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Analysis of Atmospheric Precursor of Extreme Summers in Central Europe

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List of Acronyms

AO	Arctic Oscillation
ASO	August - September - October
AVHRR	Advanced Very High Resolution Radiometer
BeNeLux	Belgium - Netherlands - Luxemburg
BEST index	bivariate ENSO time series index
BSRN	Baseline Surface Radiation Network
°C	degree Celsius
CEDI	Central European Drought Index
CM SAF	Satellite Application Facility on Climate Monitoring
DJ(FM)	December - January - February - March
DWD	Deutscher Wetterdienst
ECMWF	European Center for Medium-Range Weather Forecast
ENSO	El Nino Southern Oscillation
ERA-40	European Center for Medium-Range Weather Forecast 40 year re-analysis
ERA-interim	European Center for Medium-Range Weather Forecast interim re-analysis
ERBE	Earth Radiation Budget Experiment
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FMA(M)	February - March - April - May
GCM	Global Climate Model
GCOS	Global Climate Observing System
GDAS	Global Data Assimilation System

GEWEX	Global Energy and Water Exchanges Project
GND(I)	Greenland - North Sea - Dipole (- Index)
GPCC	Global Precipitation Climatology Center (see also WZN)
GTS	Global Telecommunications System
IPCC	Intergovernmental Panel on Climate Change
ISCCP	International Satellite Cloud Climatology Project
JJA	June - July - August
Lat	Latitude
Lon	Longitude
m a.s.l.	meter above sea level
MAGIC	Mesoscale Atmospheric Global Irradiance Code
MARS	ECMWF archiving system for meteorological data
mdfa	monthly means of daily forecast accumulations
MERRA	Modern ERA Re-analysis for Research and Applications
MFG	METEOSAT first generation satellite(s)
MJJ	May - June - July
MOL	Meteorological Observatory Lindenberg
MVIRI	METEOSAT Visible and Infrared Imager
NAM	Northern Annular Mode
NAO	North Atlantic Oscillation
NCAR	(United States) National Center for Atmospheric Research
NCEP	(United States) National Centers for Environmental Prediction
NDJ	November - December - January
NOAA	(United States) National Oceanic and Atmospheric Administration
PCA	Principal Component Analysis
ScaRaB	Scanner for Radiation Budget
SIS	Solar incoming irradiation at the surface
SOI	Southern Oscillation Index
SRM	seasonal region mean
ssrd	surface solar irradiation downward
SST	Sea Surface Temperature
SURFRAD	US surface radiation network
SV NAM	seasonally varying Northern Annular Mode
SZA	Solar Zenith Angle

U.S. United States
WHO World Health Organisation
Wm^{-2} Watts per square meter
WMO World Meteorological Oganisation
WP work package
WZN Weltzentrum für Niederschlagsklimatologie (see also GPCC)

Chapter 1

Introduction, Motivation, Aim

1.1 Introduction

Extreme weather events generally have negative impacts on human health and well being, infrastructure and the environment. Droughts, floods, extreme temperatures, windstorms, tropical cyclones, storm surges, land slides and wild fires each year cost thousands of human lifes, cause damages to the economy, human infrastructure and the natural environment all over the world. Between 1980 and 2005 90 % of all natural catastrophes were caused by meteorological events, which killed 1.45 million people and caused economic losses of 900 billion U.S. dollars (WMO, 2014).

Within the context of global warming an increase in extreme weather events and meteorological catastrophes are expected to increase in the future (IPCC, 2013).

According to Working Group 1 (The Physical Science Basis) of the Intergovernmental Panel on Climate Change a worldwide increase of meteorological catastrophes is expected, with varying likelihood depending on the region and the type of event. For Europe an increased frequency and duration of heat waves is likely during the 21^{st} century (IPCC, 2013). Impacts of heat waves on various fields of life are exemplarily described in the following.

Heat is a major thread to human health, especially in the cities of the temperate regions of the Earth (WHO, 2013). In general, heat stress is greater in cities than in rural areas (Howard, 1833, in Oke 1982). This is due to what is referred to as "urban heat island" (Oke, 1982): the high building density in cities and the large heat conservation of the materials used, such as concrete and asphalt (WHO, 2013), a reduced latent heat exchange with the atmosphere, due to reduced evapotranspiration compared to rural areas, reduced thermal radiance emittance due to high aerosol loads, and reduced fresh air drainage (Schönwiese, 1994) lead to higher temperatures in cities compared to the surrounding environment (Oke, 1982). This effect is particularly important during heat waves, since it "prevents temperatures in summer from cooling during the night" (WHO, 2013, p. 9), and thus induces increased heat stress to the inhabitants. Baccini *et al.* (2008) describe the relationship between maximum apparent temperature[1] and mortality rates and found that this relationship is city specific. In general, this means that the "thermal comfort zone" (WHO, 2013) in Mediterranean cities is higher than in north-continental cities (Baccini *et al.*, 2008). Baccini *et al.* (2008, p. 711) further found that a 1° C "increase in maximum apparent temperature above the city-specific threshold" already results in an increase of mortality.

Heat impacts on human health mainly affect the cardiovascular system (WHO, 2013). The human body is generally able to keep its core body temperature at 37°C (Jendritzky *et al.*, 2007). If, for example due to high environmental temperatures, this thermoregulation is overcharged, the core-body temperature rises, which, depending on the individual constitution, sooner or later leads to heat disorders (WHO, 2013). At particular risk are people of more the 75 years of age, babies and young children of less than 5 years of age, chronically ill, socially isolated persons, disabled persons, and residents of nursing homes (Baccini *et al.*, 2008).

During the European hot summer in 2003 the excess mortality attributed to heat stress is estimated at 70000 for 16 European countries (Robine *et al.*, 2007).

One of the most prominent effects of global warming but also of singular extreme heat summers is the retread of glaciers. Glaciers are an important fresh water reservoir, especially in alpine regions. Their mass balance (relation of growth and decline) is determined by radiation, temperature and precipitation (ProClim(Ed.), 2005). Important factors determining their growth and shrinkage are the precipitation in spring and early summer and the climate during summer. A fresh snow pack during spring and early summer saves the ice from melting, due to its high albedo (ProClim(Ed.), 2005). During summer month the amount (and type) of precipitation, solar radiation, and temperature determine the mass reduction: warm, dry, and sunny weather leads to increased melt (ProClim(Ed.), 2005). Consequently, during the extensive heat and drought summer of 2003, the largest loss of ice masses of alpine glaciers ever registered within one year occurred (BUWAL, 2004; ProClim(Ed.), 2005).

Also the reduction of permafrost is an issue in alpine regions: the enhanced thawing of permafrost, especially during hot summers (ProClim(Ed.), 2005), in-

[1]apparent temperature: combination of temperature and humidity to describe the thermal discomfort of humans (Baccini *et al.*, 2008, and references therein)

fluences the stability of steep rock slopes and leads to enhanced rock fall (Gruber *et al.*, 2004; ProClim(Ed.), 2005).

Low precipitation amounts and high temperatures lead to enhanced evaporation and thus to low river discharge and low water levels. Reduced water levels forces fish and other mobile animals, living in aquatic ecosystems to concentrate in smaller water bodies (Bundesanstalt für Gewässerkunde (Ed.), 2004). This increases the probability of physical contact among individual and thus enhances the dispersal of certain diseases and vermin (Bundesanstalt für Gewässerkunde (Ed.), 2004). For example, the mass extinction of morays in a section of the river Rhein during summer 2003 is attributed to such dispersal of an infectional disease and certain vermin (Bundesanstalt für Gewässerkunde (Ed.), 2004).

At low water levels water temperatures rise faster (BUWAL, 2004). This is important since the entire metabolism of water ecosystems (Dyck and Peschke, 1989) is determined by water temperatures, whereby for water organisms not the longterm average, but the duration of temperature stress is important (BUWAL, 2004). For certain species who are adapted to cool waters, this eventually leads to life-threatening situations (BUWAL, 2004) if water temperatures remain high over a relevant period of time. Moreover, at increased water temperatures the oxygen solubility is reduced (Mc Cutcheon *et al.*, 1992), which has impacts on the biochemical processes in aquatic ecosystems (Dyck and Peschke, 1989). At the same time, the activity of bio organisms increases, thus increasing the demand for oxygen (BUWAL, 2004). These factors combined lead to oxygen-stress and a reduced ingestion in the following (BUWAL, 2004). The critical limit of oxygen in water bodies is 4 mg/l (Bundesanstalt für Gewässerkunde (Ed.), 2004). Below this limit several fish species may be at risk (Bundesanstalt für Gewässerkunde (Ed.), 2004). Another problem at high water temperatures is nitrification: at high pH-values ammonium is turned into ammonia, which is poisonous for fish (Bundesanstalt für Gewässerkunde (Ed.), 2004). However, problems with low oxygen content and chemical water ingredients were seldom observed in summer 2003, which is attributed to the high water quality and the reduced pollution of waste waters (Bundesanstalt für Gewässerkunde (Ed.), 2004).

Low water levels and high water temperatures in aquatic environments also affect human infrastructure and economy: Thermoelectric power plants, for example, rely on the availability of cooling water. Förster and Lilliestam (2010) explain that during heat waves this availability might be limited due to low river discharge and / or high water temperatures. In this context water temperature is important in two ways: (1) warmer water has a reduced cooling capability, and (2) environmental laws limit the temperature of waste water (which has been used for cooling) that is routed back into the river (Förster and Lilliestam, 2010). If not enough cooling water is available at sufficiently low temperatures, thermoelectric power plants have to reduce power production or need or shut down entirely (Förster and Lilliestam, 2010, and references therein).

Low river discharge also affect inland water transportation. For example ships on the river Rhine could only use 20-30% of their load capacity during several phases of the 2003 extreme summer (Undine, 2014).

Water availability, sunlight, and temperature are important climatic constraints to vegetation growth (Nemani *et al.*, 2003). For the extreme heat and drought summer in Europe 2003, Ciais *et al.* (2005) estimated a reduction of net primary production by approximately 30% compared to modelled average values for the time period 1900 - 2003, which was accompanied by a significantly reduced carbon dioxide uptake. The reduction of net primary production during heat and drought events has, of course, impacts on natural ecosystems as well as for forestry and agriculture:

Analysis of tree rings in Bavarian forests showed that the growth of spruce in temperate forests was significantly reduced in the year after the extreme heat and drought summer 1976, and regeneration processes were slow (Utschig *et al.*, 2004). Furthermore, dry and warm conditions can promote vermin populations. For example Lobinger (2004) found that in 2003 the conditions were ideal for the reproduction of beetles. In combination with the weakened trees, which, due to water shortage, were not able to produce enough resinosis to repel insects, this led to massive damage of spruce and larch trees by bark beetles (Lobinger, 2004). Because large populations develop during hot and dry years, the massive bark beetle reproductivity also impacts the following years and can only be pushed back by cold and wet conditions (Lobinger, 2004).

In the agricultural sector the reduced net primary productivity can lead to serious economic losses due to reduced crop growth. However, here the timing of the drought determines which crops are most affected (Ciais *et al.*, 2005). I.e. if dry conditions occur shortly before harvest the damages are not as large as when dry conditions occur at the beginning of the growing season (Ciais *et al.*, 2005). For 2003 the insurance company Munich Re Group (2004) estimated the losses in European crop to 1 billion Euros.

These examples illustrate the damage potential of extreme heat and drought events and the vulnerability of humans, infrastructure as well as natural and anthropogenic environments.

1.2 Motivation

In view of the negative impacts of extreme summer heat and the fact that an increase in frequency and duration of heat waves is "virtually certain" for the 21^{st} century (IPCC, 2013, p. 5), an early warning well in advance to the onset of an exceptionally hot summer would certainly be beneficial. It would allow to better prepare and facilitate precautionary and mitigation measures. For example, rescue services and medical facilities would have more time to prepare for more heat related missions and the implementation of dedicated heat emergency working plans, respectively, and to prepare their staff-management accordingly. Furthermore, disseminating information to the general public on how to prepare to and behave in the event of strong heat is expected to be beneficial (WHO, 2013; Ebi *et al.*, 2004). If it were possible to provide early warnings, more time would be available to prepare and distribute these information.

The extremely hot and dry summer in Europe in 2003 sparked high interest and prompted several studies on the development of heat events. Although some progress has been made, the processes leading to the development of extreme heat events are not yet fully understood and are thus a common subject of recent research.

Several authors agree that both large-scale atmospheric circulation (e.g. Cassou *et al.* 2005; Carril *et al.* 2008) and the interactions between soil moisture and the atmosphere (e.g. Seneviratne *et al.* 2006; Vautard *et al.* 2007; Fischer *et al.* 2007; Hirschi *et al.* 2011; Weisheimer *et al.* 2011; Quesada *et al.* 2012) are important factors in the development of strong summer heat events in Europe.

The importance of soil-moisture deficits prior to the summer months for the development of heat waves in Europe has been pointed out by Fischer *et al.* (2007) based on model experiments and by Hirschi *et al.* (2011) and Quesada *et al.* (2012) based on observations. It has been shown that dry soils favor the occurence of hot days, although not all dry winter - spring transition seasons are followed by hot summers (Quesada *et al.*, 2012; Hirschi *et al.*, 2011). Accordingly, the physics of seasonal forecast models, such as the European Center of Medium Range Forecast (ECMWF) forecasting system S3, have improved with regards to soil-moisture - atmosphere interactions (Weisheimer *et al.*, 2011). However, the seasonal prediction skill for European summers remains poor (Quesada *et al.*, 2012). One reason for this might be the regionally varying strength of the relationship between dry soils and hot days: while models seem to capture this relationship for southern Europe well, it seems to be overemphasized for Central Europe (Hirschi *et al.*, 2011). This in turn might have its origin in the different factors constraining evapotranspiration in the different regions: in southeastern Europe evapotranspiration is limited by soil-moisture, whereas in Central Europe evapotranspiration is limited by energy (Teuling *et al.*, 2009, in Hirschi *et al.* 2011), i.e. solar irradiation. Thus, further observation based analysis of hot summers in different parts of Europe are important to better understanding their development.

However, the occurrence of dry soils alone does not lead to an extremely hot and dry summer. The occurrenc of specific atmospheric circulation regimes is the prerequisite for the development of extreme heat and drought events in Europe (Hirschi *et al.*, 2011; Quesada *et al.*, 2012). Research on the influence of atmospheric circulation on the development of heat waves has generally revealed that a dominance of anticyclonic pressure systems and atmospheric blockings of the westerlies, respectively, are associated with heat events in Europe (Cassou *et al.*, 2005; Della-Marta *et al.*, 2007). However, these studies correlate summer heat events with atmospheric pressure patterns occuring simultaneously. To the knowledge of the author of this thesis, none of the studies found a characteristic pattern in the atmospheric circulation in the winter - spring transition season preceding extremely hot summers in Europe.

The study presented in this thesis focuses on the analysis of hot and dry summers in Central Europe regarding atmospheric circulation patterns as well as land surface - atmosphere interactions in the winter - spring transition season prior to the extreme events.

1.3 Aim and Scope

The analysis of extreme summers is closely linked to the question how extreme summers are defined. For heat waves Robinson (2001) proposed a set of definitions, but there is no commonly agreed defintion (e.g. Meehl and Tebaldi 2004). Most authors define heat waves with an air temperature anomaly threshold, exceeded over a certain number of successive days (e.g. Robinson 2001; Cassou *et al.* 2005; Della-Marta *et al.* 2007; Vautard *et al.* 2007; Carril *et al.* 2008; Hirschi *et al.* 2011; Quesada *et al.* 2012). However, both the temperature anomaly thresholds and the number of days on which the threshold must be exceeded vary among the studies. The focus of this work is not on single heat waves, but on extreme heat and drought events on a seasonal scale.

The aim of this thesis is to identify potential precursor of highly extreme hot and dry summers in Central Europe regarding both large-scale atmospheric circulation, as well as land surface - atmosphere interactions. For this purpose, the relation of extremely hot and dry summers (June - July - August, JJA) and their preceding winter - spring transition season (February - March - April, FMA) is analysed for the study area Central Europe, (47°N - 56°N; 4°E - 15°E, i.e. Germany and adjacent regions), using solar irradiation and precipitation as central proxies. The geopotential at 850 hPa height is analysed over the northern hemisphere in order to identify potential characteristic patterns in the large-scale atmospheric circulation prior to the extreme summers.

Consequently, the hypothesis to be tested in this thesis are as follows:

- **H1** Extremely hot (and thus sunny) and dry summers in Central Europe are preceded by winter - spring transitions with positive anomalies in solar irradiation and negative anomalies in precipitation.
- **H2** Extremely hot (and thus sunny) and dry summers in Central Europe are preceded by characteristic atmospheric pressure patterns determining the excess of solar irradiation and the deficit of precipitation in the prior winter - spring transition season.

In testing these hypothesis, the study contributes to an improved understanding of the development of extremely hot and dry summers in Central Europe regarding the interplay of large-scale atmospheric circulation and land surface - atmosphere interactions. The analysis and the results of this work are expected to contribute to the improvement of the predictability of extreme summers.

Chapter 2

Data, Structure and Outline

This section briefly describes the data used in the study to analyse the extreme summers and their development. It also outlines the following chapters of the thesis and the structure of the study.

2.1 Data

As outlined in section 1.2 the occurrence of specific atmospheric circulation regimes is the prerequisite for the development of extreme summers and land surface - atmosphere interactions increase the probability of their development. The variables solar irradiation and precipitation are determined by the atmospheric circulation and also influence the atmospheric circulation via land surface - atmosphere interactions. Furthermore, solar irradiation and summer surface temperatures in Europe are closely related (Makowski *et al.*, 2009). The development of hot and dry summers is thus closely related to the amount of solar irradiation and precipitation. Consequently, this study focuses on these two variables as central proxies to define and analyse extreme summers and their development. To determine the corresponding atmospheric circulation regimes, that are finally responsible for the amount of solar irradiation and precipitation, the geopotential in 850 hPa is analysed.

An overview of the data sets used in this thesis is given in table 2.1. Two high quality, widely available data sets on geopotential and precipitation were used: re-analysis data from the European Center of Medium Range Weather Forecast (ECMWF) and data from the Global Precipitation Climatology Center (GPCC).

Re-analysis data describe the status of the atmosphere and relevant land surface variables (such as skin temperature and soil moisture) from the past using quality controlled input data. The assimilation system and the global forecast models used

Table 2.1: Overview of data sets used in this thesis. For abbreviations refer to the list of acronyms and for further details refer to section 2.1, chapter 3 (solar irradiation) and chapter 4 (solar irradiation, precipitation, geopotential).

Variable	Data set	Time period used	Reference
solar-irradiation	ERA-40	Jan 1958 - Dec 1982; Dec 1988	Kållberg et al. 2005
	MAGICSOL	Jan 1983 - Nov 1988; Jan 1989 - Dec 2005	Posselt et al., 2011; Hammer et al., 2003
	ERA-interim	Jan 2006 - Dec 2006	Dee and Upala, 2009
	operational data from CM SAF	Dec 2007 - Jan 2011	Müller et al., 2009; Posselt et al., 2009
precipitation	GPCC	Jan 1958 - Aug 2011	Schneider et al., 2014
geopotential	ERA-40	Jan 1958 - Dec 1978	Kållberg et al. 2005
	ERA-interim	Jan 1979 - Aug 2011	Dee and Upala, 2009

to calculate the hindcasts are improved compared to models contemporary with the observations, and they are stable, i.e. they experience no changes. The results of re-analysis can thus be regarded as the best integrated, consistent representation of the state of the atmosphere of the past. The re-analysis data over the longest time period provided by ECMWF are the 40-year re-analysis (ERA-40) described in Kållberg *et al.* (2005) and Uppala *et al.* (2005), and the interim re-analysis (ERA-interim) described in Berrisford *et al.* (2009) and Dee *et al.* (2011). The geopotential data set used in this thesis is composed of ERA-40 (1958 - 1988) and ERA-interim (1989 - 2011) data.

The precipitation data set of the GPCC has the largest number of quality controlled inputs from in situ measurements compared with other gridded and station based precipitation data sets (Schneider *et al.*, 2014), and is thus expected to be the most accurate precipitation data set currently available over land.

A variety of data sets on solar irradiation are available, each with different quality. The MAGICSOL [2] data set based on measurements of the visible channel of the MVIRI sensor on METEOSAT first generation satellites is well suited for the purpose of this study. However, the MAGICSOL data set is restricted to the availability of MVIRI data and thus only covers the years 1982 - 2005. Hence for a proper analysis this datset would need to be extended using data from other sources, such as re-analysis. An evaluation of the solar irradiation data set is subject to work package 1. The work package of this thesis are outlined in the following section.

[2]due to historical reason this data set is called Heliosat in chapter 3

2.2 Structure and Outline

The structure of this thesis and the flow of work packages, as described in the following, is shown schematically in figure 2.1.

