0.0
	TN98N	87.7	54.4	12.3	1.8	94.7	54.4	5.3	0.0	86.0	52.6	14.0	0.0	94.7	68.4	5.3	0.0
Cold	TX2N	8.8	0.0	91.2	38.6	14.0	3.5	86.0	38.6	3.5	0.0	96.5	49.1	24.6	0.0	75.4	10.5
	TX5N	14.0	0.0	86.0	43.9	19.3	3.5	80.7	42.1	3.5	0.0	96.5	64.9	26.3	0.0	73.7	17.5
	TX10N	15.8	1.8	84.2	49.1	22.8	3.5	77.2	45.6	1.8	0.0	98.2	71.9	29.8	0.0	70.2	19.3
Warm	TX90N	87.7	50.9	12.3	3.5	84.2	52.6	15.8	5.3	89.5	50.9	10.5	5.3	98.2	84.2	1.8	0.0
	TX95N	86.0	50.9	14.0	3.5	84.2	45.6	15.8	3.5	84.2	45.6	15.8	5.3	98.2	84.2	1.8	0.0
	TX98N	86.0	43.9	14.0	3.5	84.2	40.4	15.8	3.5	82.5	35.1	17.5	7.0	96.5	82.5	3.5	0.0
	HWDI	84.2	22.8	15.8	0.0	73.7	21.1	26.3	3.5	64.9	5.3	28.1	3.5	89.5	36.8	5.3	0.0
	WSDI90	82.5	24.6	17.5	0.0	75.4	24.6	24.6	3.5	73.7	14.0	26.3	3.5	96.5	49.1	3.5	0.0
Cold	CSDI10	19.3	0.0	80.7	22.8	28.1	0.0	71.9	19.3	17.5	0.0	82.5	35.1	29.8	0.0	70.2	7.0
	FD**	15.8	0.0	84.2	52.6	15.8	0.0	84.2	52.6	15.8	0.0	84.2	52.6	15.8	0.0	84.2	52.6

The warming is asymmetric with stronger warming in the warm tail of the distribution, which is most clear in summer. Table 2 shows a summary of the changes observed for the 1901-2000 period underlining the above findings taking T_{min} and T_{max} indices as example. The summary for precipitation (not shown) revealed a majority of positive trends for all indices. That means precipitation totals increased as well as the frequency and amplitude of different extremes. The highest fraction of positive/negative trends was found in winter (80/20), followed by spring and autumn (ca. 70/30) and summer (ca. 60/40).

The aforementioned trend fractions were obtained from stations over whole Europe. In another step stations for different regions were averaged, for example Southern Scandinavia (SSCAND) was one of those regions consisting of 8 long-term records located in Denmark and Southern Sweden. The trend values for the regional average were generally lower, because relatively high variability among the stations in most regions (see Fig 12-14 in paper I). Homogeneity issues became obvious for some of the stations. Figure 2 shows examples for single-station long-term temperature trend and long-term regional precipitation trends. The steeply decreasing trend in the number of frost days throughout the whole period at Uppsala (Fig 2a) is an example for the strong warming signal, especially over the GBA. When it comes to precipitation the high spatial variability of trend becomes obvious, as well among the regions (Fig. 2b) as well as within the regions. For the GBA the precipitation are relatively weak. Significant trends are mainly found for the south-western regions.

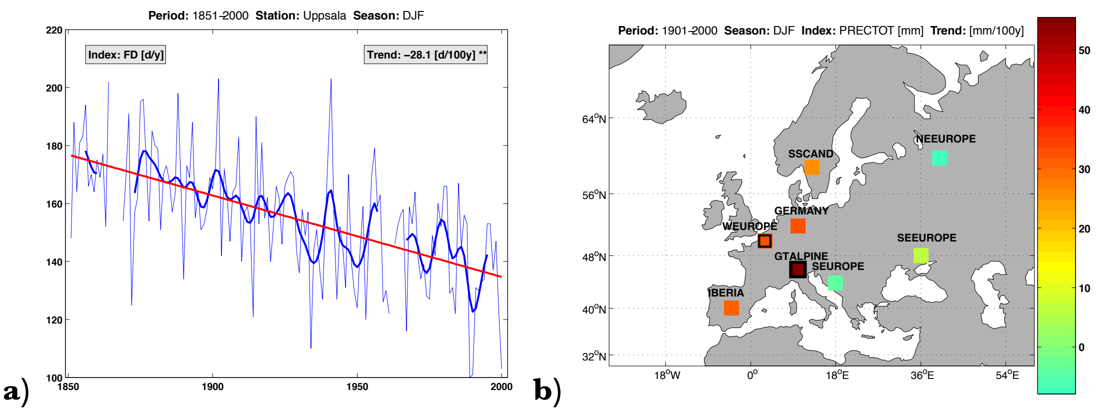

Figure 2. Examples of long-term trends. **a)** Trend in [d/100a] in the annual number of frost days between 1851-2000 for Uppsala/Sweden. **b)** Trend in [mm/100a] of winter total precipitation for different regions. Bold outlines mark significant trends. (Chen et al. 2006)

As in paper I we talk about trends and tendencies. Usually tendencies are weaker trends and not significant. However, they can provide important information about the direction of change. Calculating linear trends is very sensitive to inhomogeneities, especially when they appear in the beginning and in the end of the analysis period. This was considered by using regional averages dampening the effect of single stations with doubtful homogeneity. In this context the results of single stations should be interpreted with some care if the station history is unknown.

4.3. Thermal growing season changes in the GBA

Utilizing growing season indices based on 48 daily mean temperature observations we found a clear signal of an extended growing season. Growing season (GS) start, end and length for three different periods – 1901-1950, 1951-2000, and 1901-2000 – were analyzed in paper II (Fig. 2 in paper II). For all periods a general earlier start, later end and thus a longer growing season are evident. The strongest and most significant signals are found for the 100-year period. The start was shifted up to 23 days earlier at Danish stations. The biggest changes for the GS end were observed for the stations Copenhagen, Stockholm and Helsinki with a delayed GS end of 12.6, 11.7 and 10.5 days, respectively. The GS length extended most at Danish stations with up to one month (33.5 d). For only one station, namely Archangelsk/Russia, a shorter growing season by 3.6 days could be identified.

The thermal growing season is a relatively simple approach to determine the length of the annual period of potential growth. Parameters are usually derived using daily mean temperatures. There is no single universal index and the variety of indices used in the literature is huge. However, the general properties of the indices are similar. The thermal growing season starts when a certain temperature threshold is exceeded for a number of consecutive days, and it ends when a threshold is fallen below for a certain number of consecutive days. The thresholds and number of days vary. Different indices applied on the Greater Baltic Area were compared in Walther and Linderholm (2006), where clear differences among the GS calculation methods could be found. In some cases unrealistically early growing season starts can be generated by some indices due to unusually warm periods in early spring, which in reality would be counteracted by limited light conditions. The inclusion of a frost criterion turned out to be useful in terms of more realistically capturing the growing season in this area.

Because only Tmean is considered for the calculation, the change of GS parameters mainly follows trends in Tmean. It can be expected that the thermal conditions supporting vegetation growth in a warming climate would increase, which is initially confirmed by these findings. However, because periods of consecutive days above (below) a certain threshold are used for calculating the GS start (end), increased mean temperatures in combination with high daily variability would not necessarily lead to changed parameters. On the other hand, unchanged averages of Tmean in combination with decreased daily variability could lead to changed parameters. This type of indices cannot give information about the real growing conditions. For example, earlier start of the GS can be indicated by the indices but in reality the availability of sunlight in early spring could still limit the plant growth in higher latitudes. For this purpose phenological data are much more suitable. In contrast to the thermal GS indices phenological measurements integrate a huge number of environmental factors affecting the plant sampled. However, the thermal indices define a frame for the potential growing season and can be obtained easily. Compared to phenological observations, mean temperature measurements are widely available. Further increase in growing season length is likely to be observed in many regions under conditions of continued increase of mean temperatures (Ruosteenoja et al. 2011). In this context and as mentioned earlier, it is of big interest to further study the climate conditions within and prior to the growing season, because the effect of changed start, end and length on ecosystems and field-crop production largely depends on those.