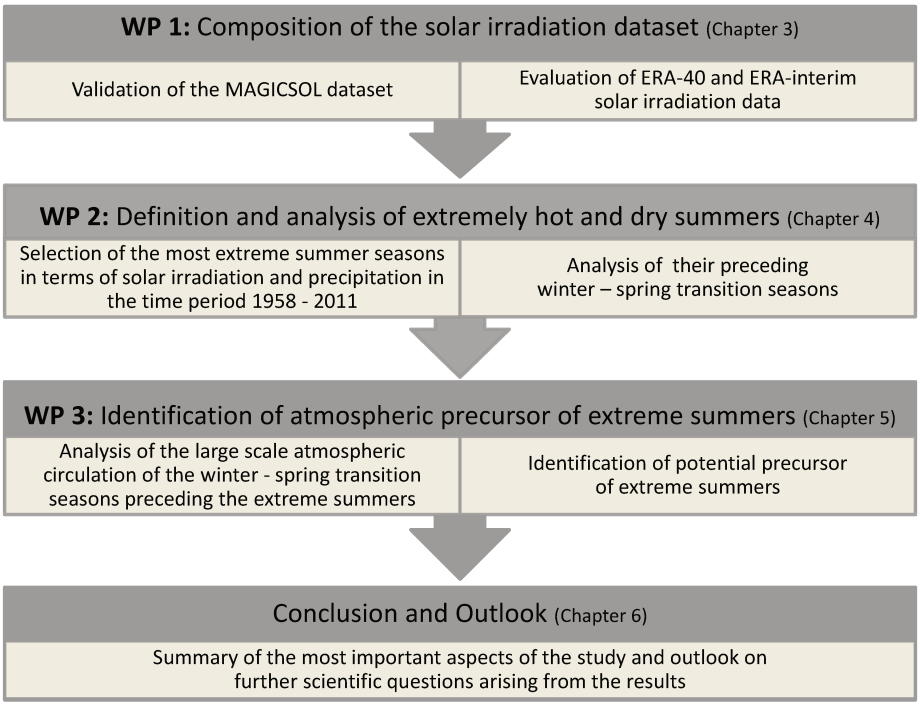

Figure 2.1: Structure of this thesis

In this thesis solar irradiation and precipitation are used as a measure for extremely hot and dry summers (see section 2.1). For precipitation a well established long term data set of high quality exists, but for solar irradiation the situation differs. Hence, **H1** (see section 1.3) was tested in two steps:

- in work package 1 (**WP 1**) data sets of solar irradiation were evaluated to decide which data set is best suited for the analysis.
- in work package 2 (**WP 2**) the extreme summers were defined and analysed together with their preceding winter - spring transition seasons.

These two work packages are outlined in the following.

WP 1: In chapter 3, the MAGICSOL data set is validated against in situ solar irradiation measurements with very good results. Hence it can be used for the evaluation of re-analysis based data in order to find the optimal data set to prolongate the time series. A series of solar irradiation data sets from re-analysis were available at the time work on this thesis began. However, all but ERA-40 and ERA-interim showed restrictions which prevented them from being used in the study presented here: The accuracy of NCEP / NCAR solar irradiation data is not sufficient on the regional scale (Babst *et al.*, 2008), the NCEP 20^{th} century re-analysis was not available at the time the study started, and the Modern Era Re-analysis for Research and Applications (MERRA) does not provide the temporal coverage necessary for this study. Consequently ERA-40 and ERA-interim are the only re-analysis data sets in question to complemente the MAGICSOL datset. Thus, the main aspect of chapter 3 is the evaluation of the ERA-40 and ERA-interim solar irradiation data sets with regards to their suitability for the analysis of extreme summers in Central Europe, using the MAGICSOL data set as reference.

WP 2: In a second step, extremely hot and dry summers (JJA) in Central Europe are defined and selected according to the anomalies of solar irradiation and precipitation. The selected events were analysed with an emphasis on the preceeding winter - spring transition season February - March - April (FMA) in order to gain more insights into the early stages of the development of such extreme events. Thus, chapter 4 also addresses the question if a large excess of solar irradiation and a large deficit of precipitation in the winter - spring transition season might be a proxy for the approach of an extreme summer. If so, it would be possible to use information on the amount of solar irradiation and precipitation of the winter - spring transition season as a predictor for extremely sunny (and thus hot (Makowski *et al.*, 2009)) and dry summer seasons in Central Europe.

Indeed, two out of three highly extreme summers (upper 10^{th} percentile, see chapter 4 for definition) in the study area and time period analysed were preceeded by winter - spring transition seasons with extremely positive anomalies in solar irradiation and extremely negative anomalies in precipitation. One extreme summer was not preconditioned in the preceeding winter - spring transition season and one winter - spring transition season with precondition characteristics (high solar irradiation and low precipitation) was followed by a normal sunny and a rather wet summer. Extremely strong ENSO events preceded both of these years during the winter season. The potential influence of ENSO on the development of extreme summer seasons in Central Europe is highlighted in chapter 4 and discussed in more detail in chapter 5.

The second hypothesis [H2] (see section 1.3) was tested in work package 3 (**WP 3**): The phenomena presented in chapter 4 must have their origin in the large-scale atmospheric circulation. Often the North Atlantic Oscillation (NAO) and the Atlantic Oscillation (AO) are mentioned as important factors for the weather in Europe (e.g. (Walker and Bliss, 1932; Barnston and Livezey, 1987; Ionita *et al.*, 2012)). These oscillation patterns are important for the winter season in Europe, but seem to be less important for the summer conditions (Behera *et al.*, 2013, and references therein). However, Wang *et al.* 2011 and Ogi *et al.* 2003, 2004a suggest that the NAO may influence the European summer season indirectly by influencing winter conditions, which in turn have effects on the summer conditions, for example via winter precipitation that influences soil-moisture and thus the land surface - atmosphere interactions (Wang *et al.*, 2011). The latter are one of the important triggers of heat waves, as outlined above (see section 1.2) and discussed in chapter 4. Both NAO and AO are therefor analysed in chapter 5 with regard to their potential impact on the development of extremely hot and dry summers. However, the results lead to the conclusion that NAO and AO are not connected with extremely hot and dry summers in Central Europe. But the analysis of geopotential height anomalies revealed a characteristic pattern that occurs during the winter - spring transition season prior to the extreme summers. This led to the definition of a novel index, the Greenland - North Sea - Dipole index, defined and discussed in chapter 5.

Within this scope the effects of El Niño Southern Oscillation (ENSO) on the development of extreme summers in Central Europe are discussed in more detail. This leads to a further novel index, the Central European Drought Index (CEDI). This index is dedicated to reflect the coupling of the synoptic scale circulation, expressed by the GNDI, with the global scale circulation, expressed by ENSO. It is expected that the CEDI contributes to the improvement of the predictability of extremely hot and dry summers, and hence to an ealry warning system for central Europe.

Chapter 6 summarises the most important aspects of this thesis and provides an overview on further scientific questions arising from the findings presented.

Chapter 3

Evaluation of ERA-40 and ERA-interim re-analysis incoming surface shortwave radiation data sets with mesoscale remote sensing data

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Evaluation of ERA-40 and ERA-Interim Re-analysis Incoming Surface Shortwave Radiation data sets with Mesoscale Remote Sensing Data

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Abstract

In this paper an evaluation of the European Center for Medium Range Weather Forecasting 40-year re-analysis (ERA-40) and interim re-analysis (ERA-Interim) solar irradiation data sets is presented. The goal of the study is to evaluate the accuracy of the downward solar surface radiation fluxes of ERA-40 and ERA-Interim. A positive result of these examinations would justify the use of ERA-40 and ERA-Interim, respectively, to investigate long-term changes of anomaly patterns. Unlike other recent studies that operate on a global scale, this study concentrates on regional aspects of climate research. As reference, high-resolution remote sensing data derived from METEOSAT using the Heliosat method are used. The study area covers Germany and adjacent countries. Structures were found which indicate that ERA-40 does not properly represent cloud and fog occurrence. Especially during the solar season May, June, July (MJJ) large deviations of up to 40 and 60 W/m^2, respectively, compared to the reference data set were found. During the solar seasons of August, September, October (ASO) and November, December, January (NDJ) the deviations are negligible for both re-analysis data sets as well as for ERA-40 during the season of February, March, April (FMA). The results lead to the conclusion that in and around Germany, the accuracy of the parameter surface solar irradiation downward (ssrd) of ERA-40 and ERA-Interim re-analysis is limited, especially during the season of MJJ and in ERA-Interim also during the season of FMA.

Zusammenfassung

In diesem Artikel wird eine Evaluierung des Datensatzes der bodennahen Globalstrahlung aus der 40-jährigen Re-analyse (ERA-40) und der Interim Re-Analyse (ERA-Interim) des Europäischen Zentrums für Mittelfristige Wettervorhersage vorgestellt. Ziel der Studie ist es, die Genauigkeit der am Erdboden einfallenden Solarstrahlung der ERA-40 und ERA-Interim Datensätze zu bewerten. Die Ergebnisse dieser Untersuchungen ermöglichen es, die Qualität der entsprechenden Strahlungs-Datensätze aus ERA-40 und ERA-Interim zum Monitoring und der Analyse von zeitlichen und räumlichen Änderungen von Anomalien zu bewerten. Im Gegensatz zu anderen aktuellen Studien, in denen ähnliche Vergleiche auf der globalen Skala durchgeführt wurden, konzentriert sich die vorliegende Studie auf regionale Aspekte. Als Referenz werden räumlich hoch aufgelöste Fernerkundungsdaten des europäischen Wettersatelliten METEOSAT, abgeleitet mithilfe der Heliosat Methode, verwendet. Das Untersuchungsgebiet deckt Deutschland und angrenzende Länder ab. Es wurden Strukturen gefunden, die darauf hindeuten, dass ERA-40 das Auftreten von Wolken und Nebel nicht korrekt repräsentiert. Insbesondere in den Monaten mit der höchsten solaren Einstrahlung Mai, Juni, Juli (MJJ) (solarer Sommer) treten im Vergleich zum verwendeten Referenzdatensatz große Abweichungen von bis zu 40 bzw. 60 W/m^2 auf. Während der solaren Jahreszeiten Herbst und Winter, August, September, Oktober (ASO) und November, Dezember, Januar (NDJ), sind die Abweichungen für beide untersuchten Reanalyse Datensätze vernachlässigbar, für ERA-40 sind die Abweichungen auch in den Monaten Februar, März, April (FMA) vernachlässigbar. Die Ergebnisse führen zu dem Schluss, dass die Genauigkeit der Globalstrahlung am Erdboden aus ERA-40 und ERA-Interim in und um Deutschland noch verbessert werden muss und die ERA Strahlungsdaten für die Ableitung und das Monitoring von Anomalien noch signifikante Fehler aufweisen. Dies gilt für beide Datensätze während der Jahreszeit MJJ und für ERA-Interim auch für die Jahreszeit FMA.

3.1 Introduction

Radiation is the driving force for all atmospheric processes and its interaction with various media controls the energy distribution on Earth. The fact that GCOS (Global Climate Observing System) defined the radiation budget as an essential climate variable confirms its indispensability for climate monitoring GCOS (2009). Solar irradiance is the driving factor for the global wind systems, its anomalies causes droughts, heat waves and anomalies in evaporation.

The evaluation of the accuracy of solar irradiance in re-analysis data is therefore essential to investigate the performance of the re-analysis data for climate monitoring and climate analysis tasks. Re-analysis data is based on general circulation model output. In this context results of evaluation studies are also important for the improvement of current GCMs. This study aims at providing an estimate on the quality of ERA-40 / ERA-Interim SIS data with regard to regional climate studies in Germany and adjacent countries.

Recent publications such as Yang *et al.* (1999) and Allan *et al.* (2004) determine the differences between several re-analysis data sets in their ability to show anomalies in various climate parameters on a global scale. Yang *et al.* (1999) evaluated outgoing longwave radiation and reflected solar radiation of the NCEP-NCAR reanalysis to top-of-the-atmosphere measurements from the Earth Radiation Budget Experiment (ERBE) on the global scale. They found generally good agreements in the global annual mean of the outgoing longwave radiation as well as for the clear-sky reflected solar radiation. However, regions with "significant systematic biases" (Yang *et al.*, 1999, p.49) were identified for the outgoing longwave radiation as well as overestimations of total sky reflected solar radiation, indicating that the global energy budget in the NCEP-NCAR re- analysis is not balanced. Yang *et al.* (1999) assume that the latter might be due to "[...] shortcomings in the cloud/moisture parameterizations of the re-analysis GDAS [Global data assimilation system]" (Yang *et al.*, 1999, p. 490f). Allan *et al.* (2004) found that ERA-40 underestimates "clear-sky absorbed solar irradiation" compared to ScaRaB (Scanner for Radiation Budget). Markovic *et al.* (2009) found that the annual cycle of the incoming solar radiation over North-America is very well represented by ERA-40, compared to SURFRAD (US surface radiation network) measurements. Averaged over six SURFRAD sites the incoming solar radiation budget ERA-40 generally has a bias of less than +/- 10 W/m^2. However, Markovic *et al.* (2009) also found that ERA-40 has a tendency to underestimate very low values of solar incoming radiation during winter and suggest that this might be due to an underestimation of the reflectivity of optically thick clouds during winter in ERA-40.

This study supplements the above-mentioned publications by presenting a regional evaluation for Central Europe of the ERA-40 and ERA-Interim re-analysis concentrating on radiation data sets with validated high-resolution remote sensing data briefly described in section 3.2.1.

High-resolution remote sensing data is particularly useful as a reference since the direct comparison of re-analysis data with ground-based data suffer from the large differences between the points of measurements which leads to inaccuracies due to interpolation errors. On the other hand the high spatial resolution of satellite data (here METEOSAT First Generation) allows an appropriate validation using observed surface data as a reference. Once validated and regridded, the remote sensing data serve as a reliable reference for the evaluation of re-analysis data within a larger area.

Our comparisons concentrate on the solar incoming surface irradiance (SIS) covering the area 47° N - 56° N, 4° E - 15° E. This region is a transition zone between maritime and continental climate conditions, which is well suited for climate monitoring of changes on the synoptic scale (Bissolli and Dittmann, 2001, and references therein).

The data used in the present study are briefly described in section 3.2. The results of the evaluation are presented in section 3.3, and in section 3.4 a final discussion and conclusion is provided.

3.2 Data

3.2.1 ERA-40 data set

From the European Center for Medium Range Weather Forecast (ECMWF) 40-year re-analysis (ERA-40) the parameter surface solar radiation downward (ssrd) from the data stream monthly means of daily forecast accumulations (mdfa) 12 - 24 h is used. These are the monthly means based on two successive 12 to 24 h forecasts. The data are available from the ECMWF homepage (`www.ecmwf.int/services/archive/`) and are described in Kållberg *et al.* (2005) and Uppala *et al.* (2005). The mdfa ssrd data have an approximate horizontal resolution of 125 km for surface fields (Kållberg *et al.*, 2005). However, via the online archive they are only provided on a 0.25° X 0.25° grid. In the following the ERA-40 mdfa ssrd data set will be referred to as ERA-40 SIS (solar incoming radiation at the surface) data.

3.2.2 ERA-Interim data set

ERA-Interim is the current re-analysis project of ECMWF aimed to improve the ERA-40 re-analysis data set. It covers the period from 1989 to present and is updated monthly (Dee and Uppala, 2009). The parameter surface solar radiation downward (ssrd) from the data stream monthly means of daily forecast accumulations (mdfa) 12 - 24 h in the grid resolution of 0.25° X 0.25° was downloaded from (`www.ecmwf.int/services/archive/`). Just as the ERA-40 data described above, also the ERA-Interim data used are monthly means based on two successive 12 to 24 h forecasts. In the following the ERA-Interim ssrd data will be referred to as ERA-Interim SIS data.

Table 3.1: Comparison of Heliosat SIS to SIS measured at BSRN stations accross Europe. MAB is the Mean Absolute Bias of the difference in the monthly means.

BSRN Station	Lat	Lon	Analyzed Months	Mean Bias (Wm^{-2})	MAB (deviation) (Wm^{-2})	Frac. Months > 15 Wm^{-2} (%)
Lindenberg	52.21	14.12	101	−5.4	6.98	8.9
Payerne	46.82	6.94	132	−1.8	7.79	12.9
Camborne	50.22	4.93	60	−1.0	6.50	10.0
Carpentras	44.08	5.06	112	−3.4	5.46	3.6
Lerwick	60.13	−1.18	59	8.8	9.23	27.1
Toravere	58.25	26.46	60	−0.8	4.79	10.0
Palaiseu-Cedex	48.71	2.21	3	2.1	2.12	0.0

Table 3.2: Validation results of monthly means of different SIS data sets based on measurements at the BSRN stations Lerwick, Toravere, Lindenberg, Cabauw, Camborne, Palaiseu Cedex, and Carpentras.

Data set	Analyzed Months	Mean Bias (Wm^{-2})	MAB(deviation) (Wm^{-2})	Frac. Months > 15 Wm^{-2} (%)
ERA-Interim	832	5.2	8.76	17.5
GEWEX	710	−0.61	8.96	19.0
ISCCP	736	−2.6	8.68	17.8
Heliosat	538	−1.5	6.73	10.4

3.2.3 Reference data: Heliosat

The reference data set of the surface incoming solar radiation used here is based on data from the MVIRI (METEOSAT Visible and Infrared Imager) instrument on board the METEOSAT First Generation (MFG) satellites. The Heliosat algorithm is used to retrieve SIS. In a first step, the Heliosat method retrieves the instantaneous cloud albedo (sometimes called cloud index) for each satellite pixel based on a statistical evaluation of the reflectivities in the solar satellite channel. First the METEOSAT images are normalized with respect to the solar zenith angle. To this end a relative reflectivity ρ is introduced:

$$\rho = \frac{C - C_0}{cos(SZA)} \tag{3.1}$$

where SZA is the solar zenith angle, C are the counts detected by the satellite and C_0 is the dark offset of the satellite instrument. The cloud index n is calculated based on the relative reflectivities from equation 3.1, using the following equation:

$$n = \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}} \tag{3.2}$$

ρ_{min} corresponds to the clear-sky planetary reflectance, corrected for Rayleigh backscattering. Maps of the planetary clear-sky reflectance are computed on a monthly basis by a statistical analysis of the darkest pixels. The monthly calculation is done to account for seasonal variations of the ground reflectance. ρ_{min} in equation 3.2 is used to distinguish the effect of the clear-sky reflectance from that of the clouds. The maximum reflectivity ρ_{max} is computed separately for each satellite radiometer (the 95th percentile of all pixels) to account for differences in the sensor properties in the different METEOSAT satellites (Hammer, 2001). Within this Heliosat version ρ_{max} is calculated for the complete disk. ρ_{max} changes slightly with time as a consequence of satellite instrument aging, but this had been taken into account. ρ_{max} acts as calibration parameter in equation 3.2. The typical range of the cloud index is between 0 for cloud free and 1 for overcast conditions. However, due to the statistical approach slightly lower and higher values might occur for instantaneous pixels. The cloud index describes the fraction of irradiance reflected by clouds. Using a clear-sky model the solar surface irradiance can be calculated using equation 3.3. This relation can be derived from the law of energy conservation

$$G = (1 - n) * G_{clear} \tag{3.3}$$

and is slightly modified empirically for cloud index values higher than 0.8. Equation 3.3 is applied to derive the solar surface irradiance for all-sky G using G_{clear} the solar surface irradiance for clear-sky. More detailed information on the Heliosat method, including a description of the applied clear-sky model radiation components can be found in Hammer *et al.* (2003).

A 10-year (1995 - 2005) homogeneous time series of monthly mean values based on Heliosat has been calculated. These satellite data are provided on full MVIRI resolution (i.e. approximately 3 X 5 km for Central Europe) and have been regridded to a 0.05° X 0.05° grid, using the nearest neighbor approach.

Heliosat is well validated in the region investigated and it is also of good quality compared to other SIS data sets. Detailed validation results for Heliosat SIS are presented in table 3.1, table 3.2 shows validation results for different data sets of SIS. Stations of the Baseline Surface Radiation Network (BSRN) (Ohmura *et al.*, 1998) were used as reference. The Heliosat data set used here is available over Europe, thus only seven BSRN stations available across Europe were used for evaluation. The values presented in table 3.1 and table 3.2 are defined as follows:

$$MeanBias = \frac{\sum_{i=1}^{n}(\overline{SIS}_{DataSet(i)} - \overline{SIS}_{BSRN(i)})}{n} \quad (3.4)$$

$$MeanAbs.Bias(deviation) = \frac{\sum_{i=1}^{n}(|\overline{SIS}_{DataSet(i)} - \overline{SIS}_{BSRN(i)}|)}{n} \quad (3.5)$$

with

$\overline{SIS}_{DataSet(i)}$: Monthly Mean of SIS derived from respective data set
$\overline{SIS}_{BSRN(i)}$: Monthly Mean of SIS measured at respective BSRN station
n: number of months available for evaluation

Note: The mean bias can be misleading since negative and positive deviations can eliminate each other. Thus, the Mean Abs.Bias (deviation) is the more meaningful parameter.

The last column in the tables named "fraction of month > 15 W/m^2" gives the fraction of the number of months analysed in which the difference between the monthly mean measured at the BSRN station and the respective data set is above 15 W/m^2. The GCOS accuracy requirement for climate monitoring of SIS is 10 W/m^2 (GCOS, 2009). To account for measurement errors in the BSRN data (estimated to be 15 W/m^2 (Ohmura *et al.*, 1998)) this criterion was relaxed to 15 W/m^2 in the present study.

At most stations, there is a small negative bias for Heliosat SIS (table 3.1). When only the months with the maximum solar radiation (May to July) are considered the mean bias is - 9.6 W/m^2. One exception is the station of Lerwick, Shetland Islands, where the Heliosat-derived surface radiation exceeds the BSRN measurement by 15.9 W/m^2. The mean bias at all stations for the monthly mean values between November and January is 2.9 W/m^2, i.e. Heliosat slightly overestimates the surface radiation. However, compared to the other data sets evaluated, Heliosat has the lowest Mean Abs. Bias (deviation) and the lowest fraction of months that exceed the GCOS accuracy requirement (table 3.2). The Mean Abs. Bias (deviation) of the Heliosat data is below 10 W/m^2 for all stations. Comparably good results were found by Drews *et al.* (2008), Beyer *et al.* (2006) and Drews (2007).