4.4. Spatio-temporal sub-daily precipitation characteristics over Sweden

Despite the geographical location in high northern latitudes, distinct spatiotemporal diurnal features could be identified. During the summer season (AMJJAS) there is an average afternoon peak between 14-18 LST in most of the inland stations (Fig. 4 in paper IV). The strength of the afternoon peak is linked to the precipitation intensity show. The diurnal cycle of higher precipitation amounts is more distinctive pointing at the importance of convective rainfall activities connected to the diurnal variation of available surface energy (Fig. 5 in paper IV). Along the eastern coast the maximum occurs during the night an early morning linked to a different boundary layer properties over the coastal waters with cooler temperatures over the surface and a shallower boundary layer leading to increased condensation and rainfall in these hours. However, this peak is much weaker compared to the afternoon maximum at inland stations. In winter (ONDJFM) the diurnal cycle is expectedly of modest amplitude due to limited incoming solar radiation.

The performance of the Rossby Centre regional climate model (RCA3) in terms of simulating diurnal precipitation characteristics was evaluated in papers IV and V. In paper IV an initial comparison of the 50km simulation was done whereas paper V contains a more comprehensive assessment using different resolutions and precipitation types. A clear coupling between performance and model resolution was found. Focusing on inland stations and total precipitations we found that all simulations overestimate the peak amount, but the 6 km model performed best in simulating the peak timing with least deviation to the observed (Fig. 5 in paper V). The separate analysis of the diurnal cycle of modeled large-scale and convective precipitation gave interesting results on the contribution of theses precipitation types. With increasing model resolution the contribution of convective precipitation was decreasing while large-scale precipitation increased. Convective precipitation is usually obtained from the convective parameterization scheme. The decrease of convective precipitation is showing that less precipitation is parameterized and instead explicitly modeled and in this way showing up as large-scale precipitation. In Fig. 5

(paper V) this shows clearly. The summer afternoon peak timing of large-scale precipitation from the 6 km simulation best coincides with the observed afternoon peak. This clearly shows that higher resolution simulation can add value to the performance. Surprisingly there is no gradual improvement in performance regarding the simulated peak timing. Another obvious improvement at finer resolution is the more realistic diversity of the results. Whereas the coarser resolutions show a quite uniform pattern with too early peak timing, the picture becomes more realistic with the 6 km model. Another previously known feature is the too frequent simulation of precipitation events of relatively light intensity (Fig. 8 in paper V), especially in the mountain regions where convective precipitation is triggered too easily.

Precipitation characteristics on different temporal and spatial scales are likely to change in the future. Sub-daily precipitation can potentially change in different ways. The shape of the average diurnal cycle can undergo changes. The afternoon peak could become more narrow and higher meaning higher precipitation intensities within a shorter time, i.e. more extreme precipitation events. On the contrary, a flattened cycle would mean less intensity distributed over a longer time period. In terms of infrastructural planning and hydrological modeling these are important details to consider. Further, the diurnal cycle can just be entirely shifted up or down in terms of precipitation intensity. Hourly precipitation data from future simulations were analyzed for the period 2086-2098 and compared to present climate diurnal cycle. All present climate and future simulations were averaged into one diurnal cycle, respectively and additionally compared to the average observed diurnal cycle obtained from 1996-2008 observations. Despite the relatively large diversity among the simulations in terms of forcing GCMs and emission scenario applied, the general signal is quite clear (Fig. 3). Averaged over all inland stations we find that the summer afternoon peak remains relatively constant in terms of amount and shape, whereas there is an increase in nighttime precipitation between 20-06 LST. The picture becomes more diverse when separating stations according to their location in the southern or northern domain. In the south, the summer afternoon peak shows a slight decrease (7%), whereas it is increasing in the north by about 5%. Nighttime precipitation shows an increase in both domains, but is stronger in winter (9%) than in summer (5%). In winter the diurnal cycle is, as expected, less pronounced. However, an overall increase in precipitation intensity of about 17% is evident for all inland stations and somewhat less for stations along the eastern coast.