Table 3.2 shows validation results for different data sets of SIS. ERA-Interim (Berrisford *et al.*, 2009), GEWEX (Global Energy and Water Cycle Experiment version 3.0) (Gupta *et al.*, 2006) and ISCCP (International Satellite Cloud Climatology Project, data downloaded from `$http://isccp.giss.nasa.gov/$` in August 2009) (Zhang *et al.*, 2004) are global datasets. For consistency reasons the same stations as in table 3.1 were used for evaluation. Also compared to other SIS data sets, Heliosat performs well: it shows the least Mean Abs. Bias (deviation) as well as the least fraction of months with a deviation of $> 15\ W/m^2$ to the BSRN measurements.

It is well known that Heliosat-retrieved SIS is limited in the Alps. This is due to the general limitation to properly separate snow and clouds in satellite data with limited spectral resolution and due to a lack of topography corrections of satellite data necessary in heterogenous terrain. To overcome this shortcoming, the enhanced Heliosat version for the alpine region has been developed Dürr and Zelenka (2009). The results of this enhanced Heliosat version are promising. However, there is some overlap between the enhanced Heliosat version and the time period covered by ERA-interim but no data are yet available for the time period covered by ERA-40. Thus, the region of the Alps has been neglected in this study.

3.3 Evaluation of ERA-40 and ERA-Interim data

The overlapping time period between the 10-year Heliosat data set (1995 - 2005) and the ERA-40 / ERA-Interim data is January 1995 - August 2002 and January 1995 - December 2005, respectively. To analyse the differences between Heliosat and the re-analysis data sets we define solar seasons. In contrast to the meteorological seasons the solar seasons take into account the change of solar radiation over the course of a year. Hence, solar summer is defined as May, June, and July (MJJ), solar winter as November, December, and January (NDJ), solar spring and solar fall correspondingly. With these definitions, spatial features in the data sets are better visible. To compare the same number of years for each season, the comparison of Heliosat and ERA-40 was done for the 7-year seasonal means of the period February 1995 - January 2002 and the comparison of Heliosat and ERA-Interim was done for the 10-year seasonal means of the period February 1995 - January 2005. Since the Heliosat data have a higher spatial resolution than the ERA-40 and ERA-Interim data, all calculations were done on a 0.25° X 0.25° grid, the grid-resolution at which ERA-40 and ERA-Interim data were downloaded from the ECMWF archive. The remapping of the Heliosat data was done using the conservative remapping method described by Jones (2009).

As shown in section 3.2.3, the Heliosat data are regarded as reliable for the region under consideration and were thus used as reference data set to evaluate SIS of ERA-40 and ERA-Interim.

The results are presented and discussed in the following:

Figure 3.1 presents the differences between ERA-40 SIS and Heliosat SIS for the four solar seasons. In FMA (February, March, April) and NDJ (November, December, January) the deviations are within the uncertainties of the Heliosat

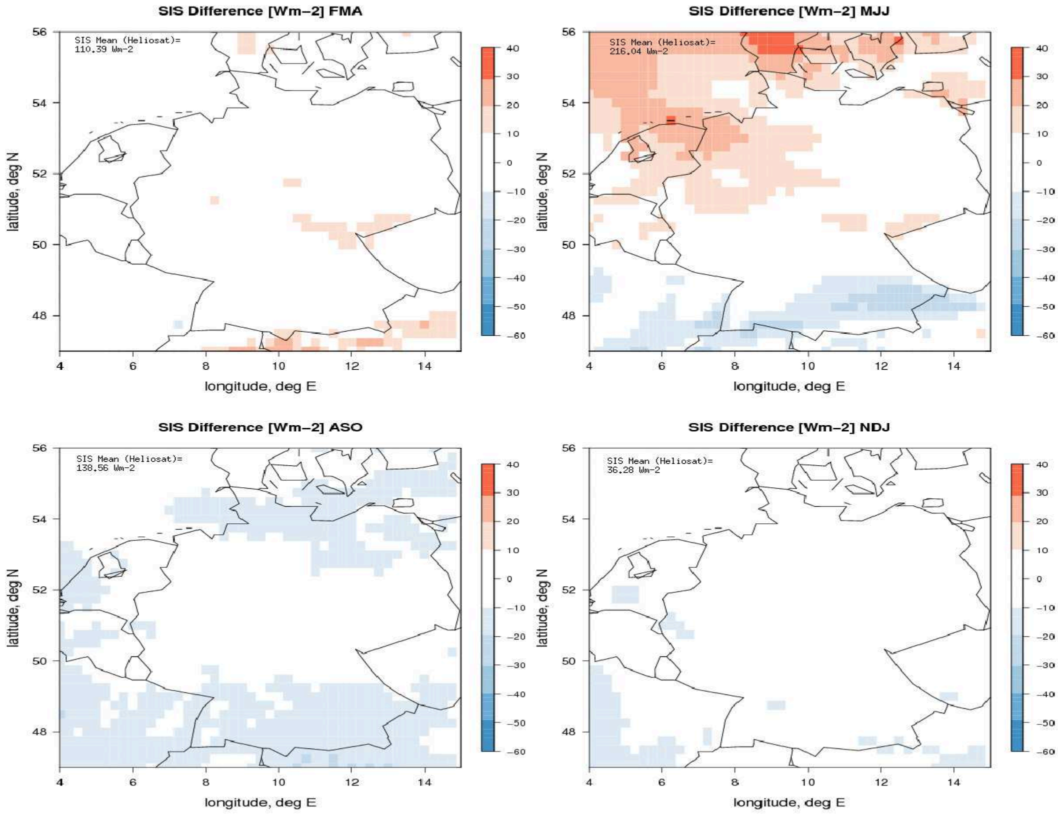

Figure 3.1: Comparison of ERA-40 SIS and Heliosat SIS. Difference of 7-year seasonal means (ERA-40 - Heliosat) for February, March, April (FMA), May, June, July (MJJ), August, September, October (ASO), and November, December, January (NDJ). Positive deviations (red) indicate that ERA-40 overestimates SIS. Negative deviations (blue) indicate that ERA-40 underestimates SIS.

SIS data (mostly below 10 W/m^2), whereas in MJJ (May, June, July) deviations of up to 40 W/m^2 are reached. The seasonal mean differences in ASO (August, September, October) range between -10 and -20 W/m^2 in extended regions.

Interesting regional features can be observed in the deviations between ERA-40 and Heliosat in the seasonal mean of MJJ. A dipole structure is observed in the study area: ERA-40 overestimates SIS in the northwest of the study area, e.g. in the Netherlands, in Denmark and over the North-Sea. In contrast SIS is underestimated by ERA-40 in the Danube valley. This dipole structure might be related to the pattern of the cloud albedo, which is higher in the North than in the South: In regions with low cloud indices, such as the Danube valley or the upper Rhine valley, ERA-40 overestimates SIS compared to Heliosat. In regions

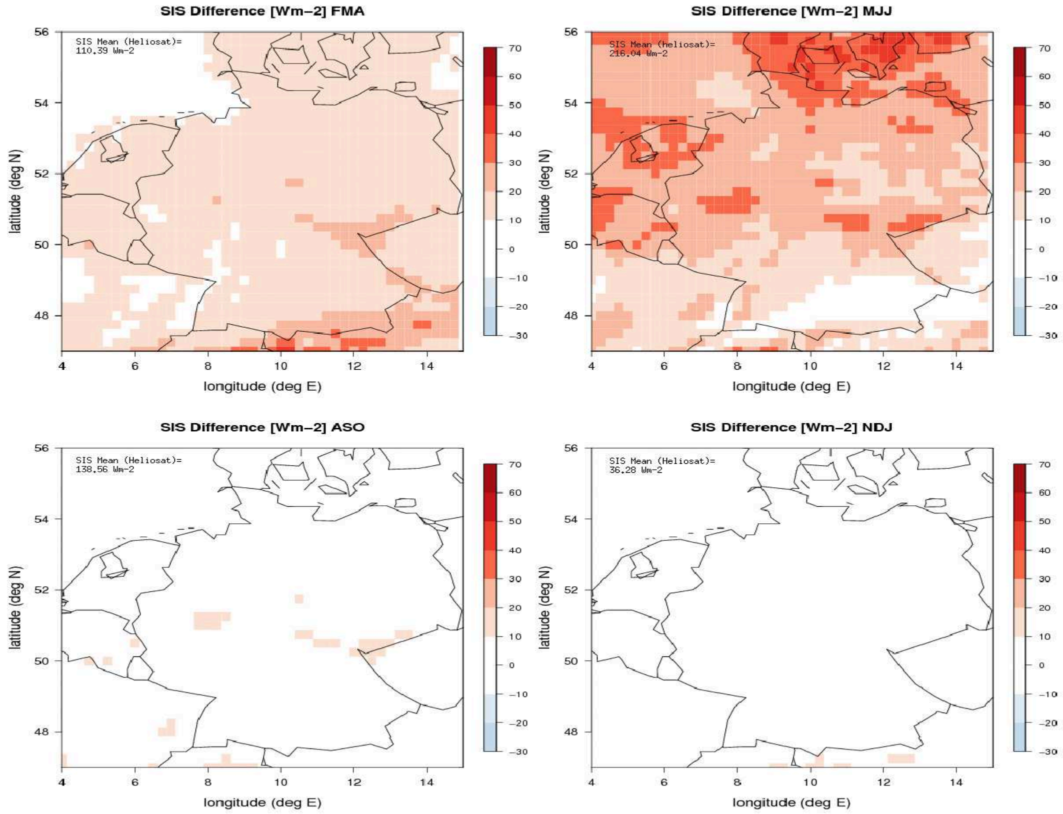

Figure 3.2: Comparison of ERA-Interim SIS and Heliosat SIS. Difference of 10-year seasonal means (ERA-Interim - Heliosat) for February, March, April (FMA), May, June, July (MJJ), August, September, October (ASO), and November, December, January (NDJ). Positive deviations (red) indicate that ERA-40 overestimates SIS. Negative deviations (blue) indicate that ERA-40 underestimates SIS.

with higher cloud indices the deviations between ERA-40 and Heliosat are below 10 W/m^2. However, it seems that generally over water (North Sea) the deviations are larger than over land (except Denmark) (figure 3.3).

During ASO the deviations between ERA-40 and Heliosat indicate a slight underestimation of SIS by ERA-40.

In figure 3.2 the differences between ERA-Interim and Heliosat are presented. ERA-Interim overestimates SIS compared to Heliosat in FMA and MJJ. In FMA the deviations are between 10 and 20 W/m^2 throughout most of the study area. Compared to ERA-40, ERA-Interim lost quality during FMA when using Heliosat SIS as reference. Again, a dipole structure is visible in MJJ. Here, the deviations in the north of the study area reach values of up to 40 - 50 W/m^2. As in the

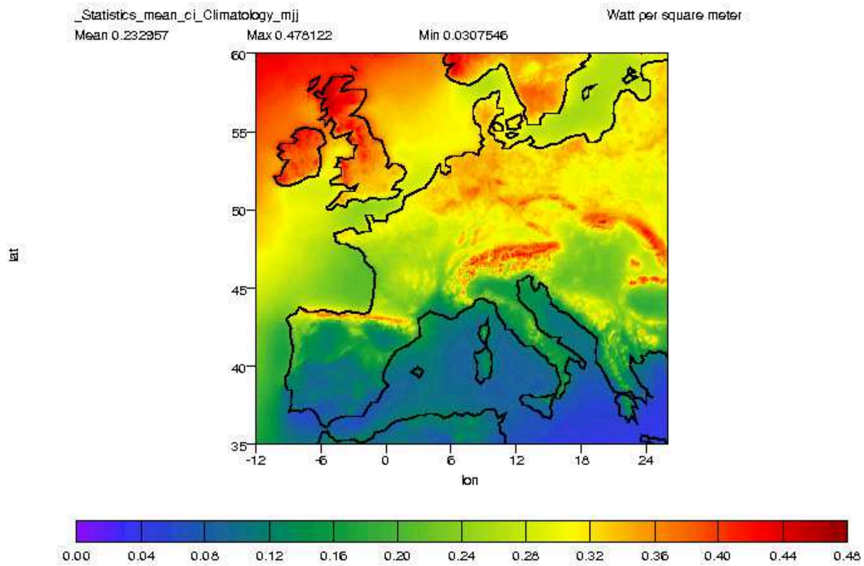

Figure 3.3: 11-year (1995 - 2005) seasonal mean of May, June, July of cloud index as retrieved by Heliosat.

deviations between ERA-40 and Heliosat the feature of the Danube valley is also visible, but the deviations here are not larger than 10 W/m^2. Generally speaking higher deviations correspond to areas with a relatively high cloud index (such as Denmark, the northern half of Germany and BeNeLux), whereas the lower deviations occur in regions with lower cloud indices (such as the Danube valley). The deviations in ASO and NDJ are mainly below 10 W/m^2 and thus within the uncertainty of the Heliosat data.

3.4 Discussion and Conclusion

The ERA-40 re-analysis project offers a time series of more than 40 years, which principally can be used to determine trends and extrema of climate parameters on the global scale. The ERA-Interim project covers data from 1989 and continues to present. Several improvements have been made in ERA-Interim compared to ERA-40 (Berrisford *et al.*, 2009). To evaluate the suitability of ERA-40 and ERA-Interim SIS (surface solar radiation downward) data for climate applications on regional scale, an evaluation was conducted using high-resolution satellite-based Heliosat data as reference.

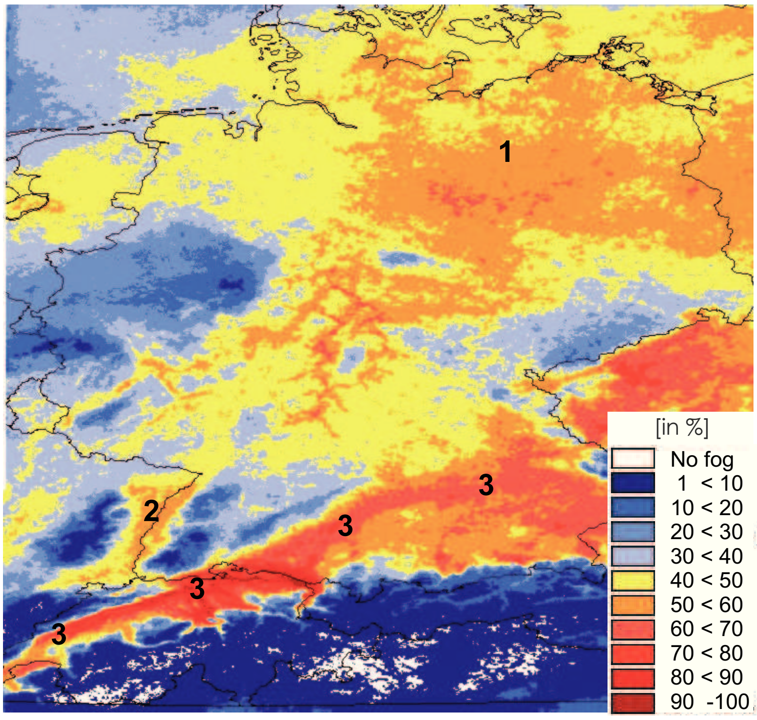

Figure 3.4: Fog frequency retrieved from NOAA-AVHRR (1989-1999, period September to May, (Bendix, 2002, reprojected). Fog relative frequency is the number of fog occurrences (absolute frequency of fog) per pixel divided by the number of satellite images used (456). The indicated areas with a high fog frequency (1) Mecklenburg Lake area, (2) Upper Rhine Valley and (3) Danube Valley agree well with the areas with a high deviations between ERA-40 SIS and Heliosat SIS during ASO.)

Dominant factors controlling solar surface irradiance are aerosols, water vapor and clouds. For all-sky conditions the clouds play the dominant role. For example figure 3.3 illustrates that in Central Europe around 30 % of the incoming solar irradiance is reflected by clouds for the seasonal long term mean (May, June, July). For winter time the values are even higher (not shown). For clear-sky conditions aerosols and water vapor dominate the spatial distribution of solar irradiance. However, the variability of the all-sky solar irradiance is dominated by changes in cloud albedo in Central Europe (e.g. Norris and Wild (2007)). The effect of aerosols on the solar surface irradiance is not large enough to explain the large deviations between Heliosat and the two ERA data sets (Hatzianastassiou *et al.*, 2007). It is therefore likely that the deviations between Heliosat and ERA-40 / ERA-Interim is dominated by clouds.

The spatial distribution of the patterns in MJJ indicates that a misinterpretation of clouds in ERA-40 might play a dominant role for the deviations in SIS between Heliosat and ERA-40: In regions with low cloud indices ERA-40 underestimates SIS compared to Heliosat. In regions with higher cloud indices (figure 3.3) ERA-40 overestimates SIS or the deviations are negligible. Hence it is reasonable to assume that parts of the observed deviations are due to limits in the representation of clouds in the ERA-40 data set. Problems in the representation of clouds in ERA-40 were also found by other authors: Betts *et al.* (2003) found differences in the annual cycle of downwelling shortwave flux between ERA-40 and ISCCP which they assume is due to the cloud reflectivity in ERA-40, which seems to be too low in fall, winter, and spring, and too high in summer. Allan *et al.* (2004) found that ERA-40 overestimates SIS over marine stratocumulus regions and attribute this to an underestimation of cloud fraction. Further Allan *et al.* (2004) found that away from the marine stratocumulus region the poor radiation simulation by ERA-40 is due to inaccurate radiative properties of clouds.

Another reason for the deviations between ERA-40 and Heliosat could be an overestimation of fog in ERA-40. With regard to the comparison, ERA-40 mostly underestimates SIS in fall (ASO) and winter (NDJ). The regional pattern of the bias during fall (ASO) is in good spatial agreement with the fog frequency climatology derived from data of the Advanced Very High Resolution Radiometer (AVHRR) flown on the National Oceanic and Atmospheric Adiministrations (NOAA) polar-orbiting satellites (figure 3.4). The areas of underestimation are river valleys and basins with high fog frequency: (1) The Mecklenburg Lake area and the valley of the river Elbe (2) the Upper Rhine Valley (3) the Alpine foreland as the Swiss Plateau between the Alps and the Swiss Jura and the German and Austrian part of the Danube Valley (figure 3.4).

The seasonal course in the year with regard to fog types in Germany and adjacent areas is predominantly characterized by radiation fog in river valleys and basins during spring and fall while during the winter extended low level stratus fields ("Hochnebel") dominate with a significantly reduced topographically affected structure (e.g. Bendix 1998). For example in fall, areas with negative deviations are areas of high fog frequency (figures 3.1 and 3.4). This is especially obvious during the months of May and September 2000 (not shown). Interesting in this context are the great deviations in the Netherlands and NW-Germany during May and September (May and September not explicitly shown, but visible in MJJ and ASO, respectively). Here, a clear seasonal cycle is observed because fog and haze formation depends on the thermal contrast between land and sea. In September, the sea is relatively warm but the land shows already considerable nocturnal cooling. Consequently, warm-moist air advected from the sea over cooled land induces fog and haze formation. Thus, the problem of underestimation of ERA-40 SIS (or missing fog/haze in Heliosat) occurs in September. In May, sea is still relatively cold but the land is already warming, which means less fog formation inland. Here, the reason of SIS overestimation might be that the ERA-40 data set has too much cloud. ERA-40 is well-known for an overestimation of cloud cover over non-convective oceanic regions; (`http://www.ecmwf.int/research/era/Data_Services/section3.html`) which might explain the high deviations over the North Sea in MJJ.

As Heliosat compares well with the ground-based stations also for regions with significant fog occurrence (e.g. Payerne, Cabauw) it is plausible that ERA-40 has problems with either the correct modelling of fog itself or the radiative transfer processes within fog.

There exists only little information on the validation of fog in the ERA-40 data set. Teixera (1999) investigates fog in the ERA-15 data set on a global scale, which makes it unfeasible to draw coherent conclusions for the results presented in this paper. The Heliosat algorithm is able to consider the effect of fog, but as an increase of the cloud albedo compared to clear-sky, which results in an increased uncertainty of Heliosat SIS in fog situations. A more specific detection and analysis of fog would require observations in the 3.9 μm spectral band only available on NOAA-AVHRR (Bendix, 2002), TERRA-MODIS (Moderate Resolution Imaging Spectroradiometer flown on NOAA's Terra satellite) (Bendix *et al.*, 2006) and the SEVIRI (Spinning Enhanced Visible and Infrared Imager) on board EUMETSAT's METEOSAT Second Generation Satellite (MSG) (Cermak and Bendix, 2008; Cermak *et al.*, 2009) but not on the MVIRI (Visible and Infrared Imager) inboard METEOSAT First Generation Satellites.

Differences in the seasonal mean values of up to 40 W/m^2 (MJJ) lead to the conclusion that care must be taken when using ERA-40 SIS data for climate applications in the region under consideration (47° N - 56° N, 4° E - 15° E). The comparison indicates that important regional climate phenomena such as fog in basins and river valleys or mesoscale cloud patterns might not be well represented by ERA-40. Thus, ERA-40 SIS data have to be handled carefully when using them for regional climate applications in Central Europe. The results of Allan *et al.* (2004), who compared ERA-40 data to satellite data, indicate that the same holds for the global scale.

The comparison of the deviations between ERA-40 - Heliosat and ERA-Interim - Heliosat indicates that in large regions ERA-Interim SIS is about +10 W/m^2 higher than ERA-40 SIS. Compared to ERA-40, SIS in ERA-Interim has improved in ASO and NDJ throughout the study area. ERA-Interims performance is also better in specific regions with low cloud albedo such as the Danube valley: Here the deviations between ERA-Interim and Heliosat are below 10 W/m^2 (figures 3.1 and 3.2). However in FMA and MJJ ERA-Interim overestimates SIS compared to Heliosat by up to 50 W/m^2. In ERA-Interim the region of overestimation of SIS in the North of the study area is intensified and enlarged compared to ERA-40 (figure 3.2). ERA-Interim incorporates many important improvements such as model resolution and changes in physics, the use of four-dimensional variational (4D-Var) assimilation, and various other changes in the analysis methodology. Moreover, the water cycle representation had been modified (Dee and Uppala, 2009). Significant differences between ERA-40 and ERA-Interim have to be expected as a result of the substantial and extensive modifications. Concerning solar irradiance significant differences between ERA-40 and ERA-Interim, especially in relation to the Heliosat data have been identified in this study. The better results of ERA-Interim in ASO and NDJ as well as in the Danube valley could be a result of a better treatment of fog and low stratus fields, e.g. as a consequence of the modified water cycle representation. Yet, the large and in relation to ERA-40 increased differences in FMA and MJJ might indicate that cloud physics or the effect of clouds on the solar irradiance have not been improved. The substantial improvement of the re-analysis system as a whole has not significantly increased the accuracy of the solar surface irradiance within the time period and region investigated. The substantial overestimation during solar summer leads us to conclude that also ERA-Interim SIS data have to be handled with caution when used for regional climate applications in Central Europe.

In addition to the region of interest discussed here, comparisons between ERA-40 SIS and Heliosat SIS were also made for a larger region of Central Europe (35°N - 60°N; 7.5°W- 24.5°E). The findings in this extended region compare well with the results of the smaller region: ERA-40 overestimates SIS in regions with high cloud albedo and underestimates SIS in regions with low cloud albedo. However, for the larger area (35°N - 60°N; 7.5°W - 24.5°E) Heliosat data need further validations. Thus, the evaluation of ERA-40 for the larger region is not presented here. Validations of the Heliosat data set are currently ongoing.

The longwave component of the surface downwelling radiation budget from ERA-Interim has been evaluated on the global scale using surface observations from 41 BSRN stations (Trentmann *et al.*, 2010). In contrast to the evaluation in the shortwave region, the quality of the re-analysis data is acceptable for climate monitoring of the longwave downwelling radiation. Only 10 % of the more than 5000 monthly mean values exceed the GCOS accuracy requirement for climate monitoring.

It was shown in this letter, that well-validated high-resolution satellite data such as those retrieved from METEOSAT using the Heliosat method are well suited to evaluate the quality of re-analysis data.

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The work presented in this paper has been funded by EUMETSAT in the context of the CM-SAF as part of the Satellite Application Facilities Network. In this study radiation parameters of the ECMWF re-analysis data sets ERA-40 (Kållberg *et al.*, 2005) and ERA-Interim (Berrisford *et al.*, 2009) were used. They were obtained from the ECMWF online catalog `http://www.ecmwf.int/services/archive/d/catalog/`. Data of the International Satellite Cloud Climatology Project (ISCCP) (Zhang *et al.*, 2004) were obtained from the web-site `http://isccp.giss.nasa.gov` maintained by the ISCCP research group at the NASA Goddard Institute for Space Studies, New York, NY. in August, 2009. Data of the Global Energy and Water Cycle Experiment (GEWEX) (Gupta *et al.*, 2006) were obtained from `http://eosweb.larc.nasa.gov/PRODOCS/srb/table\_srb.html`. The color paletts in figure 3.1 and figure 3.2 were designed using the interactive palette selection of the ColorBrewer project (`http://colorbrewer.org`). The authors thank Alan Betts and the anonymous reviewers for their constructive criticism and fruitful comments.

Chapter 4

Analysis of Extreme Summers and Prior Late Winter / Spring Conditions in Central Europe

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Analysis of extreme summers and prior late winter / spring conditions in Central Europe

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Abstract

Drought and heat waves during summer in mid latitudes are a serious threat to human health and agriculture and have negative impacts on the infrastructure, such as problems in energy supply. The appearance of such extreme events is expected to increase with the progress of global warming. A better understanding of the development of extremely hot and dry summers and the identification of possible precursor could help improve existing seasonal forecasts in this regard and could possibly lead to the development early warning methods.

The development of extremely hot and dry summer seasons in Central Europe is attributed to a combined effect of the dominance of anticyclonic weather regimes and soil moisture - atmosphere interactions. The atmospheric circulation largely determines the amount of solar irradiation and the amount of precipitation in an area. These two variables are themselves major factors controlling the soil moisture. Thus, solar irradiation and precipitation are used as proxies to analyse extreme sunny and dry late winter / spring and summer seasons for the period 1958 - 2011 in Germany and adjacent areas.

For this purpose, solar irradiation from the European Center for Medium Range Weather Forecast 40-year as well as interim re-analysis data set and remote sensing data are used. Precipitation data are taken from the Global Precipitation Climatology Project. To analyse the atmospheric circulation geopotential data at 850 hPa also taken from the European Center for Medium Range Weather Forecast 40-year as well as interim re-analysis data sets.

For the years in which extreme summers in terms of high solar irradiation and low precipitation are identified, the previous late winter / spring conditions of solar irradiation and precipitation in Germany and adjacent areas are analysed. Results show that if the El Niño / Southern Oscillation (ENSO) is not very intensely developed, extremely high solar irradiation amounts together with extremely low

precipitation amounts during late winter / spring might serve as precursor of extremely sunny and dry summer months to be expected.

4.1 Introduction

Extremely hot and dry summers in (central) Europe have large negative socio-economic impacts: According to the World Health Organization (WHO) more then 70000 death in 12 European countries could be attributed to heat stress during the summer of 2003 (World Health Organization (WHO), 2010). The extreme conditions during that summer caused an estimated loss of 1 billion Euros in the crop production of Germany (Munich Re Group, 2004), and the energy sector had to cope with a lack of cooling water for power plants and an increased demand (Förster and Lilliestam, 2010). It would thus be helpful if such events could be forecast well in advance to install precautionary and adaptation measures in due time. Understanding the reasons and / or identifying possible precursor would help to improve the forecast of such events.

However, according to recent publications, e.g. Weisheimer *et al.* (2011), state of the art climate models have problems simulating summer heat waves associated with droughts. The results of Seneviratne *et al.* (2006) and Vautard *et al.* (2007) for example, lead these authors to the conclusion that current state of the art climate models underestimate the importance of soil moisture - atmosphere feedbacks. Consequently, a lot of work has been done in recent years to better understand the processes that lead to such events (Della-Marta *et al.*, 2007, and references therein). In this context a lot of attention was attributed to the importance of soil moisture for the development of heat events. Seneviratne *et al.* (2006) found that the increase in temperature variablity in central and eastern Europe, as projected by climate models, cannot exclusively be attributed to changes in the atmospheric circulation alone, but that land-atmosphere coupling needs to be accounted for. Recently Orth and Seneviratne (2012) point out the potential importance of soil moisture memory for the predictions of droughts and floods in Europe. And Quesada *et al.* (2012) found that high precipitation amounts during winter and spring "inhibit hot summer days" in southern Europe, whereas summers after dry winter / spring seasons show either a "high or a low frequency of hot days" in this same region.

Quesada *et al.* (2012) further conclude that the occurrence of specific weather regimes in initially dry cases is important to the development of strong summer heat events. Other authors identified specific atmospheric circulations regimes over the North Atlantic that are connected to heat events in Europe. For example Cassou *et al.* (2005) attributed the occurrence of hot days over France to to what they call "blocking" and "atlantic low". Where "blocking" refers to negative pressure anomalies over Greenland and high pressure anomalies over Europe, and "atlantic low" refers to negative pressure anomalies over the North Atlantic and positive anomalies over continental Europe. Others, for example Beniston and Diaz (2004), found that the large positive atmospheric pressure anomalies that lead to extreme summers as the one 2003, were associated with a northward shift of the Hadley circulation. And Black *et al.* (2004) point to the northward displacement of the Azores high associated with a dominance of anticyclonic weather regimes which was an important factor for the development of the 2003 European heat summer.

The afore mentioned publications focus on specific factors associated with heat waves and droughts: Either the synoptic scale meteorology, global circulations or the soil moisture - atmosphere feedbacks. As they all deal with similar extreme phenomena, it is likely that heat waves and droughts in central Europe are driven and affected by the combination of various meteorological processes on different scales. The current paper aims to analyse and discuss the effect of the different factors leading to heat waves and droughts in an integrated manner. The authors think that this approach provides new and additional insights into the development and pre-conditions of summer droughts and heat waves.

Solar irradiation and precipitation are driven by atmospheric dynamics: a nticyclonic systems lead to high solar irradiation and low precipitation, cyclonic systems to the opposite. Furthermore, solar irradiation and precipitation are the major drivers of soil moisture (e.g., Orth and Seneviratne 2012), which has been shown by various authors to be an important factor in the development of heat waves (see above). In addition solar irradiation is closely related to surface temperature during summer in central Europe (Makowski *et al.*, 2009). Thus, these two variables are used as proxies to integratively analyse heat and drought events during summer and prior late winter / spring conditions in Central Europe.

As a central aspect in this study, the following hypothesis is analysed and discussed: Late winter / spring months with positive anomalies in the incoming solar irradiation at the surface and negative anomalies in precipitation indicate the occurrence of extremely sunny (and thus hot) and dry subsequent summer season in Central Europe. The analysis of this hypothesis comprises discussion and analysis of atmospheric dynamics on different scales as well as soil moisture - atmosphere feedbacks and includes a literature review.

The paper is structured as follows: The data used are described in section 4.2. The methods used to analyse the data are described in section 4.3. The results of the analysis are presented in section 4.4. Whereas the section 4.4.1 deals with the analysis of solar irradiation and precipitation anomalies in the study area (47 ° N - 56° N, 4° E - 15° E) and anomalies in the geopotential at 850hPa over Europe, the Mediterranean, the North Sea, and the Bay of Biscay (35° N - 75° N, -10° E

- 25° E). And section 4.4.2 contains the results referring to a possible influence of the El Niño - Southern Oscillation (ENSO) on European late winter / spring and summer conditions. In section 4.5 the major aspects of the analysis results are discussed in the context of previous and recent research. Section 4.6 provides a final summary of the paper.

4.2 Data

4.2.1 The solar irradiation data set

The 23-year climate data set of incoming solar irradiation at the surface (further referred to as solar irradiation) is based on the retrieval of cloud information from the METEOSAT Visible and Infrared Imager (MVIRI) on board the METEOSAT first generation satellites. The retrieval is based on the Heliosat method described in detail in Hammer (2001) and Hammer *et al.* (2003).

The original Heliosat method has been improved to better account for degradation and changes in the sensitivity of the satellite instruments and for clouds over snow (Posselt *et al.*, 2011). Moreover, the original clear sky model of the Heliosat method has been replaced by the Mesoscale Atmospheric Global Irradiance Code (MAGIC), which is described in detail in Müller *et al.* (2009). The data set is provided free of charge by EUMETSAT's (European Organisation for the Exploitation of Meteorological Satellites) Satellite Application Facility on Climate Monitoring (CM SAF) at `www.cmsaf.eu` and hereinafter referred as MAGICSOL data set. The MAGICSOL method as well as the underlying Heliosat method is well verified by various authors: Beyer *et al.* (2006), Drews (2007), Drews *et al.* (2008), Posselt *et al.* (2011), Journée and Bertrand (2010). The accuracy of solar irradiation from MAGICSOL is found to be clearly better than 10 W/m^2 and the data set performs better than other well known solar irradiation data sets, as for example Global Energy and Water Cycles Experiment (GEWEX) or International Satellite Cloud Climatology Project (ISCCP), (Träger-Chatterjee *et al.*, 2010).

Since MVIRI data are not available before 1983 and after 2005, the MAGICSOL data set is elongated using the European Center for Medium Range Weather Forecast (ECMWF) 40-year re-analysis data set (ERA-40) (Uppala *et al.*, 2005) for the period 1958 - 1982, ERA-interim for the year 2006, and from 2007 until 2011 the operational product of solar incoming radiation at the surface provided by CM SAF (Müller *et al.*, 2009) (further referred to as CM SAF SIS) is used. It was shown by Träger-Chatterjee *et al.* (2010) that the ERA-40 solar irradiation data set shows weaknesses in resolving some regional phenomena in the study area. However, since the focus of this study is on the average conditions in three monthly time scales and for the entire study area as a whole, the ERA-40 solar

Table 4.1: Composition of the solar irradiation data set used in this study. See section 4.2.1 for abbreviations.

Time range	Data source
Jan 1958 - Dec 1982	ERA-40
Jan 1983 - Nov 1988	MAGICSOL
Dec 1988	ERA-40
Jan 1989 - Dec 2005	MAGICSOL
Jan 2006 - Dec 2006	ERA-interim
Jan 2007 - Dec 2011	CM SAF

irradiation data set is the best re-analysis data set currently available for the study area, the time range in question and the context of this study. Other re-analysis data sets have not been used here for several reasons: The solar irradiation data of the ERA-interim re-analysis have a lower accuracy in the study area than ERA-40 (Träger-Chatterjee *et al.*, 2010). The solar irradiation data of the re-analysis of the National Center for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) have only limited accuracy on the regional scale (Babst *et al.*, 2008). Further re-analysis data sets were either not yet available at the time the study started (e.g. NCEP 20^{th} century re-analysis) or the time range covered is not sufficient (e.g. the Modern Era re-analysis for Research and Applications, MERRA). However, since ERA-40 ends in 2002 and CM SAF SIS data are not available before 2007, for the year 2006 ERA-interim data are used. December 1988 is substituted by ERA-40 since this months is missing in the MAGICSOL data set, because not as many images as required by the algorithm are available to calculate the monthly mean. This lack of images is presumably due to technical issues concerning the transition of METEOSAT-2 to METEOSAT-3 (Lüst 1992; Eoportal.org 2002). Table 4.1 provides an overview on the composition of the solar irradiation data set used here.

4.2.2 The precipitation data set

The Global Precipitation Climatology Center (GPCC) hosted at Deutscher Wetterdienst (DWD) (`http://gpcc.dwd.de`) provides gridded data sets of land-surface precipitation data with global coverage. The data sets are based on in situ gauge measurements. The method of interpolating the gauge measurements is described in Rudolf and Schneider (2005). The products provided by GPCC are described in Schneider *et al.* (2011). The GPCC full data product version 6, available for the period January 1958 until December 2010, is used. The period January 2011 to December 2011 is covered by the monitoring product version 4. The monitoring product is based on station data distributed via the Global Telecommunications System (GTS) of the World Meteorological Organization (WMO) and is available two months after the end of an analysis months (Schneider *et al.*, 2011). The full data product is based on a larger number of stations than the monitoring product, the input data are quality controlled, and it is irregularly updated (GPCC, 2012).

4.2.3 The geopotential data set

The geopotential in 850 hPa height was investigated for the time series 1958 - 2011 using monthly mean of daily mean data from ERA-40 (1958 - 1988) (Uppala *et al.*, 2005) and ERA-interim (1989 - 2011) (Dee *et al.*, 2011).

4.2.4 El Niño - Southern Oscillation Index

The Southern Oscillation Index (SOI) is a measure of the state of the Southern Oscillation. It is a "standardized index based on the observed sea level pressure differences between Tahiti and Darwin, Australia" (NOAA, 2010). However, as the ENSO cycle is a fluctuation of sea surface temperature (SST) and atmospheric pressure in the pacific area (NOAA, 2010), the bivariate ENSO time series (BEST index), developed by Smith and Sardeshmukh (2000), which combines both, SST and sea level pressure is used. The BEST index is a combination of the Southern Oscillation Index (SOI) and the sea surface temperature (SST) in the region 5°N - 5°S and 170°W-120°W (Niño 3.4 region). It is described in detail in Smith and Sardeshmukh (2000) and is available at `http://www.esrl.noaa.gov/psd/people/cathy.smith/best/\#years` starting in 1871. For the current study the mean values of December and January (DJ) based on the 1 month running means are calculated. The December - January mean is used since the peak of an ENSO event usually occurs "near the end of the year" (Sarachik and Cane, 2010, p.9).

4.2.5 The soil moisture data set

As supporting information the ERA-40 (1958-1988) (Uppala *et al.*, 2005) and ERA-interim (1989-2011) (Dee *et al.*, 2011) monthly means of daily means of the parameter volumetric soil water are used. This parameter is available in 4 different layers: 0 - 0.07m (level 1), 0.07 - 0.28m (level 2), 0.2 - 0.7m (level 3), and 0.7 - 1.9m (level 4). The strongest variability, especially during the summer months, appears in level 1 and level 2, whereas the curves of these two levels are almost identical. It is therefor reasonable to use level 2 for the further analysis in this study.

However, Betts and Ball (1999) and Hirschi *et al.* (2006) found that ERA has problems to correctly represent the annual cycle of soil water. To get a rough estimate on the quality of the ERA soil water data in the study area, the variance coefficient for the late winter / spring mean values (February - March - April mean) of the ERA time series (1958 - 2011) are compared to those of in situ measurements of two stations in Germany: one near Gießen (GI) located at 50.85° N and 8.69° E, 172m above sea level (available 1997 - 2010) and one of the station "Falkenberg" at the Meteorological Observatory Lindenberg (MOL) located at 52.17° N, 14.12° E, 73m above sea level (available 2000 - 2010). The variance of the ERA data and the in situ measurements show large differences. For FMA/JJA the variance of the in situ measurements are about 0.1/0.15 (GI) and 0.13/0.34 (MOL) compared to values for the ERA data of 0.03/0.06 near GI and 0.03/0.07 near MOL. This indicates that ERA data might not be well suited for the analysis of inter-seasonal variations. However, it is assumed that the general characteristics of the extreme events discussed here, i.e., the serious droughts during the summer months of the years in question, are reasonably captured.

4.3 Method

It is hypothesised that the most extreme summer seasons in terms of solar irradiation and drought in the study area comprising Germany and adjacent areas (47° N - 56° N, 4° E - 15° E, see also figures 4.1 and 4.2) are preconditioned during the preceeding late winter / spring months of the respective year. Here, late winter / spring is defined as February - March - April (FMA) and February - March - April - May (FMAM), respectively.

To get a first impression on the relation of solar irradiation and precipitation regimes in late winter / spring and the following summer season the lagged auto correlation coefficients according Pearson (Wilks, 2006, p.50ff) are calculated. The hypothesis that signals of approaching extremely sunny and dry summer seasons in Central Europe are visible in the preceeding late winter / spring months is then tested applying the following analysis:

First, to account for the study area as a whole, the multi months sum of the monthly means of solar irradiation and precipitation are determined. From these sums the regional means of the study area are calculated for the two late winter / spring seasons February - March - April (FMA) and February - March - April - May (FMAM) and for the summer season June - July - August (JJA). The result is the seasonal region mean (SRM) defined as:

$$SRM = \sum_{season} (\frac{1}{n} * \sum_{i=1}^{n} x_i) \tag{4.1}$$

with

SRM: seasonal region mean
season: period of successive calender months
n: number of pixel / grid boxes within the study area
i: counter
x_i: monthly mean value of parameter x at pixel / grid box i

Second, to analyse the most extreme sunny and dry summers regarding the characteristics of solar irradiation and precipitation during their preceeding late winter / spring season, the upper / lower percentiles of SRM_{JJA} of solar irradiation and precipitation are identified.

An extremely sunny and dry summer is defined as being among the Xth upper / lower percentile regarding SRM_{JJA} of solar irradiation and precipitation at the same time. For the years with extremely sunny and dry summers the preceeding late winter / spring seasons FMA and FMAM, respectively, are analysed with regard to *SRM* of solar irradiation and precipitation. The analysis is performed also regarding the sensitivity to the selection of the Xth percentile. Therefor two modes of analysis are applied:

- analysis of highly extreme events: upper / lower 10^{th} percentile of *SRM* of solar irradiation AND precipitation in late winter / spring and summer.
- analysis of all extreme events: upper / lower 20^{th} percentile of *SRM* of solar irradiation AND precipitation in late winter / spring and summer.[3]

Based on the results of these two modes of analysis the probability of occurrence p_{all} of an extremely sunny and dry summer season in the entire 54-year time series is calculated, as well as the probability of occurrence $p_{precond}$ of such a summer season after extremely sunny and dry late winter / spring seasons:

$$p_{all} = n/N_{all} \tag{4.2}$$

$$p_{precond} = n/N_{extremeFMA(M)} \tag{4.3}$$

with

p_{all}: probability of occurrence of an extremely sunny and dry summer in the entire 54-year time series
N_{all}: number of all years in the time series
n: number of extremely sunny and dry summers

[3]Note that the highly extreme events are part of all extreme events, but not vice versa.

$p_{precond}$: probability of occurrence of an extremely sunny and dry summer after extremely sunny dry late winter / spring season

$N_{extremeFMA(M)}$: number of years in the time series with extremely sunny and dry summers

In addition to the two surface parameter, the atmospheric circulation of the extreme years are analysed using the anomalies of geopotential in 850 hPa height of late winter / spring and summer. The seasonal anomalies of the geopotential are calculated as the deviation of the seasonal mean from the longterm seasonal mean of the 54-year time range 1958-2011.

The results of the analysis described above are presented in the following section.