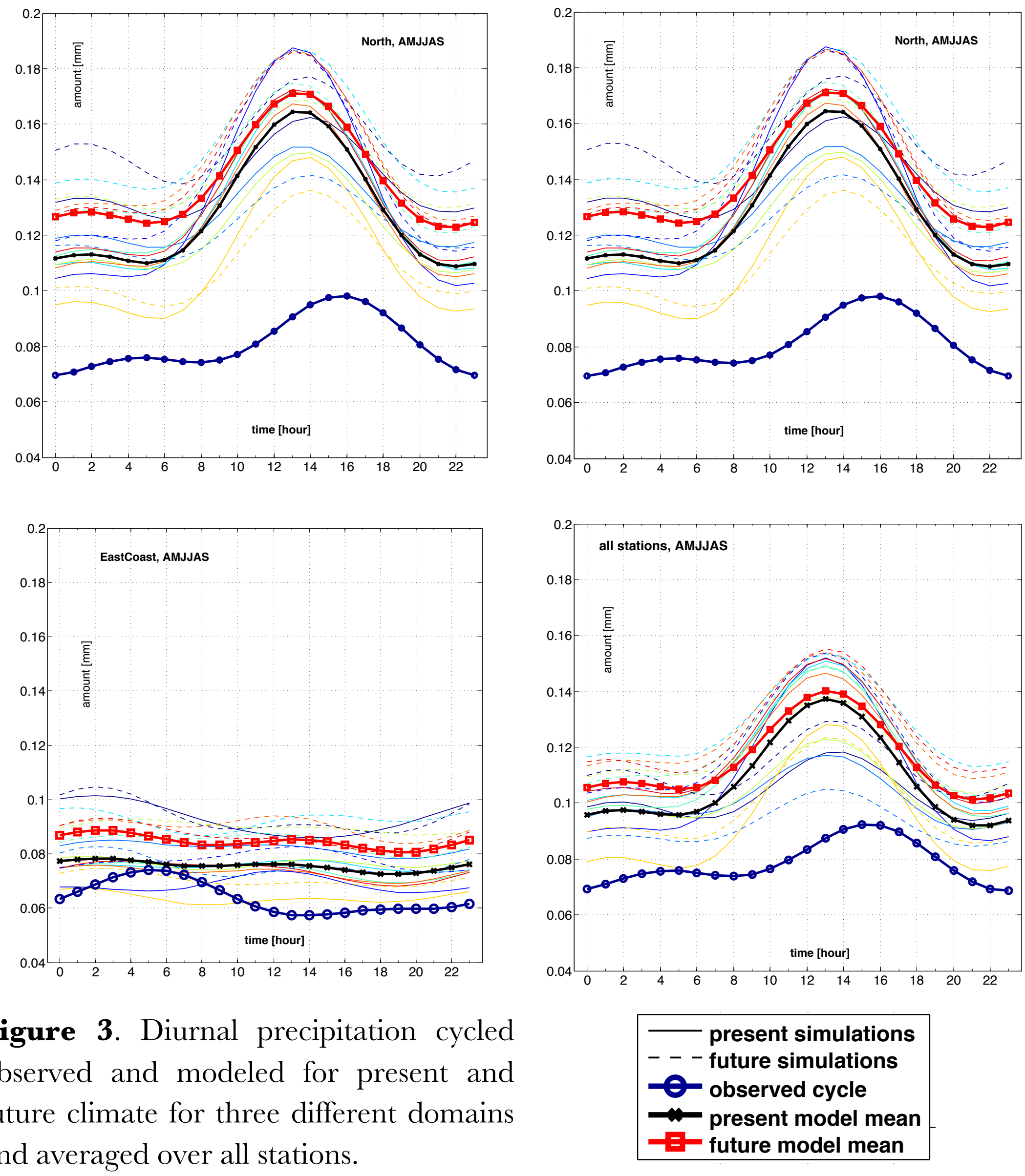

Figure 3. Diurnal precipitation cycled observed and modeled for present and future climate for three different domains and averaged over all stations.

The simulated afternoon peak occurs 2-4 hours earlier compared to the observed, both in the present climate and future climate simulation. Considering the model resolution of 50km this result is in line with findings in paper V mentioned above, were a resolution dependency of the peak timing was found.

The signal of increased precipitation intensity partly confirms findings summarized by IPCC (2007a) pointing at an overall increase in precipitation amounts over Northern latitudes mostly during winter and slightly drier conditions in some areas during summer. So even if the changes observed are of rather small amplitude, they seem to be the response to an intensified hydrological cycle through the water vapor feedback under climate change conditions with overall increased precipitation rates mainly in the winter season.

5. Conclusions

The overall aim of this thesis was to contribute to the assessment and understanding of climate variability in the European domain focused on the Greater Baltic Area. By investigating climate phenomena on different spatio-temporal scales, new findings in the covered fields were obtained.

We have got a better picture of the multicentury variability of the SNAO and its relationship to the occurrence of drought in Northern Europe. The relationship is strongest for the instrumental period, is getting weaker back in time and is holding for about 310 years into the past keeping in mind that this is based on the local reconstruction of the SPI, which may not have enough spatial representativeness as a drought index for the larger Northern European domain. The reconstructed SNAO has relatively large decadal variability, which is not evident from the local standardized precipitation index, which was used as a drought proxy. This underlines the need to further work on improving drought reconstructions using better proxies. The strong positive trend in NAO during winter between 1960-90 is coinciding with the sharp rise in mean temperatures worldwide.

One of the most comprehensive databases holding long-term daily records of precipitation and temperature was built-up and analyzed revealing a distinct signal of 20^{th} century warming. The instrumental records clearly show increased extreme events of higher magnitudes for most of Europe. More frequent and stronger warm extremes, less frequent cold extremes and a general tendency towards more frequent and stronger precipitation extremes. Despite potential uncertainties related to the data quality, the results obtained are reasonable and confirm findings from other studies. The changes can be well explained with the physical knowledge we have about the climate system, assuming that in a warming climate the level of temperature extremes my increase and the hydrological will be intensified. It became obvious that further efforts are needed to check and correct instrumental records for inhomogeneities, which is still a challenging task when it comes to daily data. More time-series would be beneficial to obtain more robust signals of changing extremes.

In connection to the 20^{th} century warming trends evident from the climate indices, significant changes in the parameters of the thermal growing season (GS) over the Greater Baltic Area were found using daily mean temperatures as a base for calculation. A lengthening was found for most of the 48 stations with spring dates shifting the most. This implies that the warming is larger in spring. It also shows that the warming seem to be relatively constant because the GS parameters are obtained using consecutive periods of high or low temperatures. Single very warm days would not yet lead to an initiation of the start. The ecological impacts of the detected extension can be manifold but have not been studied explicitly. As pointed out earlier, a lengthening can mean increased food production and CO2 uptake by the biosphere, but there seem to be large regional differences as shown by other authors. In order to better assess the consequences of a longer GS, the climate conditions within the growing season should be studied in more detail because the start and end dates just give a potential frame for plant growth etc. A long growing season with unfavorable conditions such as drought or frequent precipitation extremes can be worse in terms of biomass production than a shorter season with ideal growing conditions.

Precipitation properties play an important role during the growing season. The sub-daily precipitation characteristics over Sweden were studied in detail using both observations and simulations. Distinct spatio-temporal patterns of the diurnal precipitation were identified. In the summer season a clear afternoon peak was found for inland stations, being most pronounced for higher precipitation intensities. This peak is linked to convective precipitation activities following the diurnal variation of solar radiation input. Along the east coast an early morning peak was evident as consequence of the proximity to the Baltic Sea where the boundary layer is shallow in the period of strongest radiative cooling triggering rainfall in the early morning. The simulations relatively well captured the general spatio-temporal patterns. Obvious deficiencies were the too early peak timing due to too sensitively initiated convection, and too frequent light-rain events, especially in the mountains. The 6km simulation, which is rather experimental and at the resolution limit considering that the model is hydrostatic, is performing best in terms of peak timing and precipitation frequencies. Less convective precipitation, which is the main contributor to the afternoon peak, has to be parameterized and is instead modeled explicitly. Since the parameterization scheme used was identical among the model runs, this finding is indicating a need for improvement of the scheme. It also shows that finer model resolution provide an added value in terms of performance even if the general patterns are captured even at larger model grid-size and that we have a generally well-performing model at hand. The future simulations indicate a shift in the diurnal cycle towards higher nighttime rainfall and a more or less unchanged peak. The simulations supporting this conclusion are relatively diverse in terms of setup and a more systematic approach with different model resolutions and a similar setup in terms of forcing GCMs would be interesting to evaluate. However, from the simulations used for the future estimate the signal is relatively robust, nighttime rainfall is likely to increase.