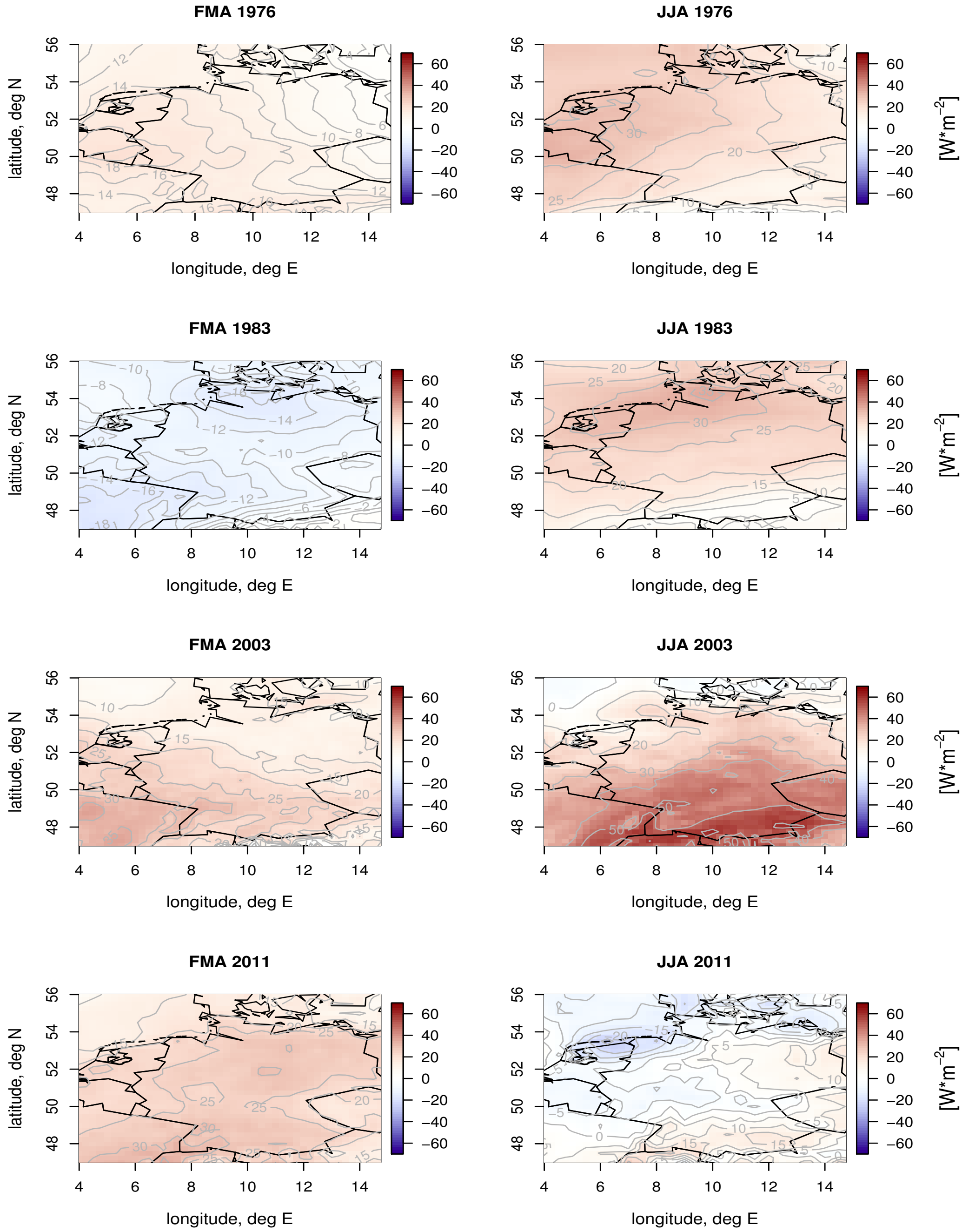

Figure 4.1: Seasonal anomaly of solar irradiation [Wm^{-2}] in 1976, 1983, 2003, and 2011. Left column: FMA anomaly, right column: JJA anomaly.

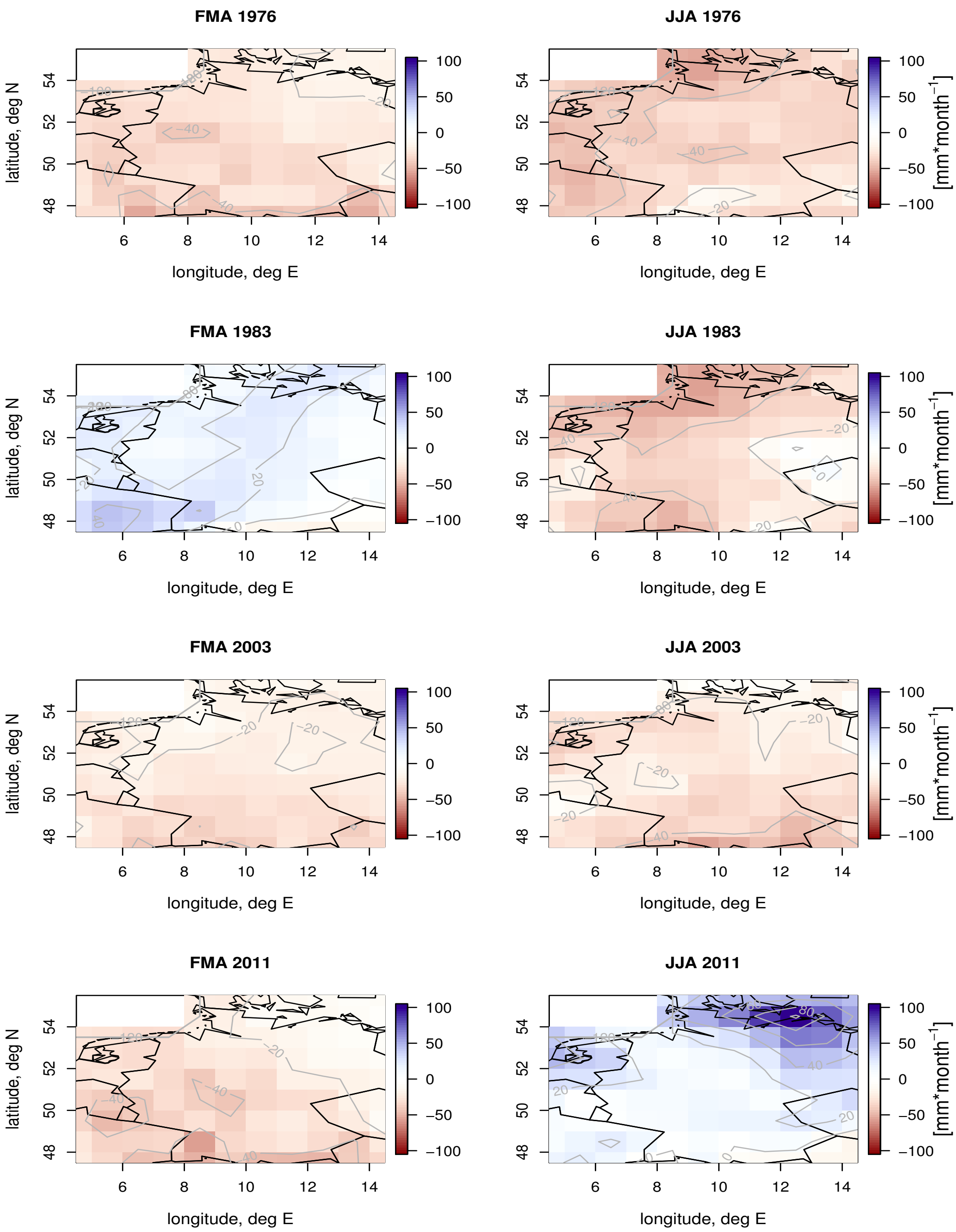

Figure 4.2: Seasonal anomaly of precipitation [mm*month^{-1}] in 1976, 1983, 2003, and 2011. Left column: FMA anomaly, right column: JJA anomaly.

4.4 Results

The probability of occurrence of a hot and dry summer among the highly extreme events and among all extreme events is 0.05 and 0.09, respectively. The lagged autocorrelation coefficients of the SRM values between FMA(M) and the proceeding JJA are 0.21 (0.24) for solar irradiation and 0.1 (0.1) for precipitation regarding the entire time series 1958-2011. However, these values are dominated by the majority of years in which no extremely hot and dry late winter / spring and summer seasons, respectively, occurred.

Figure 4.3 and figure 4.4 show the SRM anomalies for solar irradiation and precipitation, respectively, for late winter / spring (white and grey, respectively) and summer (black). The five years with the largest positive (negative) anomalies in solar irradiation (precipitation) during summer are marked with an "x". Summer seasons marked in both plots are regarded as (highly) extreme sunny and dry summers, i.e., 1976, 1983, and 2003. Two of these summers, namely 1976 and 2003, have preceeding late winter / spring seasons with positive (negative) anomalies in solar irradiation (precipitation). Whereas in 1983 the anomalies of solar irradiation and precipitation have opposite signs during late winter / spring compared to the following JJA season. The extreme summers of 1976 and 2003 are discussed in detail in several publications, e.g., Schär and Jendritzky (2004), Deutscher Wetterdienst (1976), Deutscher Wetterdienst (2003). In contrast, the summer of 1983 is not as much discussed in the literature as the other two extreme events. However, it is mentioned in the analysis of European heat waves with respect to the influence of the tropical Atlantic of Cassou *et al.* (2005) in the context of ENSO influence (discussed later in this paper).

4.4.1 Regional anomaly analysis

The analysis of extremely sunny and dry summers and their preceeding late winter / spring conditions is conducted regarding two definitions of late winter / spring: February - March - April (FMA) and February - March - April - May (FMAM). The results for the two analysis modes applied, accounting for all extreme events and highly extreme events, respectively, (see section 4.3), are shown in table 4.2. Beside extremely sunny and dry summer seasons with preceeding similarly extremely sunny and dry FMA(M) seasons, the analysis reveals two categories of years in which the FMA(M) - JJA connection in terms of large solar irradiation excess and precipitation deficit in both seasons does not exists:

- (A) Sunny and dry summers without preceeding late winter / spring season with positive / negative anomalies in solar irradiation / precipitation.
- (B) Sunny and dry late winter / spring seasons with following summers with

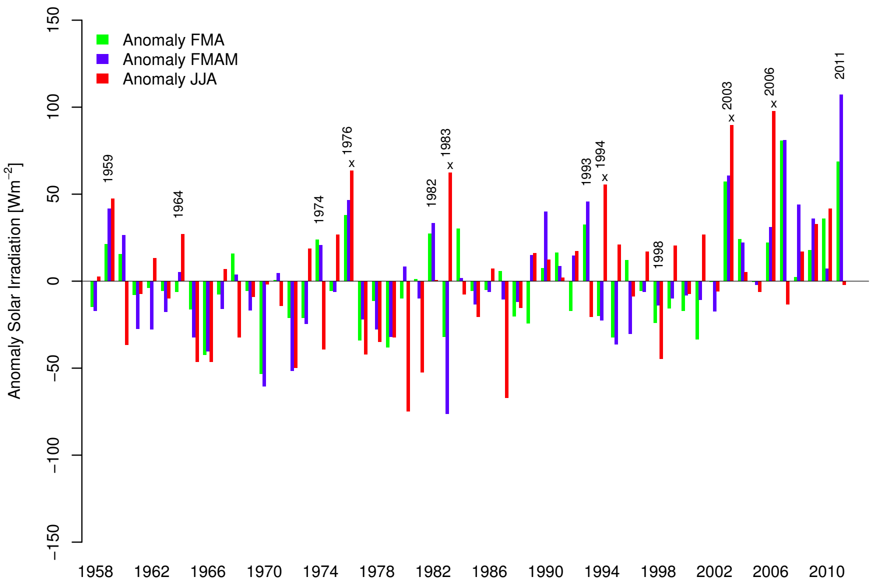

Figure 4.3: SRM anomalies of solar irradiation [Wm^{-2}] during FMA (green), FMAM (blue), and JJA (red) in all years of the time series 1958-2011. Years marked with "x" are the 10% with the highest SRM_{JJA} anomalies in the time series. Years additionally marked with their date are discussed in section 4.4 and / or 4.5.

close to normal or slightly negative / positive anomalies in solar irradiation / precipitation.

The analysis of the highly extreme events reveals that two out of three highly extremely sunny and dry summers have preceeding highly extreme FMA(M) seasons with regard to positive anomalies in solar irradiation and negative anomalies in precipitation. Here it makes no difference if the late winter / spring season is defined as FMA or FMAM, the results are the same for either definition. In this mode the probability for a highly extremely sunny and dry summer to occur after a highly extreme FMA(M) seasons is raised to 0.67, as opposed to 0.05 after any FMA(M) season. Thus, highly extreme sunny and dry summers are often preconditioned in FMA(M). However, the analysis of highly extreme events also reveals that (1) the highly extreme sunny and dry summer 1983 is not preceeded by a highly extreme sunny and dry late winter / spring season (category (A)), and (2) the highly extreme late winter / spring season 2011 which is followed by normally sunny and wet summer (category(B)) (tab. 4.2 and figures 4.3, 4.4).

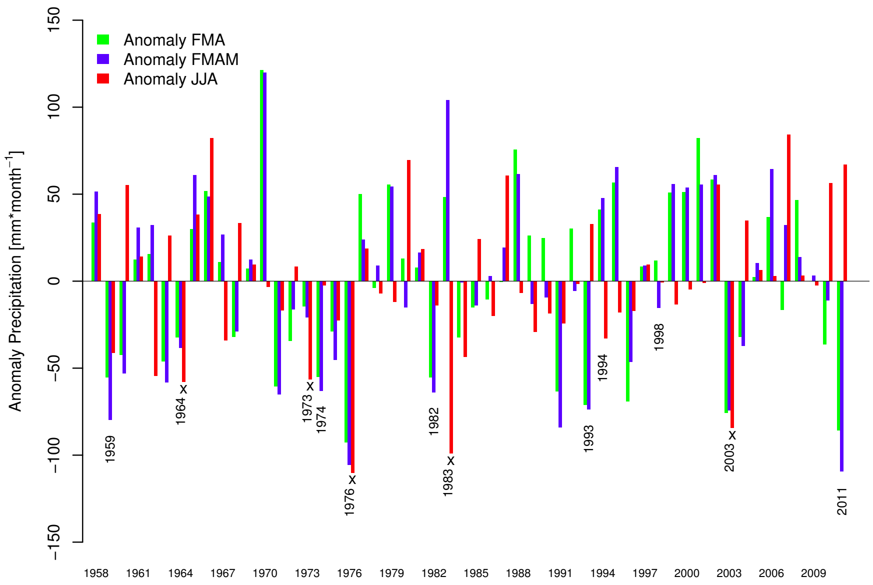

Figure 4.4: SRM anomalies of precipitation [mm*month^{-1}] during FMA (green), FMAM (blue), and JJA (red) in all years of the time series 1958-2011. Years marked with "x" are the 10% with the lowest SRM_{JJA} anomalies in the time series. Years additionally marked with their date are discussed in section 4.4 and / or 4.5.

The analysis of all extreme events reveals that two (three) out of six extreme sunny and dry summers have preceeding FMA(M) seasons showing similar anomalies in solar irradiation and precipitation, respectively. Furthermore, the analysis of all extreme events, filters six additional years with decoupled FMA - JJA seasons than the analysis of the highly extreme events: three of category (A) (1959, 1964, 1994) and three of category (B) (1974, 1982, 1993). Defining late winter / spring as FMAM four additional years with decoupled late winter / spring - summer seasons than in the analysis of the highly extreme events are found: two of category (A) (1964, 1994) and two of category (B) (1982, 1993). Analysing all extreme events the probability for an extremely sunny and dry summer to occur is 0.34 (0.5) after a similarly extreme FMA(M) season. However, both values are below the probability of occurrence found in the analysis of the highly extreme events. For all extreme summer seasons, May has a positive effect in pre-conditioning.

Extremes leading to serious droughts and prolonged heat waves in central Europe are characterised by their low frequency of occurrence. Hence it should be

Table 4.2: Results of the analysis. Highly extreme events: upper / lower 10^{th} percentile of solar irradiation / precipitation in FMA and JJA. Extreme Events: upper / lower 20^{th} percentile of solar irradiation / precipitation in FMA / FMAM and JJA.

	Years with synoptically pre-conditioned FMA	Years with synoptically pre-conditioned FMAM	Years with extremely sunny and dry JJA	preceeding mean DJ BEST index
highly	1976	1976	1976	-1.59
extreme			1983	2.57
events	2003	2003	2003	1.16
	2011	2011		-2.71
extreme		1959	1959	0.63
events			1964	0.94
	1974			-1.93
	1976	1976	1976	-1.59
	1982	1982		-0.24
			1983	2.57
	1993	1993		0.49
			1994	0.14
	2003	2003	2003	1.16
	2011	2011		-2.71

expected that any pre-conditioning of extreme summers by late winter / spring conditions is more pronounced for the highly extreme events. The results support this assumption. Thus, for the remainder of this paper we focus on the highly extreme events. As shown above, the inclusion of May does not affect the results. May is therefore not considered for the late winter / spring conditions further on.

The analysis reveals that the highly extreme sunny and dry summers in the time series, 1976 and 2003, have preceeding FMA seasons with already large positive anomalies of solar irradiation and large negative anomalies of precipitation. In accordance with that a clear positive anomaly of the geopotential is visible north of 45° N and Central Europe, respectively, in FMA and JJA of both years, whereas the JJA anomaly is stronger in 1976 than in 2003 (fig. 4.5).

In FMA 1976 the positive geopotential anomaly reaches from the British Islands over the North Seas and enlarges in latitude direction towards Scandinavia and eastern Europe, covering the BeNeLux and Germany. In the following summer season the spatial extend of the strongest anomaly is reduced and covers mainly the British Islands, the North Seas, parts of northern France, BeNeLux, the northern half of Germany and large parts of Scandinavia. The anomaly in eastern Europe is reduced compared to the prior FMA. Also in 2003 the positive geopotential anomaly is larger and more spread out in FMA than in JJA. Compared to 1976 the FMA anomaly of the geopotential is stronger, and the subsequent JJA anomaly is weaker but larger in its spatial extend covering almost all of the Europe. The dominance of the high-pressure systems in FMA in 1976 and 2003 (fig. 4.5) leads to enhanced solar irradiation values at the surface and less precipitation than normal (figures 4.1 and 4.2). These two factors enhance the evapotranspiration and hence the drying of the soils. The already dry soils in late winter / spring combined with the low precipitation amounts throughout FMA and the following summer months result in extremely low soil moisture conditions (fig. 4.6). [4]

[4]As stated in section 4.2, the authors are aware that care must be taken using ERA-40 and ERA-interim soil water data. However, it is assumed that the general characteristics of the extreme events discussed here, i.e. the serious droughts during the summer months of the years in question, are reasonably captured.

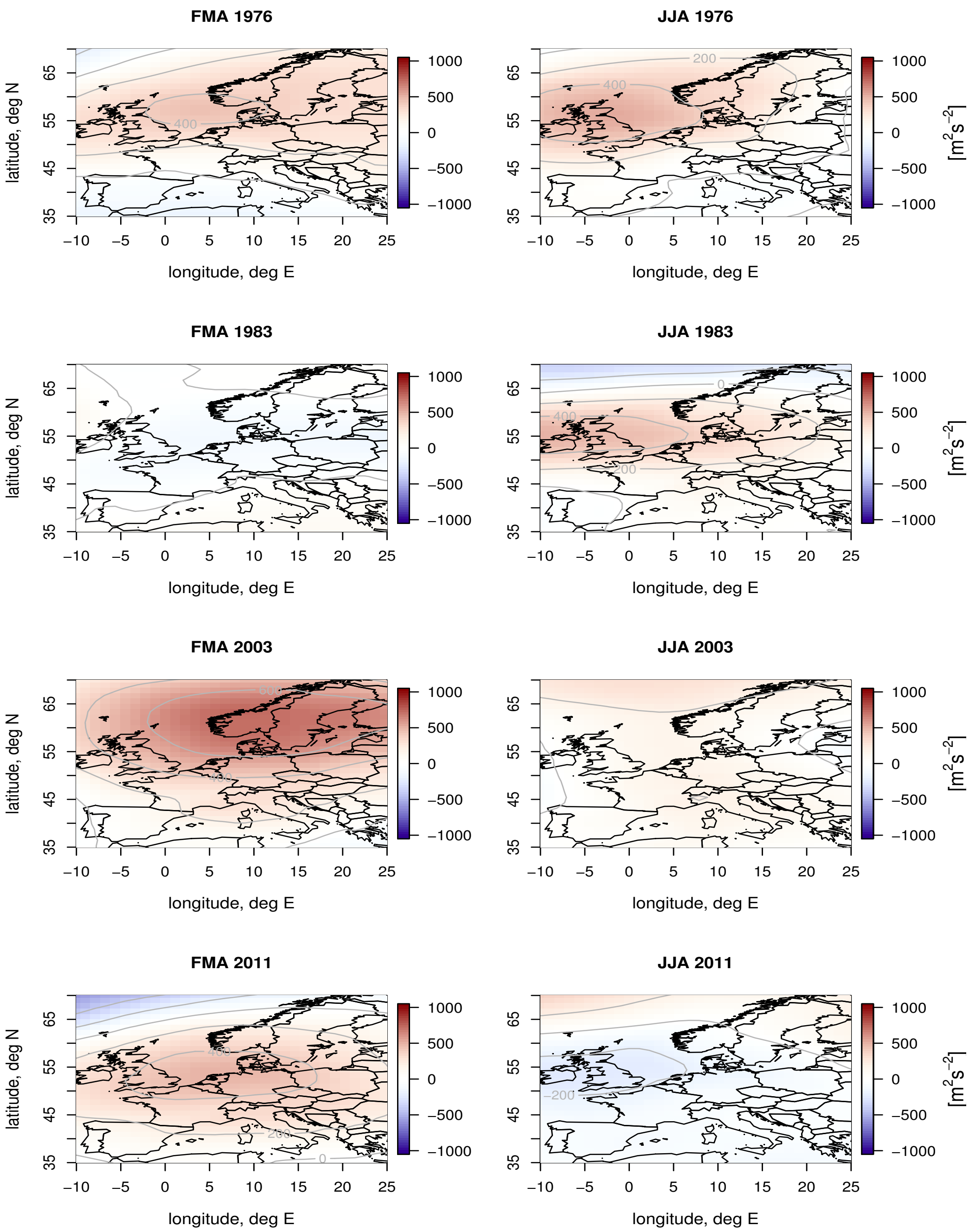

Figure 4.5: Seasonal anomaly of 850 hPa geopotential [$m^{-2}s^{-2}$] in 1976, 1983, 2003, and 2011. Left column: FMA anomaly, right column: JJA anomaly.