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References

Alexandersson, H., T. Schmith, K. Iden and H. Tuomenvirta (1998). Long-term variations of the storm climate over NW Europe. ***Global Atmosphere and Ocean Systems*** **6**: 97-120.

Angelis, C. F., G. R. McGregor and C. Kidd (2004). Diurnal cycle of rainfall over the Brazilian Amazon. ***Climate Research*** **26**: 139-149.

Barry, R. G. and A. M. Carleton (2001). Synoptic and Dynamic Climatology, Routledge Publishing, London and New York.

Benestad, R. E., I. Hanssen-Bauer and D. Chen (2008). Empirical-Statistical Downscaling, World Scientific Publishing Company Incorporated.

Beniston, M. (2004). The 2003 heat wave in Europe. A shape of things to come? ***Geophysical Research Letters*** **31**: 2022-2026.

Brunet, M. and P. Jones (2011). Data rescue initiatives: Bringing historical climate data into the 21st century. ***Climate Research*** **47**(1-2): 29-40.

Chen, D. (2000). A monthly circulation climatology for Sweden and its application to a winter temperature case study. ***Int. J. Climatol*** **20**: 1067-1076.

Chen, D., A. Walther, A. Moberg, P. D. Jones, J. Jacobeit and D. Lister (2006). Trend Atlas of the EMULATE indices, Dept of Earth Sciences, University of Gothenburg, Sweden. **C73:** 798.

Dai, A. (2001). Global Precipitation and Thunderstorm Frequencies. Part II: Diurnal Variations. ***Journal of Climate*** **14**: 1112-1128.

Della-Marta, P. M., J. Luterbacher, H. von Weissenfluh, E. Xoplaki, M. Brunet and H. Wanner (2007). Summer heat waves over western Europe 1880–2003, their relationship to large-scale forcings and predictability. ***Climate Dynamics*** **29**: 251-275.

Della-Marta, P. M. and H. Wanner (2006). A method of homogenizing the extremes and mean of daily temperature measurements. ***Journal of Climate*** **19**(17): 4179-4197.

Doherty, T. J. and S. Clayton (2011). The Psychological Impacts of Global Climate Change. ***American Psychologist*** **66**(4): 265-276.

Folland, C. K., J. Knight, H. W. Linderholm, D. Fereday, S. Ineson and J. W. Hurrell (2009). The Summer North Atlantic Oscillation: Past, Present, and Future. ***Journal of Climate*** **22**: 1082-1103.

Gould, S. J. (1965). Is uniformitarianism necessary? ***American Journal of Science*** **263**(3): 223-228.

Hegerl, G. C., H. Hanlon and C. Beierkuhnlein (2011). Climate science: Elusive extremes. ***Nature Geosci*** **4**(3): 142-143.

Hegerl, G. C., T. R. Karl, M. Allen, N. L. Bindoff, N. Gillett, D. Karoly, X. Zhang and F. Zwiers (2006). Climate Change Detection and Attribution: Beyond Mean Temperature Signals. ***Journal of Climate*** **19**: 5058-5077.

Hellström, C. (2005). Atmospheric conditions during extreme and non-extreme precipitation events in Sweden. ***Int. J. Climatol*** **25**: 631-648.

Hurrell, J. W. (1995). Decadal trends in the north-Atlantic oscillation - regional temperatures and precipitation. ***Science*** **269**: 676-679.

Hurrell, J. W. and C. Deser (2009). North Atlantic climate variability: The role of the North Atlantic Oscillation. ***Journal of Marine Systems*** **78**(1): 28-41.

IPCC (2007a). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2007b). IPCC Fourth Assessment Report: Working Group II Report "Impacts, Adaptation and Vulnerability", Cambridge University Press.

Karlsen, S. R., K. A. Hegda, F. E. Wielgolaski, A. Tolvanen, H. Tømmervik, J. Poikolainen and E. Kubin (2009). Growing-season trends in Fennoscandia 1982-2006, determined from satellite and phenology data. ***Climate Research*** **39**(3): 275-286.