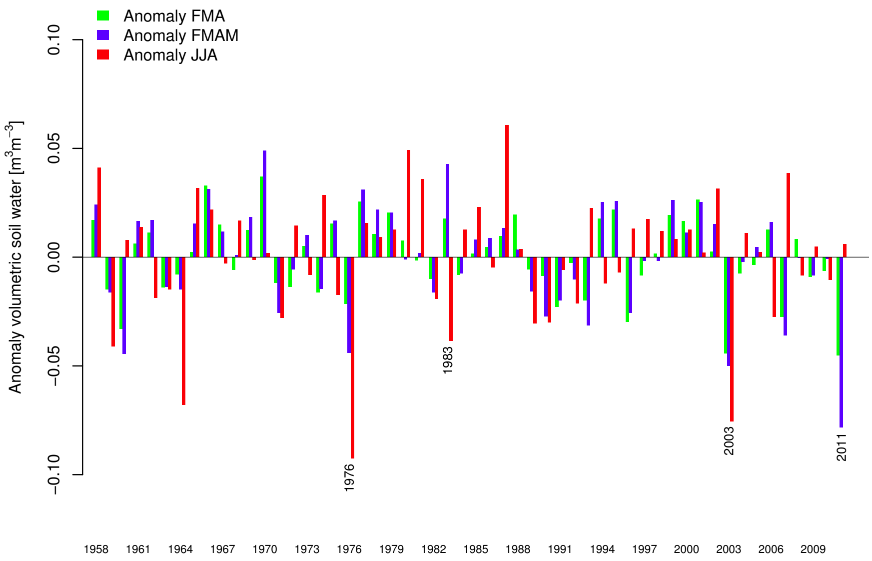

Figure 4.6: SRM anomalies of volumetric soil water [m^3m^{-3}] during FMA (green), FMAM (blue), and JJA (red) in all years of the time series 1958-2011. Years marked with their date are discussed in section 4.4 and / or 4.5.

Under these conditions convective precipitation is not favored and the negative precipitation anomaly, and thus also the negative soil moisture anomaly, further increases. Thus, the missing convection leads to an increased positive solar irradiation anomaly due to a lower cloud coverage than usual, which in turn leads to enhanced solar irradiation. The lack of soil moisture together with the high amount of solar irradiation most probably leads to a strong increase in sensible heat flux and only a minor increase in latent heat flux, i.e. an increased Bowen-ratio (Bowen, 1926), which in turn leads to even dryer soils (fig. 4.7). This proposed mechanism is also supported by the findings of other authors: e.g., Zampieri and D'Andrea (2009) (see section 4.5).

Even for the highly extreme late winter / spring and JJA seasons, respectively, two "disconnected" years are discovered: The highly extreme hot and dry summer of 1983 does not have a preceeding sunny and dry late winter / spring, but the contrary (category (A)). And in 2011 the FMA - JJA relation behaves the opposite: the highly extreme sunny and dry FMA season was followed by a close to normally sunny and rather rainy summer (category(B)). Logically also the geopo-

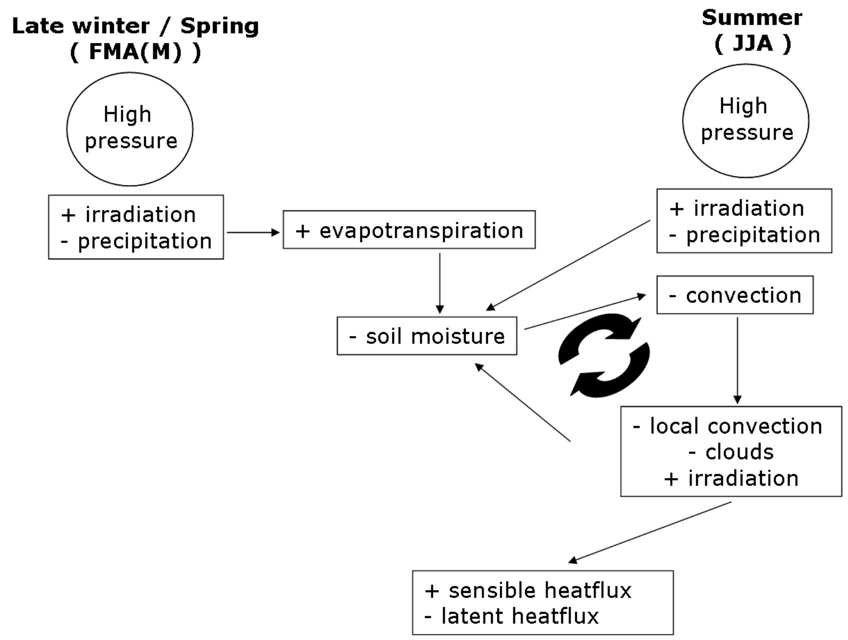

Figure 4.7: Feedback loop solar irradiation - soil moisture.

tential anomalies in those years look opposite: 1983 is characterized by a negative anomaly in FMA and a clearly positive anomaly centered over the British Islands and the North-Seas reaching northern France, BeNeLux, Germany, Denmark and southern Scandinavia and becoming weaker further east. The contrary is the case in 2011: FMA is characterized by a strong positive geopotential anomaly centered over the northern half of Germany, Denmark and the North Seas and the following JJA is characterized by a negative geopotential anomaly centered over the British Islands and covering most of Europe. The consequences of the geopotential anomalies in FMA and JJA in 1983 (2011) can be seen in figures 4.1 and 4.2: negative (positive) anomaly in solar irradiation, positive (negative) anomaly in precipitation during FMA and positive (negative) anomaly in solar irradiation, negative (positive) anomaly in precipitation in JJA.

A possible explanation for the "missing" FMA - JJA connection in these two years (despite the large anomalies in FMA (2011) and JJA (1983)) might be a "global" extreme climate event, that might lead to extreme seasons without synoptic-scale late winter / spring - summer connections of the extremes (as apparent in 1976 and 2003). Hence, the reason for the extremes in 1983 and 2011 might be forced by extremes in global oscillations and not by forces on synoptic scale. For such extremes it cannot be expected that connections / pre-conditions are apparent in the synoptic scale. This might explain the "disconnection" of late winter / spring and summer extremes in 1983 and 2011. Such a "global" extreme event could be the El Niño Southern Oscillation (ENSO). Its effect on extremes is discussed in the following subsection.

4.4.2 Potential impacts of regional and global circulation anomalies

A measure for the state of the Southern Oscillation is the BEST index (Smith and Sardeshmukh, 2000) (section 4.2). The mean BEST index of the December-January (DJ) season 1982/83 was 2.57 (table 4.2) (Sardeshmukh and Smith, 2012), indicating a strong El-Niño event prior to the extreme summer 1983, which is not preconditioned in late winter / spring. Cassou *et al.* (2005) speculate, that the notably anomalous conditions during 1983 might be a consequence of the post El-Niño influences in the western tropical Atlantic and over Africa. Alternatively, these ENSO related teleconnections might have affected the conditions during FMA 1983. At that time the geopotential anomaly is (slightly) negative over the study area and adjacent regions, indicating a dominance of cyclonic conditions that result in a negative anomaly in solar irradiation and positive anomaly in precipitation (figures 4.1 and 4.2). A dominance of cyclonic conditions in southern and Central Europe connected to El Niño events is described by Frädrich (1994), who found that this connection is strongest in January and February after the peak of the El-Niño event. This could explain why the summer of 1983 was extremely hot and dry whereas the prior FMA season was dominated by cyclonic conditions with low values of solar irradiation and high amounts of precipitation and soil moisture.

The contrary, a very strong La Niña event, indicated by an extremely low mean DJ BEST index of -2.71 (table 4.2) (Sardeshmukh and Smith, 2012), is observed prior to JJA 2011. The FMA conditions in 2011 showed a clear signal for a hot and dry summer to be expected: A clear positive anomaly in the geopotential centered over Central Europe is visible (fig. 4.5). Consequently the anomalies of solar irradiation and precipitation, relative to the mean of the period 1958-2011, are among the highest and lowest, respectively, in the time series. However, other than expected from the FMA conditions, the JJA anomaly in the geopotential over Europe is only slightly positive over parts of Scandinavia and close to normal and slightly negative, respectively, over most of Europe (fig. 4.5). In the study area the solar irradiation is overall close to normal and the positive precipitation anomaly is among the highest of the time series (fig. 4.3 and 4.4). These observations fit well with the results of Frädrich (1990) and Frädrich and Müller (1992) who found enhanced anti-cyclonic conditions over Europe and a northward shift of the cyclone track during La Niña events, inducing negative precipitation anomalies in the area of (south)western Europe to the Black Sea and negative pressure anomalies over northern Europe. Most of these observations are also seen in 2011: a positive geopotential anomaly centered over Central Europe and covering large parts of the continent, including most of Scandinavia. The latter differs from the observations of Frädrich and Müller (1992), however, it is assumed that the cyclonic storm track during the 2010/11 La Niña event is shifted further north than during other events. The reason might be the strength of this event, reaching a BEST index of -3.02 in February 2011, which is the smallest monthly mean value in the time series since 1871 - 2011.

Investigating all the FMA and JJA seasons in the time series that have preceeding DJ periods with absolute mean BEST indices of larger than 2 reveals one more year with an extreme ENSO event: 1997/98 with a mean DJ BEST index of +2.23, indicating a strong El Niño event. However, 1998 is a rather inconspicuous year in the context of solar irradiation and precipitation anomalies in late winter / spring and summer. The late winter / spring season in 1998 shows close to neutral anomalies in precipitation (slightly positive SRM_{FMA} anomaly and slightly negative SMR_{FMAM} anomaly) and slightly negative anomalies in solar irradiation. The proceeding summer season (1998) had a clear negative anomaly of solar irradiation (fig. 4.3) and a normal SRM_{JJA} value of precipitation (fig. 4.4).

4.4.3 Synthesis of the results

The relative short length of the data sets available limits the statistical evidence of the results presented. However, this handicap is reduced by an extensive analysis of the apparent extremes. The results are therefore not only based on statistics and support the hypothesis that the following relationship exists: Extremely sunny and dry summer seasons in Central Europe are pre-conditioned / connected with respective extremes in the preceeding late winter / spring season on a synoptic-scale. The late winter / spring conditions might indicate a equilibrium position of the system which persists into the summer season. The synoptic-scale connection of the late winter / spring and summer extremes might be useful to support the forecast of extreme droughts and prolonged heat waves in Central Europe.

However, the analysis of the global system reveals that the synoptic-scale connection might be disturbed by large-scale atmospheric teleconnections with the ENSO circulation. If the DJ mean BEST index prior to the summer season is higher than +2, indicating a strong El Niño event, it is not sure whether the upcoming JJA season might be extremely sunny and dry (1983) or not (1998), even if there was no such signal in the prior FMA season. On the other hand, if the DJ mean of the BEST index is below -2 the probability for the following JJA season to be extremely sunny and dry might not be enhanced, even if there is a clear signal for such an event based on the FMA conditions in solar irradiation and precipitation.

Taking the 54-years time series investigated as the main unit, the probability of occurrence for a highly extreme sunny and dry summer, (see section 4.3), is 0.05 (3 out of 54). In case of a preceeding highly extreme sunny and dry FMA season the probability of occurrence of a highly extreme summer is raised by a factor of 13.4 to 0.67 (2 out of 3). Accounting for extreme ENSO conditions, which might disturb the possible FMA - JJA connection the probability of a highly extreme sunny and dry summer to occur after a highly extreme FMA seasons, given that no extremely strong ENSO conditions occurred in the respective winter season, is raised to 1 (2 out of 2).

In the following section the results presented are put into context with other relevant studies previously published.

4.5 Discussion

The results presented in section 4.4, reveal that the most extreme sunny and dry summer seasons in the time series investigated, 1976 and 2003, had preceeding FMA seasons with extreme anomalies of solar irradiation and precipitation of the same sign as the following JJA season. In these two extreme years the predominance of anticyclonic conditions during FMA, coming along with large anomalies in solar irradiation and precipitation, preconditions the subsequent extremely sunny and dry summer seasons (JJA). This precondition is probably driven by the high solar irradiation and low precipitation values enforcing the positive feedback loop - high solar irradiation - dry soils - enhanced sensible heat flux and reduced latent heat flux - less rain / clouds - higher solar irradiation - described above (section 4.4, fig. 4.7). This theory is well supported by the findings of several authors: Ratcliffe (1978) estimated that during the drought that hit the British Island in summer 1976 only 10% of the solar energy available in June of that year was transformed into latent heat flux and about 90% (as opposed to usually 53%) to sensible heat flux. Koster *et al.* (2004) separated the impact of soil moisture and other factors influencing precipitation using atmospheric general circulation models. Koster *et al.* (2004) generated a global map of land-atmosphere coupling strength (their fig. 1) based on atmospheric general circulation models. Even if Central Europe is not a hot spot on this map, Koster *et al.* (2004) claim that soil moisture can be expected to influence precipitation in regions where evapotranspiration is suitably high but still sensible to soil moisture. By comparing regional climate simulations of a coupled atmosphere - land-surface model scheme to an uncoupled model scheme for selected summer heat waves in Europe Fischer *et al.* (2007) estimated that land-atmosphere interactions over dry areas increase the number of heat days by 50 - 80%. Wang *et al.* (2011) supported the findings of Fischer *et al.* (2007) by analyzing observational data of the Mediterranean region. Zampieri and D'Andrea (2009) found that spring droughts in the Mediterranean favor the development of strong heat events in "temperate continental Europe", and Hirschi *et al.* (2011) point out the importance of soil moisture deficit for the development of strong heat waves in southeastern Europe.

Although the land-atmosphere interactions seem to be an important trigger in the development of extremely sunny and dry summers, it is obvious that the occurrence of the predictor variables used here, solar irradiation and precipitation, are related to specific circulation patterns in the ocean-atmosphere systems not considered in the presented phenomenological-driven model. For example Cassou *et al.* (2005) found that two large-scale atmospheric circulation patterns that favor the occurrence of hot days in France: the so called "blocking" and the so called "atlantic low". The "blocking" refers to a positive North Atlantic Oscillation (NAO+) pattern, i.e. negative anomaly over Greenland and high pressure anomaly over Europe. During "blocking" conditions extra-tropical frontal systems are deflected northward and suppress "the local convective instabilities, leading to light winds, dryness, clear skies and warming" (Cassou *et al.*, 2005). Whereas during an "atlantic low" strong negative pressure anomalies occur over the north Atlantic and "weaker positive anomalies" over continental Europe and "the advection of warm air masses from northern Africa and the Mediterranean basin dominates" (Cassou *et al.*, 2005). Spatio-temporal analyses have shown for instance that the heat wave in summer 2003 was related to large positive anomalies in the monthly 850 hPa pressure field, reaching towards the British isles and showing a northward shift of the Hadley circulation (e.g. Beniston and Diaz 2004). This is now confirmed by the current study for the highly extreme heat waves of the record (figs 4.1, 4.2, 4.5). In this context, Ogi *et al.* (2003, 2004a) revealed that these pressure anomalies are related to dipole structures in the North Atlantic pressure and sea level pressure fields which relates to North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) pattern. They also, stressed by using results of spatial correlation analyses, that there is a clear relation of winter, spring and summer circulation patterns influencing temperature anomalies over Europe and other regions. Ogi *et al.* (2004b) found that the seasonally varying Northern Annular Mode index (SV NAM index), which reflects AO/NAO conditions, in winter is highly correlated with pressure anomalies in summer over the British isles which are proven in this study to be related with the establishment of extreme summer heat waves. The winter-summer relations of atmospheric circulation patterns is hypothesised to be coupled with Arctic coast and Eurasia snow cover variability with feedbacks to temperature (Ogi *et al.*, 2004b). Future research might investigate if the inclusion of large-scale circulation mode (as NAM) could improve the prediction quality of heat waves.

However, the analysis also reveals that the extremely sunny and dry summer in 1983 is not preceeded by a FMA season with solar irradiation anomalies and precipitation anomalies of the same sign as during JJA, and that after the extremely sunny and dry FMA season 2011 a summer season of close to normal to even slightly below (above) average conditions regarding solar irradiation (precipitation) followed (figs. 4.1, 4.2). These observations fit well with the ENSO conditions of the preceeding December - January (DJ) periods, in that the mean BEST index shows the opposite sign in DJ 1982/83 and DJ 2010/11. The observed effects of the (extreme) ENSO conditions and the (probably connected) synoptic characteristics in Europe are also described by various authors (section 4.4): As a consequence of the conditions found in 1983 and 2011 and based on the results of Frädrich (1990, 1994), Frädrich and Müller (1992), and Cassou *et al.* (2005) it is assumed that under extreme ENSO conditions, the FMA - JJA relation with regard to strong positive (negative) anomalies of solar irradiation (precipitation) in Central Europe a differentiation between El Niño and La Niña can be made: During strong El Niño conditions as observed in the winter month 1982/83 (mean DJ Best index: 2.57) and 1997/98 (mean DJ BEST 2.23), an extremely sunny and dry summer might occur (1983) or not (1998), although there is no signal in the FMA season observed. El Niño induced disturbances might be the reason for the decoupling of FMA and JJA conditions in the case of extremely sunny and dry summer seasons. On the other hand, if extreme La Niña conditions occur in the preceeding DJ period, as 2010/11 (mean DJ BEST -2.71), the following summer season might not be extremely sunny and dry (2011), although the FMA conditions show a clear sign for an extremely sunny and dry summer. In these situations the extreme FMA conditions might be due to the La Niña induced large-scales disturbances, which might terminate as the ENSO conditions return back to "normal". Thus the synoptic-scale late winter / spring - summer connection is not occurring in post extreme La Niña years.

The analysis presented is undertaken for the study area 47 ° N - 56° N, 4° E - 15° E. However, the findings might be also valid for other areas. For example Hirschi *et al.* (2011) found that drier surface conditions lead to an intensification of hot extremes in southeastern Europe, Barriopedro *et al.* (2011) came to similar conclusions for the hot summer of 2010 in western Russia, and Wang *et al.* (2011) found similar relationships in the Mediterranean. A first attempt to check if the results are valid for a larger area is made, by applying the methods described to the region 30° N - 70° N, -20° E - 70° E (not shown). This larger area seems to be too large for a FMA - JJA relation in terms of solar irradiation excess and precipitation deficit. Within this larger area many different mechanisms apply (different synoptic regimes at a time, different regional phenomena), such that positive and negative anomalies of the variables in question equalise. However, as indicated by other authors the mechanisms found might be valid for other areas within Europe then the region under investigation in this study (Fischer *et al.* 2007, Wang *et al.* 2011, Hirschi *et al.* 2011, Zampieri and D'Andrea 2009, see above).

4.6 Conclusions and Outlook

In this study the conditions of the late winter / spring seasons prior to extremely sunny and dry summers in Central Europe are investigated using solar irradiation and precipitation as proxies. These two variables serve as proxies since (1) they are driven by synoptic-scale circulations and (2) they themselves are important factors determining soil moisture (e.g., Orth and Seneviratne 2012). And both, synoptic-scale circulations (e.g, Cassou *et al.* 2005) as well as internal feedback mechanisms associated with soil moisture, are important in the development of extreme summer heat waves in Central Europe (e.g., Seneviratne *et al.* 2006, Hirschi *et al.* 2011). The analysis is mainly based on observations of solar irradiation derived from satellites (MAGICSOL) and re-analysis data (ERA-40 / ERA-interim), and on in situ measurements of precipitation (GPCC). A hypothesis is tested which states, that summers with extremely high amounts of solar irradiation and large negative anomalies of precipitation in central Europe are indicated by prior late winter / spring seasons that show the same direction of anomalies in these variables.

The results presented support this hypothesis for the highly extreme summer seasons regarding high amounts of solar irradiation and low amounts of precipitation. The predominance of anticyclonic atmospheric circulation regimes seems to be a prerequisite for the development of very extreme summers. However, the hypothesis is refuted in years following extremely strong La Niña and El Niño events. In these years the late winter / spring - summer connection of the dominance of anticyclonic conditions in Central Europe seems to be disturbed. This fits well with findings published by other authors (Frädrich 1990, Frädrich 1994, Frädrich and Müller 1992, and Cassou *et al.* 2005).

Recent publications of Ogi *et al.* (2003) and Cassou *et al.* (2005), describe some large-scale atmospheric circulation characteristics related to extreme summer conditions in Europe. This large-scale atmospheric circulation regimes might induce the development of late winter / spring conditions with extremes in solar irradiation and precipitation leading to soil moisture deficits and subsequently inducing the positive feedback-loop described in section 4.4.1. If these conditions remain in their basic characteristics throughout summer, or re-appear due to some kind of memory in the large-scale circulation, then extreme summers as the ones in 1976 and 2003 develop. I.e., the soil-atmosphere feedback resulting from certain large-scale atmospheric patterns might then foster and stabilize the conditions for highly extreme hot and dry summers in (central) Europe (see also Ratcliffe 1978 and Fischer *et al.* 2007).

However, global circulation anomalies connected to extreme ENSO events might disturb this interaction between synoptic-scale circulations and internal feedback mechanisms.