Klein-Tank, A. M. G., J. B. Wijngaard, G. P. Können, R. Böhm, G. Demarée, A. Gocheva, M. Mileta, S. Pashiardis, L. Hejkrlik, C. Kern-Hansen, R. Heino, P. Bessemoulin, G. Müller-Westermeier, M. Tzanakou, S. Szalai, T. Palsdottir, D. Fitzgerald, S. Rubin, M. Capaldo, M. Maugeri, A. Leitass, A. Bukantis, R. Aberfeld, A. F. V. van Engelen, E. Forland, M. Mietus, F. Coelho, C. Mares, V. Razuvaev, E. Nieplova, T. Cegnar, J. A. López, B. Dahlström, A. Moberg, W. Kirchhofer, A. Ceylan, O. Pachaliuk, L. V. Alexander and P. Petrovic (2002). Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. ***Int. J. Climatol*** **22**: 1441-1453.

Lamb, H. H. (1972). British Isles Weather types and a register of daily sequence of circulation patterns, 1861-1971. ***Geophysical Memoir*** **116**: 85.

Linderholm, H. W., A. Walther and D. Chen (2005). Growing season trends in the Greater Baltic Area, Dept of Earth Sciences, University of Gothenburg, Sweden. **C69:** 92.

López-Moreno, J. I. and S. M. Vicente-Serrano (2008). Positive and Negative Phases of the Wintertime North Atlantic Oscillation and Drought Occurence over Europe: A Multitemporal-Scale Approaches. ***Journal of Climate*** **21**: 1220-1243.

Lorenzo, M. N., J. J. Taboada and L. Gimeno (2008). Links between circulation weather types and teleconnection patterns and their influence on precipitation patterns in Galicia (NW Spain). ***IJC*** **28**: 1493-1505.

Lynn, K., K. Mackendrick and E. M. Donoghue (2012). Social vulnerability and climate change: Synthesis of literature. ***USDA Forest Service - General Technical Report PNW-GTR***(838): 1-70.

Maraun, D., F. Wetterhall, A. M. Ireson, R. E. Chandler, E. J. Kendon, M. Widmann, S. Brienen, H. W. Rust, T. Sauter, M. Themel, V. K. C. Venema, K. P. Chun, C. M. Goodess, R. G. Jones, C. Onof, M. Vrac and I. Thiele-Eich (2010). Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user. ***Reviews of Geophysics*** **48**(3).

Maslow, A. H. (1943). A theory of human motivation. ***Psychological Review*** **50**(4): 370-396.

Menzel, A. (2003). Plant Phenological Anomalies in Germany and their Relation to Air Temperature and NAO. ***Climatic Change*** **57**(3): 243-263.

Menzel, A., H. Seifert and N. Estrella (2011). Effects of recent warm and cold spells on European plant phenology. ***International Journal of Biometeorology*** **55**(6): 921-932.

Moberg, A. and H. Bergström (1997). Homogenization of wedish temperature data. Part III: The long temperature records from Uppsala And Stockholm. ***International Journal of Climatology*** **17**(7): 667-699.

Moberg, A., P. D. Jones, D. Lister, A. Walther, M. Brunet, J. Jacobeit, L. V. Alexander, P. M. Della-Marta, J. Luterbacher, P. Yiou, D. L. Chen, A. M. G. K. Tank, O. Saladie, J. Sigro, E. Aguilar, H. Alexandersson, C. Almarza, I. Auer, M. Barriendos, M. Begert, H. Bergstrom, R. Bohm, C. J. Butler, J. Caesar, A. Drebs, D. Founda, F. W. Gerstengarbe, G. Micela, M. Maugeri, H. Osterle, K. Pandzic, M. Petrakis, L. Srnec, R. Tolasz, H. Tuomenvirta, P. C. Werner, H. Linderholm, A. Philipp, H. Wanner and E. Xoplaki (2006). Indices for daily temperature and precipitation extremes in Europe analyzed for the period 1901-2000. ***Journal of Geophysical Research-Atmospheres*** **111**(D22106).

Munich-Reinsurance (2002). Major Natural Catastrophes, 1950–2001. ***Population and Development Review*** **28**(1): 171-174.

Parmentier, F. J. W., M. K. Van Der Molen, J. Van Huissteden, S. A. Karsanaev, A. V. Kononov, D. A. Suzdalov, T. C. Maximov and A. J. Dolman (2011). Longer growing seasons do not increase net carbon uptake in the northeastern Siberian tundra. ***Journal of Geophysical Research G: Biogeosciences*** **116**(4).

Peltonen-Sainio, P., L. Jauhiainen, K. Hakala and H. Ojanen (2009). Climate change and prolongation of growing season: Changes in regional potential for field crop production in Finland. ***Agricultural and Food Science*** **18**(3-4): 171-190.

Qian, B., S. Gameda, X. Zhang and R. De Jong (2011). Changing growing season observed in Canada. ***Climatic Change***: 1-15.

Reichler, T. and J. Kim (2008a). How well do coupled models simulate today's climate? ***Bulletin of the American Meteorological Society*** **89**(3): 303-+.

Reichler, T. and J. Kim (2008b). Uncertainties in the climate mean state of global observations, reanalyses, and the GFDL climate model. ***Journal of Geophysical Research-Atmospheres*** **113**(D5).

Rubel, F. and K. Brugger (2009). 3-hourly quantitative precipitation estimation over Central and Northern Europe from rain gauge and radar data. ***Atmospheric Research***.

Rummukainen, M. (2010). State-of-the-art with regional climate models. ***Wiley Interdisciplinary Reviews-Climate Change*** **1**(1): 82-96.

Rummukainen, M. (2012). Changes in climate and weather extremes in the 21st century. ***Wiley Interdisciplinary Reviews: Climate Change*** **3**(2): 115-129.

Ruosteenoja, K., J. Räisänen and P. Pirinen (2011). Projected changes in thermal seasons and the growing season in Finland. ***International Journal of Climatology*** **31**(10): 1473-1487.

Scaife, A. A., C. K. Folland, L. V. Alexander, A. Moberg and J. R. Knight (2008). European Climate Extremes and the North Atlantic Oscillation. ***Journal of Climate*** **21**: 72-83.

Shen, M., Y. Tang, J. Chen, X. Zhu and Y. Zheng (2011). Influences of temperature and precipitation before the growing season on spring phenology in grasslands of the central and eastern Qinghai-Tibetan Plateau. ***Agricultural and Forest Meteorology*** **151**(12): 1711-1722.

Song, Y., H. W. Linderholm, D. Chen and A. Walther (2010). Trends of the thermal growing season in China, 1951-2007. ***International Journal of Climatology*** **30**(1): 33-43.

Theon, J. S. (1994). The tropical rainfall measuring mission (TRMM). ***Advances in Space Research*** **14**(3): 159-165.

Twardosz, R. (2007). Diurnal variation of precipitation frequency in the warm half of the year according to circulation types in Kraków, South Poland. ***Theor. Appl. Climatol.*** **89**: 229-238.

Uppala, S. M., P. W. Kallberg, A. J. Simmons, U. Andrae, V. D. C. Bechtold and a. co (2005). The ERA-40 re-analysis. ***Quaternary Journal of the Royal Meteorologigal Society*** **131**: 2961-3211.

Walther, A., J.-H. Jeong, G. Nikulin, D. Chen and C. Jones (2011). Potential future changes of the diurnal precipitation properties over Sweden. ***Geophys. Res. Abs.*** **13**(EGU2011-10793).

Walther, A. and H. W. Linderholm (2006). A comparison of growing season indices for the Greater Baltic Area. ***International Journal of Biometeorology*** **51**(2): 107-118.

Yue, S., P. Pilon and G. Cavadis (2002). Power of the Mann-Kendall and Spearman's rho test for detecting monotonic trends in hydrological series. ***Journal of Hydrology*** **259**: 254-271.

Zhang, D. D., H. F. Lee, C. Wang, B. Li, Q. Pei, J. Zhang and Y. An (2011). The causality analysis of climate change and large-scale human crisis. ***Proceedings of the National Academy of Sciences*** **108**(42): 17296-17301.

Part II

Papers