Based on the results presented an early warning method for extreme summers in Central Europe could possibly be developed using the following row of decisions: If the ENSO in the winter (DJ) season prior to the summer in question is not in an extreme state (i.e., -2 < mean DJ BEST index > +2) and if the SMR_{FMA} values of solar irradiation and precipitation are within the upper and lower 10^{th} percentile, respectively, a highly extreme sunny and dry summer with SRM_{JJA} values of solar irradiation and precipitation exceeding the 90^{th} percentile and undermining the 10^{th} percentile, respectively, can be expected.

To improve the conclusiveness of the statistics a prolongation of the time series would be very important, but is limited by the availability of appropriate gridded data sets.

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Chapter 5

Analysis and Discussion of Atmospheric Precursor of European heat summers

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Analysis and discussion of atmospheric precursor of European heat summers

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Abstract

Summers with notable droughts and heat waves significantly affect human well being, agriculture, and forestry. The economic impact of extreme hot and dry summers is immense. The monitoring, analysis and prediction of extremely hot and dry summers are therefore important tasks. In a previous study of the authors evidence has been found that extreme summers are connected with specific winter-spring conditions during the investigated time period 1958-2011. Hence, evidence has been found that these specific winter-spring conditions could serve as indicator for extremly hot and dry summers. This would enable an early prediction of extreme summers. In the present manuscript these findings are further discussed and analysed in the context of the Earth's atmospher and ocean circulation systems. Within this scope the North Atlantic circulation (NAO), the Arctic oscillation (AO), as well as the El Niño Southern Oscillation (ENSO) are analysed, using respective established indices, to investigate possible connections with extremely sunny and dry summers in Central Europe. Further, analysis of the geopotential at 860 hPa height is performed. No evidence for a connection between the NAO or AO index during the winter-spring transition and extremely hot and dry summers is found. However, inspection of the geopotential at 850 hPa height provides evidence that a "Greenland - North Sea" dipole is connected with extremely dry and hot summers in Central Europe. This findings motivated the introduction of the novel "Greenland - North Sea Dipole Index", GNDI. High values of the GNDI correlate with the occurrence of extremely hot and dry summers. However, using these index as predictor would lead to one false alarm and one missed event. Evidence is found that these shortcomings are due to the disturbance of the "dipole - summer" connection by the ENSO. In order to consider the effect of ENSO and its coupling with the Greenland - North Sea dipole a novel index the Central European Drought Index (CEDI) was developed and introduced.

This index consists of the GNDI and the BEST ENSO index. With this index it is possible to indicate all extremely hot and dry summers without any missed event or serious false alarm during the investigated time period (1958-2011). The authors conclude that the CEDI serves as an indicator of approaching summers with highly extreme positive anomalies in solar irradiation (hot) and highly extreme negative anomalies in precipitation (dry) in Central Europe.

5.1 Introduction

Extreme summers with droughts and heat waves significantly affect human well being. During the heat summer 2003, for instance, several thousand mainly elderly people diseased in Central Europe (World Health Organization (WHO), 2010), probably due to perilous dehydration (Muecke, H.-G. and Becker, P., 2008) and (or) cardiovascular problems (WHO, 2013). Beside the effect on human well-being heat summers have adverse economic effects, e.g. on agriculture (Munich Re Group, 2004) and forestry (Lobinger, 2004). In some regions severe problems with water supply occurred. The financial loss due to crop failure induced by e.g. the 2003 heat wave is estimated at 12.3 U.S. $ (Heck *et al.*, 2004). More over, extremely hot and dry summers increase the risk for forest fires (e.g. Mühr *et al.* 2012) and are likely to increase the rock-fall in the Alpine region due to intensified thawing of permafrost (Gruber *et al.*, 2004).

It is evident that the impact of extremely hot and dry summers on human well being and the environment is eminently essential. Extreme weather can not be avoided, but safety precautions and mitigation measures could be implemented. Yet, this requires sufficient handling time. Hence, early and reliable meteorological predictions of extreme drought events could significantly contribute to the mitigation of the adverse effects described above and could minimize their negative impact. However, completely reliable seasonal prediction systems are to the knowledge of the authors not existing hitherto.

The severe impact of the heat summer 2003 in Europe might be one reason why heat waves attracted wide interest, both in the public and the scientific community, and that this event has been analysed in detail from various disciplines (Fischer *et al.*, 2007, and references therein).

Several authors have analysed and discussed the development and origin of heat waves within the scope of meteorology. Long lasting anticyclonic circulation anomalies have been discussed by several authors as a key factor for mid latitudinal summer heat waves (Fink *et al.*, 2004; Ionita *et al.*, 2012; Barriopedro *et al.*, 2011; Carril *et al.*, 2008). The 2003 European heat wave (Fischer *et al.*, 2007) as well as the 1995 and 1999 heat waves over the U.S. (Palecki *et al.*, 2001; Kunkel *et al.*, 1996) were characterised by 500 hPa geopotential anomaly patterns. The anticyclonic anomalies are associated with clear skies and subsequent heating of the Earth by solar irradiation. This in turn generates stable atmospheric stratification, which suppresses local convection.

Furthermore, the circulation anomalies are blocking storm tracks and frontal systems (e.g. Chang and Wallace 1987) and are often associated with a large-scale stationary Rossby wave pattern. (Fischer *et al.*, 2007, and references therein). In the anticyclone trajectories of air parcels are bounded to the core of the cyclone in a manner that the area covered by the trajectories is much smaller then in typical summer years (Black *et al.*, 2004). Air parcels are "trapped" in the anticyclone. This behavior indicates a Lyapunov stable equilibrium state of the atmospheric circulation in this region. Extreme heat summers are characterized by a long lasting stable situation, which also indicates that the atmospheric circulation is in a regional equilibrium. For such extraordinary stable atmospheric states it could be expected that a specific atmospheric precursor state (initial state) might indicate the occurrence of extremely hot and dry summers. Such an indicator could be used to issue early warnings.

Indeed, empirical hints have been found that a precursor of extreme summers in Central-Europe exists (Träger-Chatterjee *et al.*, 2013) and that an early prediction of heat summers might thus be possible.

Träger-Chatterjee *et al.* 2013 showed that extremely sunny and dry summers in Central Europe are preceeded by a winter-spring transition with large positive (negative) anomalies of solar irradiation (precipitation), if the El Niño Southern Oscillation (ENSO) is not notably extreme.

In this study the summers (June - July - August, JJA) with the highest (lowest) values of solar irradiation (precipitation), leading to severe heat waves, are defined as extremely sunny and dry. Within this scope the summers of the years 1976, 1983 and 2003 have been identified as notably extreme. Notably extreme means, that the regional means of the seasonal sums of solar irradiation are within the upper 10 %, and the regional means of the seasonal sums of precipitation are within the lower 10 % of the time-series analysed. Träger-Chatterjee *et al.* 2013 investigated also the winter-spring transition February - March - April (FMA) prior to the above mentioned summer (June - July - August, JJA) seasons in Central Europe. They found that FMA in 1976 and 2003 were characterized by positive anomalies of geopotential in 850hPa and solar irradiance and by negative anomalies in precipitation. Träger-Chatterjee *et al.* 2013 conclude that a clear connection between the sunny and dry FMA seasons and the following extreme summers in 1976 and 2003 exists. In 1983 a strong ENSO event is observed instead of a "regional" FMA - JJA connection. Figures 4.3 and 4.4 show the anomalies of solar surface irradiance and precipitation for the respective period.

Based on the findings described above the authors claim that the stable state during extreme summer heat waves in Central Europe is associated with specific and unique initial atmospheric conditions (precursor) in the preceding winter-spring period. Consequently, we hypothesize that winter-spring indicators of atmospheric circulations can be used for seasonal predictions of extreme summer heat waves.

5.2 Materials and Methods

This study follows the definition and selection of extremely sunny and dry summers of Träger-Chatterjee *et al.* (2013), according to extremes in solar irradiation and precipitation. Please see Träger-Chatterjee *et al.* (2013) for further details about the data sources and methods. The same time period (1958 - 2011), as in Träger-Chatterjee *et al.* (2013) is investigated here in order to discuss potential precursor of extremely sunny and dry summers by analysing the atmospheric circulation. For this purpose established indices of the atmospheric circulation are used on one hand and on the other hand, novel indices are developed and defined. For the definition of the novel indices the geopotential at 850 hPa provided by the European Center for Medium Range Weather Forecast (ECMWF) is analysed. Therefore the 40-yr re-analysis data set ERA-40 (Kållberg *et al.*, 2005) for the period 1958–1988, and the ERA-Interim (Berrisford *et al.*, 2009) for 1989-2011, are used.

The North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) are very important for the weather and climate in Central Europe and the North Atlantic. Hence, the well established North Atlantic Oscillation and Artic Oscillation indices according to Hurrell *et al.* 2013b and Hurrell *et al.* 2013a are discussed in more detail in section 5.3.1. These indices have been derived by Principal Component Analysis (PCA), (Hurrell *et al.*, 2013b,a). Further, a new indicator, a distinct pressure difference index is introduced in section 5.3.2. This index results from analysis of geopotential fields at 850 hPa and aims to serve as a precursor of extremely sunny and dry summers in Central Europe. This index covers only synoptic circulations, however, extreme summers might be also affected by global scale circulations.

Several authors discussed the effect of the El Niño Southern Oscillation (ENSO) on the weather in Europe (Broennimann, 2007, and references therein). Therefore, ENSO's potential role on the development of European heat summers is discussed and analysed in section 5.3.3, using the PCA based BEST index according to Smith and Sardeshmukh (2000) is used. The analysis leads to the postulation of a novel index, which aims to consider the coupling of the synoptic and the global scale. This is discussed in section 5.3.4.

5.3 Results and Discussions

5.3.1 North Atlantic and Arctic Oscillation

The North Atlantic Oscillation (NAO) is widely accepted as the most important circulation pattern in the northern hemisphere (e.g. Walker and Bliss 1932; Barnston and Livezey 1987; Walter and Graf 2005; Hurrell and Deser 2010). According to several authors the NAO is closely associated with the Atlantic During summer the NAO is not as pronounced as during winter. Consequently its dominance on European weather during winter is stronger than during summer (e.g. Walker and Bliss 1932; Cassou *et al.* 2005; Hurrell and Deser 2010).

On the other hand, (Ogi *et al.*, 2004b) found that AO (Arctic Oscillation) [5] / NAO conditions in winter are highly correlated with pressure anomalies over the British Isles in summer.

A reason for this correlation might be that strong wintertime NAO "can interact with the slower components of the climate system (the ocean ...) to leave persistent surface anomalies into the ensuing parts of the year that may significantly influence the evolution of the climate ..." (Czaja *et al.* 2003; Rodwell 2003 both in Hurrell and Deser 2010).

Thus, to investigate whether NAO/AO indeces might be useful for the prediction of summer heat waves we analysed the behavior of the NAO and the AO in the time series 1958-2011.

For the NAO the PCA (Principal Component Analysis) based seasonal NAO index (December-January-February-March) according to (Hurrell *et al.*, 2013b) is used (see figure 5.1). This index is available from the National Center for Atmospheric Research homepage (Hurrell *et al.*, 2013b, see http link in:). In contrast to station based NAO indices, the PCA based index accounts for the movement of the NAO pressure centers Azores High and Atlantic Low (Hurrell *et al.*, 2013b). This is regarded as an advantage compared to the station based indices since the PCA based index covers most of the Atlantic (20-80°N and 90°W to 40°E) and thus captures the action centers regardless of their actual position.

Figure (5.1) reveals that the years of the summer seasons identified as being extremely sunny and dry do not show any characteristic properties, indicating that the NAO is not suited as an indicator of extreme summer heat waves ahead.

The same holds for the Arctic Oscillation. To analyse the Arctic Oscillation as a possible predictor of extremely sunny and dry summers in Central Europe, the wintertime (DJFM) Arctic Oscillation Index (also referred to as "Northern Annular Mode") according to (Hurrell *et al.*, 2013a), published at Climate Data Guide, is used (Hurrell *et al.*, 2013b, please see http link in:). This index refers not

[5] Arctic Oscillation (AO) is described by (Thompson and Wallace, 1998) as a seesaw of see level pressure (atmospheric mass) "between the Arctic basin and parts of surrounding ring".

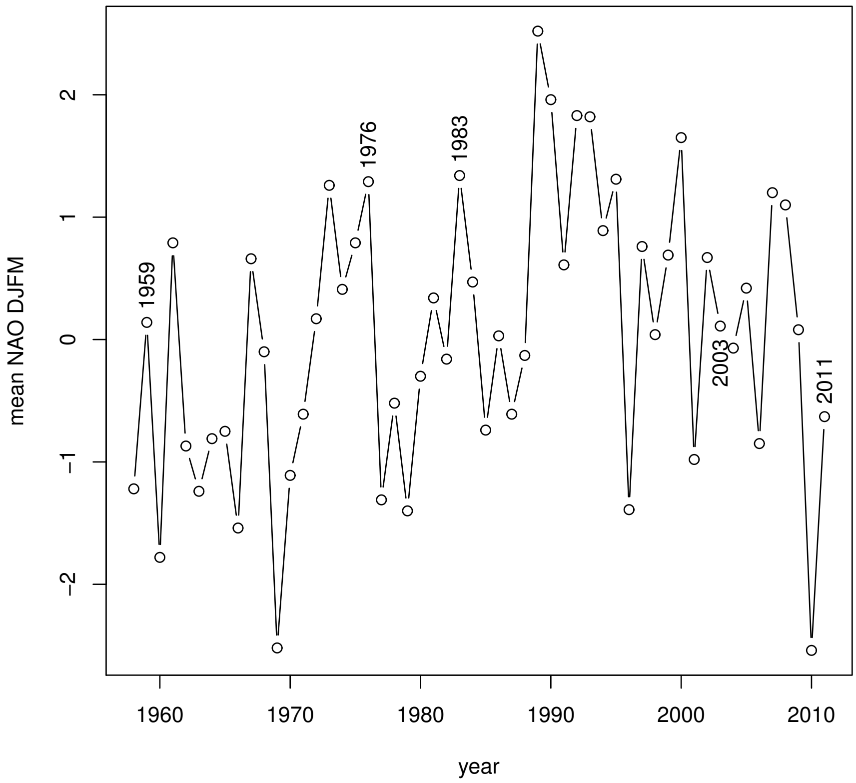

Figure 5.1: Time series of December-January-February-March Hurrell's North Atlantic Oscillation index based on Principal Component Analysis (Hurrell *et al.*, 2013b).

only to the North Atlantic (as the NAO), but to the entire northern hemisphere sea level pressure and is defined as the first EOF of the latter (Hurrell *et al.*, 2013a). Also in the time series of the AO index, no threshold value can be identified for the years with highly extreme sunny and dry summer seasons, see figure (5.2).

The analysis of NAO and AO provides no hints that they are appropriate indicators for extremely sunny and dry summers in Central Europe.

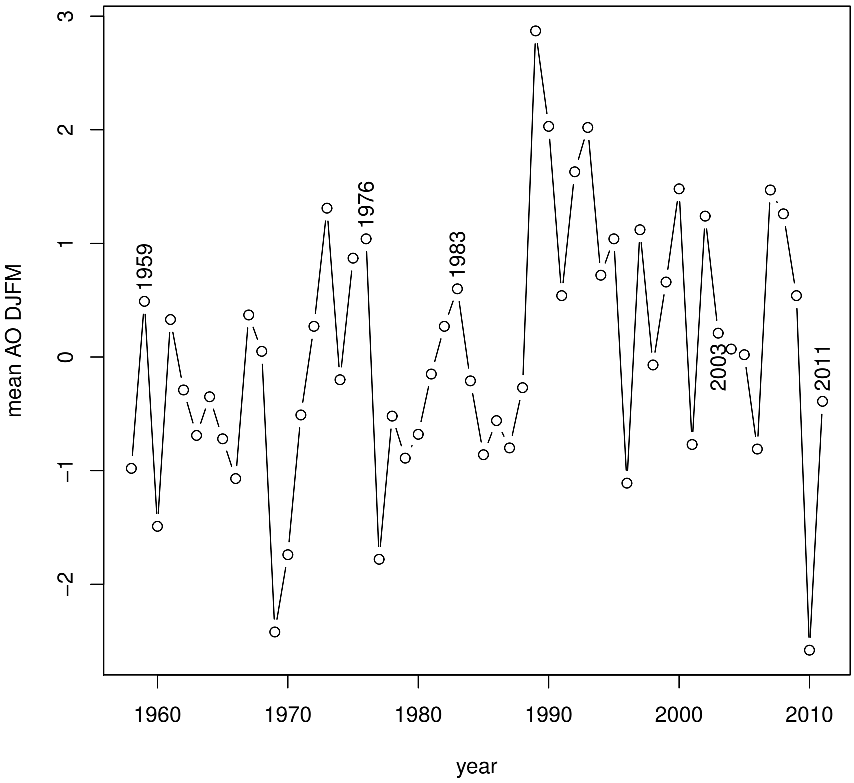

Figure 5.2: Time series of December-January-February-March Hurrell's Arctic Oscillation index based on Principal Component Analysis (Hurrell *et al.*, 2013a).

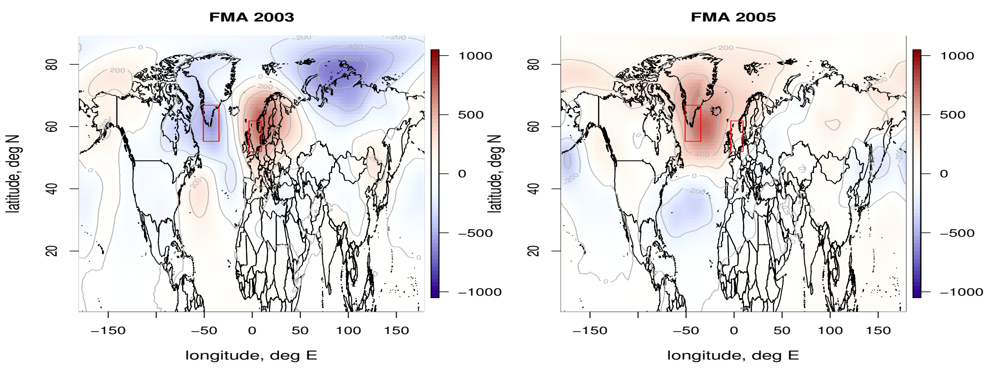

Figure 5.3: Example of the Greenland - North Sea Dipole: Geopotential Anomaly at 850hPa of FMA for 2003 and 2005. In the heat wave summers 2003 the dipole is clearly apparent while in the relative normal normal year 2005 it is not apparent.

5.3.2 Greenland - North Sea - Dipole Index, GNDI

Since no explicit connection between the NAO / AO and the occurrence of extremely sunny and dry FMA and the following JJA seasons in Central Europe could be found in the data, the atmospheric circulation over the North Atlantic is analysed using the geopotential at 850 hPa. In the years with notable extreme sunny and dry FMA seasons a conspicuous dipole structure of anomalies between southern Greenland (negative pressure anomaly) and the North Sea / Fennoscandia (positive pressure anomaly) has been found. Figure 5.3) shows an example of this dipole in comparison to a year with normal winter/spring and summer conditions.

In contrast to the NAO, which is generally described as a meridional pressure gradient over the North Atlantic (Hurrell and Deser, 2010), the anomaly maps (see figure 5.3 right hand side for the year 2003) rather show a zonal pressure gradient between southern Greenland and the North Sea / Fennoscandia.

To quantitatively analyse this dipole, the mean values of the regions southern Greenland (-50.96° to -34.78° longitude, 55.27° to 66.88° latitude) and North Sea (-3.46° to 9.34° longitude, 51.93° to 61.82° latitude) are calculated for the time series 1958 - 2011 and an anomaly measure is calculated based on these regional means for each of the two dipole regions. The exponent of the difference of these values is introduced as the novel GNDI (Greenland North sea Dipole Index). Equation (5.1) provides the mathematical definition of the GNDI. The exponential function is motivated by the non-linear characteristics of the system and in order to emphasize the role of notable dipoles.

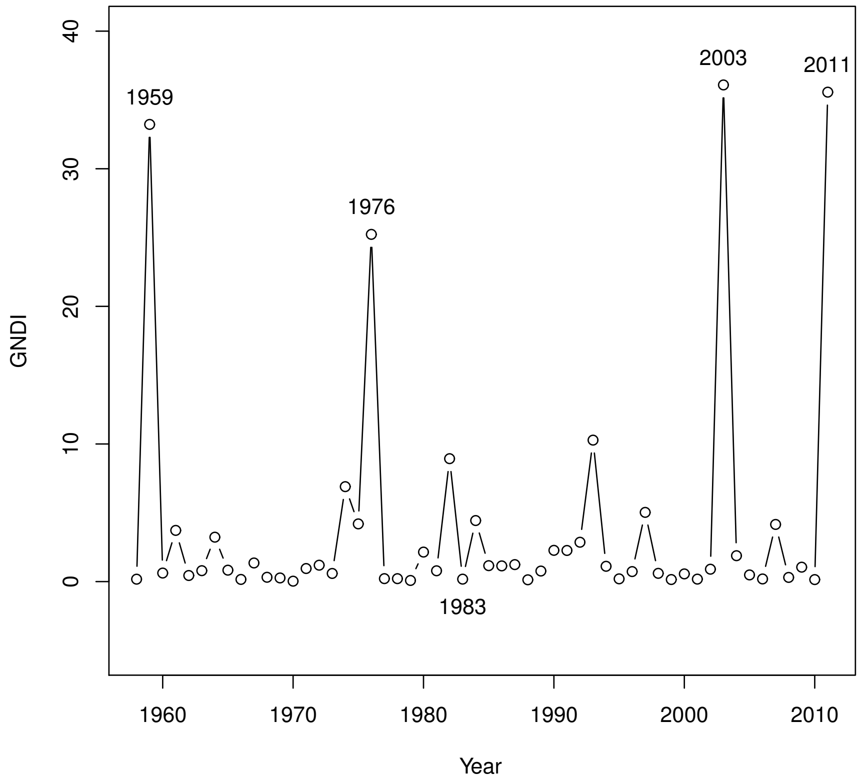

Figure 5.4: Time series of the Greenland North sea dipole index derived from anomalies in the geopotential at 850 hPa.

$$GNDI = exp(NA - GA) \text{ , with:} \tag{5.1}$$

$$NA = \frac{A_y^N - \bar{A}^N}{\sigma A^N} \tag{5.2}$$

$$GA = \frac{A_y^G - \bar{A}^G}{\sigma A^G} \tag{5.3}$$

Here, A is the anomaly of the geopotential, $\bar{A}$ is the arithmetic mean and σA is the standard deviation of the anomalies. G and N depicts North Sea and Greenland region, respectively. The time series of the GNDI is shown in Figure 5.4.

The alignment of the GNDI with the heat summer years 1976 and 2003 reveals a threshold of about 20. I.e. in years where the GNDI during FMA exceeds 20, an extremely sunny and dry summer is indicated for Central Europe. Years exceeding a GNDI value of 20 are 1959, 1976, 2003, and 2011. The FMA season of all the four years exceeding a GNDI of 20 show large positive anomalies of solar irradiation and large negative anomalies of precipitation in Central Europe, see figure 4.3 and 4.4

Two of the years, 1976 and 2003, were among the highly extreme summers regarding high solar irradiation and low precipitation in the time series, i.e. among the 10 % with the highest solar irradiation amounts and the lowest precipitation amounts (please see definition of highly extreme summers in Träger-Chatterjee *et al.* 2013).

The dipole situation associated with the highly extreme summers may depict a stable solution of the dynamics associated with the atmospheric flow. This stability in the atmospheric circulation is observed in 1976 and 2003 by the predominance of the anticyclonic weather conditions over Central Europe, which largely persists from winter-spring transition throughout summer. The stable anticyclone determines the high (low) solar irradiation (precipitation) amounts. Solar irradiation and precipitation in turn determine soil moisture which is an important factor in the development of strong heat waves (Fischer *et al.*, 2007; Hirschi *et al.*, 2011) due to its importance for the development (or suppression) of convective clouds and precipitation (Zampieri and D'Andrea, 2009; Träger-Chatterjee *et al.*, 2013).

Thus the findings provide hints for a connection between winter-spring conditions of the North Atlantic circulation and the following summer season in Central Europe. I.e. a dipole with negative geopotential anomaly over Greenland and positive geopotential anomaly over the North Sea / Fennoscandia during FMA is a valuable indicator for extremely sunny and dry summer seasons in Central Europe.

According to the definition in Träger-Chatterjee *et al.* 2013 the summer of 1959 is not among the highly extreme summer events, but among the extreme summer events, i.e. among the 20% with highest solar irradiation and lowest precipitation amounts, and is thus not contradicting the connection described above.

However, the evaluation of heat summers performed in Träger-Chatterjee *et al.* (2013) reveals that the GNDI would lead to a year with "false alarm" and one year with a "missed event": The false alarm year 2011 has a GNDI value above the threshold (see fig 5.4), which is associated with an extremely sunny and dry FMA season, but the following summer was wet and slightly more cloudy than usual and by no means extremely sunny and dry (radiation slightly below and precipitation above normal amounts, see figures 4.3 and 4.4). And 1983, the year with the missed event, has a GNDI value far below the threshold, but the cloudy and wet

FMA season was followed by an extremly sunny and dry summer (figures 4.3 and 4.4). In the following the former is referred to as a a false alarm and the latter as a missed event. In 1983 and 2011 the dipole shows a different behavior than in 1976 and 2003. In both years (1983, 2011) the dipole changes polarity between FMA and JJA. This might indicate that in these two years the winter / spring - summer connection is disturbed by another interfering large-scale circulation. Indeed, in both years, the large scale El Niño Southern Oscillation (ENSO) was in an extreme state.

In 2011, the year with the false alarm, a very strong La Niña event, and in 1983, the year with the missed event, a strong El Niño was recognized, which both might have influenced the large-scale circulation also in the northern hemisphere and thus also the summer conditions in Europe.

5.3.3 The ENSO disturbance

In the analysis presented, two years have been found for which the GNDI is not a suitable indicator for extremly hot and dry summers. In 1983 the GNDI indicated a normal summer, but an extremely hot and dry summer occurred after the cloudy and rainy FMA (missed event). In 2011, on the other hand, the GNDI indicated a hot and dry summer, but a summer with relativly "normal" solar irradiation and high precipitation occurred (false alarm).

For 2011, the dipole between Southern Greenland and the North Sea / Fennoscandia exists in FMA, but not in JJA (not shown). This means that during that year the atmospheric equilibrium / connection is presumably disturbed (superimposed) by another effect. In 1983, the situation is vice versa: A dipole is apparent but with opposite polarity, hence the GNDI is close to 0, but JJA was extremly hot and dry. As discussed in Träger-Chatterjee *et al.* 2013, the missed event and false alarm are accompanied with strong El Niño Southern Oscillation (ENSO) events in the winter seasons 1982/83 and 2010/11 (please see figure 5.5). We assume that this is not a coincidence but that ENSO is the disturbing factor, which is further discussed and analysed, hereafter.

It is widely agreed that the El Niño Southern Oscillation (ENSO) is one of the most important (Broennimann, 2007) and strongest (Graf and Zanchetin, 2012) climate patterns of the globe (Trenberth, 1991). Its impacts are not restricted to the tropical Pacific, but it affects weather and climate all over the globe (Trenberth, 1991). A summary description of ENSO and its impacts on European climate can be found in the review paper of (Broennimann, 2007).

Broennimann 2007 concludes that ENSO effects on Europe interact with many other mechanisms (e.g. Pacific Decadal Oscillation, tropical Atlantic SSTs, NAO), differ with the strength and position of the respective ENSO event, and are modulated by other environmental phenomena, such as volcanic eruptions. I.e. ENSO-induced effects on European climate are variable.

However, some common features appearing during El Niño (La Niña) winter could be identified for Europe: more cyclonic (anticyclonic) pressure systems following after El Niño (La Niña) events associated with more (less) precipitation over western and central Europe and the contrary over northern Europe Frädrich and Müller (1992).

Beside others Lau and Nath (1996) and Herceg Bulic and Kucharski (2012) show that ENSO events could lead to SST anomalies in the Atlantic. As a possible physical explanation of the connection between ENSO events and SST anomalies in the northern Pacific and Atlantic Lau and Nath 1996 describe an "atmospheric bridge": Their model experiments exhibit that a chain of air-sea-interactions resulting from "heat and radiative fluxes at the air-sea interface", which needs about 4 month time to generate considerable SST anomalies in the North Atlantic. Hence, 4 months lead time is required in their model experiments for the atmospheric bridge to affect the North Atlantic. The feedback of the SST anomalies to the weather in Central Europe needs further time. As ENSO events usually occur around Christmas the "atmospheric bridge" serves as a possible physical explanation for the effect of ENSO on European spring and summer conditions.

In summary, several authors show clear evidence that ENSO events affect the weather in Central Europe (Broennimann, 2007, and references therein). Thus, it is likely that extreme ENSO events disturb / superimpose the synoptic connection between winter-spring transition and the subsequent summer. As the ENSO events in 1983 and 2011 have been notably extreme it is a reasonable assumption that La Niña has been a reason for the relativly normal and rather rainy summer, despite of the high GNDI value and that EL Niña has been a reason for the extremly sunny and dry summer, despite of the low GNDI value. Hence, the extreme ENSO events are likely the reason for the GNDI "failure".

I.e. due to the extremely strong ENSO events in 1983 and 2011 the climate during summer of those two years is not a consequence of the prior "North Atlantic" spring conditions. Instead, the anomalies in both season, FMA and JJA, of these years are likely a consequence of global scale interactions of the ocean-atmosphere system which were strongly influenced by ENSO-induced processed. Hence, in years with extreme ENSO events GNDI alone is not suitable to indicate hot and dry summers.

The analysis performed so far indicates that for the definition of an indicator for extreme sunny and dry summers the Greenland - North Sea Dipole as well as the ENSO have to be considered. Thus, the combination (coupling) of the BEST index and the GNDI might lead to an index which can be used to improve the predictability of hot and dry summers significantly. This leads to the introduction

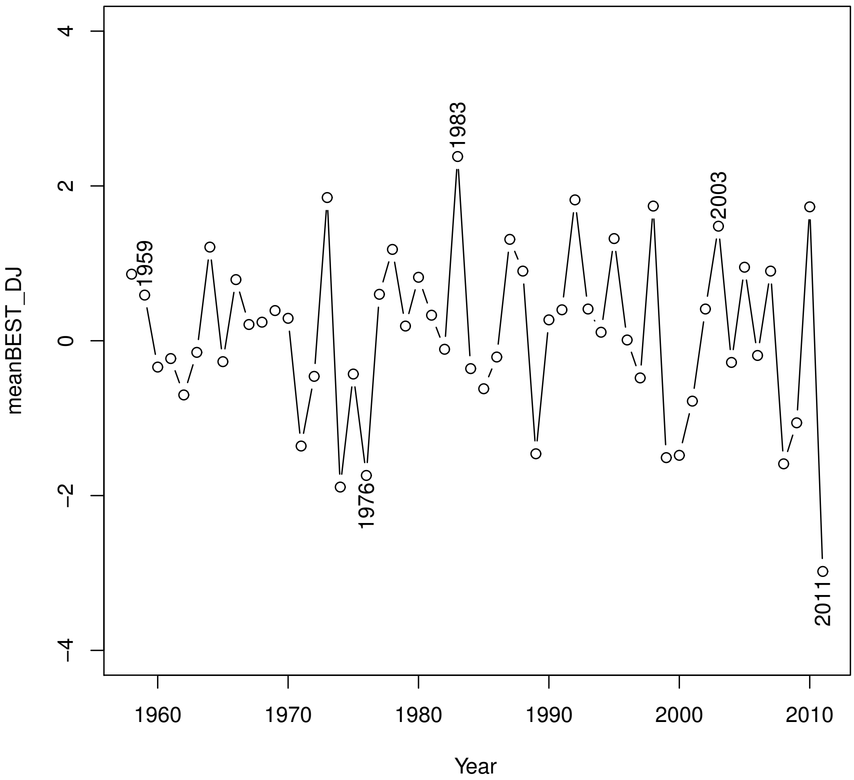

Figure 5.5: Time series of the BEST index, according to Smith and Sardeshmukh (2000). The BEST index is extreme in the years with false alarms or missed events according to GNDI.

of the novel Central European Drought Index (CEDI), which is discussed and evaluated in the next section.

5.3.4 The Central European Drought Indicator CEDI

To account for the ENSO influence on the development of Central European summer weather, discussed in section 5.3.3, the GNDI is combined with the BEST index, a measure of the state of the ENSO. Negative BEST values indicate La Niña events and positive BEST values indicate El Niño events.

In order to balance between the effect of the Greenland - North Sea dipole (expressed in the GNDI) and ENSO (expressed in a BEST term) the power of 3 of the BEST index is applied. The use of an exponential function for the BEST index (as for GNDI) is not suitable here, since it would depress large negative values of the BEST index, which indicate notable El Niño events.

Due to the large distance between Europe and the Southern Pacific, where ENSO occurs, we assume that only notably extreme ENSO events have the potential to disturb the connection of extremely sunny and dry winter-spring transition and summer seasons in Central Europe. Hence, the ENSO term is only applied if the absolute BEST value exceeds 2.

These considerations lead to the following definition of the Central European Drought Index (CEDI):

$$CEDI = \begin{cases} GNDI - |BEST_{dj}|^3 & \text{, if } |BEST_{dj}| \geq 2 \\ GNDI & \text{else} \end{cases} \tag{5.4}$$

here $|BEST_{dj}|$ is the absolute value of the BEST index averaged over the early winter season (December-January) prior to the FMA season to which the GNDI refers. Using the absolute value of BEST has the advantage that the algebraic sign of CEDI provides information whether GNDI (positive) or ENSO (negative) have been a driving factor for extreme summers.

The time series of the CEDI is shown figure 5.6. The highly extreme summers 1976 and 2003 are clearly visible as notable extremes and exceed the threshold of 20. Also the extreme summer 1959 exceeds a CEDI threshold of 20. The previously missed event of 1983 can also be predicted using the CEDI and a threshold of -10. And finally, the false alarm in 2011 is no more occurring, since the CEDI shows a very low value for this year. Notably extreme positive CEDI values are associated with an extreme dipole anomaly in the Northern Atlantic, and hence associated to the synoptic scale. Notablly extreme negative values indicate a strong EL Niño event as the reason for the extremly hot and dry summer. The sign therefore serves as an indicator of the dominant driver. It is obvious that if CEDI is dominated by very strong El Niño events (negative values) a different threshold has to be applied.

The skill of CEDI is rather high, which might be interpreted as proof of the discussion and hypothesis outlined earlier.

5.4 Conclusions

Long lasting anticyclonic circulation anomalies have been discussed by several authors as a key factor for mid latitudinal summer heat waves (Fink *et al.*, 2004;

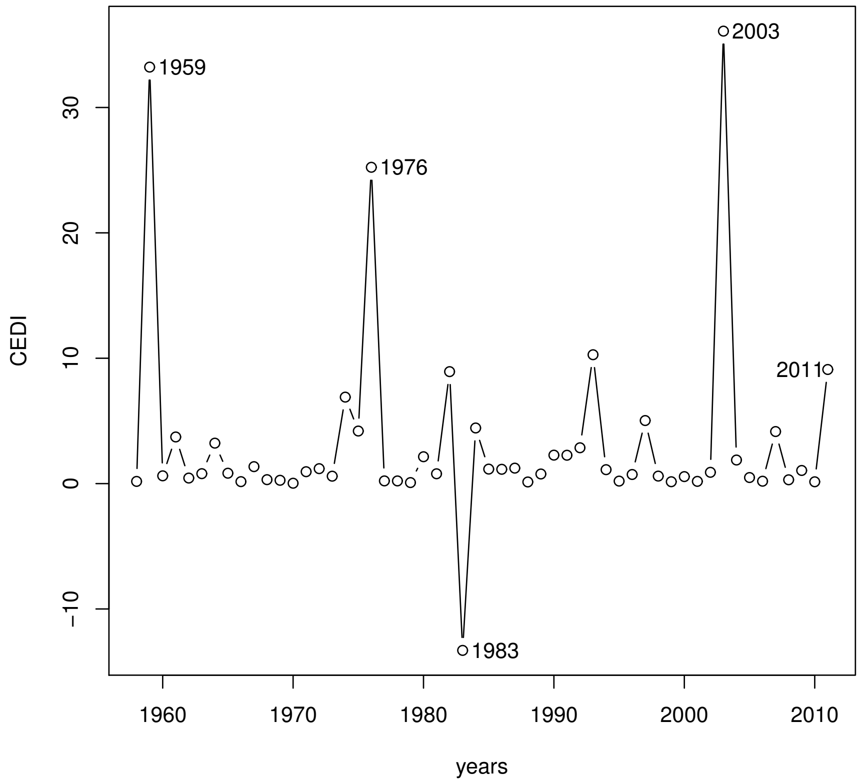

Figure 5.6: Time series of the novel Central Europe Drought Index (CEDI). The extremely dry and hot summers are clearly indicated by extreme CEDI values.

Ionita *et al.*, 2012; Barriopedro *et al.*, 2011; Carril *et al.*, 2008). These circulation anomalies block storm tracks and frontal systems (e.g. Chang and Wallace 1987) and are often associated with a large-scale stationary Rossby wave pattern (Fischer *et al.*, 2007, and references therein). More over, in the center of the anticyclone air parcel trajectories are "trapped" compared to normal summers (Black *et al.*, 2004), which is an indicator for a regional Lyapunov stable equilibrium of the atmospheric circulation

It is likely that long lasting stable atmospheric states during summer time show indicators prior to summer season.

Indeed, in (Träger-Chatterjee *et al.*, 2013) evidence has been found that extremely hot and dry summers might be connected to specific conditions during the winter-spring transitions, namely, sunny and dry conditions in Central Europe.

This connection might be useful to improve the predictability of heat waves.

In the present study the atmospheric dynamics on synoptical as well as on global scale were analysed in order to gain a deeper knowledge of winter / spring - summer the connection and its disturbance, and further, to evaluate indices for extreme summers in order to support the predictability of heat summers.

For this purpose a possible interlink of North Atlantic Oscillation (NAO) as well as Arctic Oscillation (AO) with extreme summers were investigated. No evidence for an interlink of NAO or AO with extreme summers was found. Instead, an analysis of the geopotential anomalies as proxy for the atmospheric circulation has led to the introduction of the Greenland - North Sea Dipole Index (GNDI). This index is a measure for the strength of the dipole anomaly in the geopotential at 850 hPa over Greenland and North Sea. It has been discussed that the GNDI serves as an indicator of approaching summers with very large positive anomalies in solar irradiation and very large negative anomalies in precipitation in Central Europe. The Greenland - North Sea Dipole Index (GNDI) supports the conclusions of Träger-Chatterjee *et al.* 2013, that solar irradiation and precipitation are an important proxy for the development of sunny and dry summers: The atmospheric pressure regimes which determine the high solar irradiation amounts and the low precipitation amounts, have now been identified. Hence, monitoring of the Greenland-North Sea dipole is expected to improve our knowledge of the North-Atlantic circulation system and its role for the development of extreme Central European heat waves and drought summers. While the GNDI indicates the heat summers in 2003 and 1976 it shows no evidence for the heat summer in 1983 and erroneously indicates the summer 2011 as extremely sunny and dry.

It has been analysed whether these failures are due to global scale ENSO disturbances. Indeed, evidence has been found that ENSO is the second main driver for extreme summers on one hand and likely responsible for the disturbance of the GNDI connection on the other.

In order to account for both, synoptic scale and global scale processes, a coupled index, the CEDI, is proposed. This index considers the coupling of the dominant processes for the development of extreme summers on synoptic and global scale. For the synoptic scale the novel Greenland - North Sea index and for the global scale the well established BEST index is used, which serves as a measure of the ENSO.

With the definition of the CEDI it is possible to indicate all extremely sunny and dry summers during the investigated time period (1956-2011) without any serious false alarm. Hence, clear evidence is given that this novel index contributes significantly to the analysis and prediction of droughts and heat waves in Central Europe. According to the results presented, the CEDI serves as an indicator of approaching summers with highly extreme positive anomalies in solar irradiation and highly extreme negative anomalies in precipitation in Central Europe.

However, due to the non-linear nature of the atmosphere-ocean system and the low frequency of occurrence of extremes the forecast skill of CEDI can not be finally defined yet. Though, for the investigated time period the skill score is close to 1 (no missed event, no notable false alarm). This should be astrong motivation to implement the CEDI as a novel index into operational monitoring systems.

Chapter 6

Conclusion and Outlook

6.1 Conclusion

Extreme heat and drought summers, especially in temperate regions, are a serious threat to human well-being, infrastructure, agriculture, forestry, and ecosystems. Knowing about the potential occurrence of such extremes well in advance would help to better prepare and mitigate accordingly. However, forecasting extreme heat and drought events on a seasonal scale is still challenging, since their development is not yet fully understood.

Recent publications conclude that extreme heat waves occur if anticyclonic circulation patterns during summer coincide with dry soils, which facilitate the development of high temperatures because the moisture deficit leads to a decrease in latent heat flux and increase in sensible heat flux (Fischer *et al.*, 2007; Hirschi *et al.*, 2011; Quesada *et al.*, 2012).

To the best knowledge of the author of this thesis, no study exists which analyses the atmospheric circulation patterns responsible for the soil moisture deficit in the winter - spring transition season prior to the extreme summers.

In this thesis, the characteristics of extremely hot and dry summers in Central Europe as well as their preceding winter - spring transition seasons are analysed with the aim of identifying potential precursor of extreme summers. Therefor large-scale atmospheric circulation regimes and land surface - atmosphere interactions are analysed and discussed in an integrated manner. The analysis is based on in situ as well as satellite based remote sensing observations and re-analysis data.

In contrast to earlier studies (see above), this thesis does not use air temperature to define extremely hot and dry summers, but solar irradiation in combination with precipitation as a central proxy. This is reasonable because (1) solar irradiation and summer surface temperatures in Central Europe are closely related (Makowski *et al.*, 2009) and (2) solar irradiation and precipitation are variables, which are determined by the atmospheric circulation but also influence the atmospheric circulation via land surface - atmosphere interactions.

Data from the Global Precipitation Climatology Center (GPCC) were used to describe precipitation. Due to the high density of gauge measurements used, these data are probably the most accurate precipitation data over land, which are currently available (Schneider *et al.*, 2014).

For solar irradiation, the satellite based data set MAGICSOL was used. This data set has proven to be of high accuracy (see chapter 3). Since its time coverage (1983 - 2005) is not sufficient for the purpose of the study presented, it is supplemented with re-analysis data. Due to issues with data accuracy and temporal coverage, only the ERA-40 and ERA-interim data were considered. After evaluating the solar irradiation data sets from these two re-analysis, it was decided to use ERA-40 for the time range available and to fill the remaining gap with ERA-interim data and operational data from the CM SAF.

The most extreme summer seasons (JJA) with regard to solar irradiation excess and precipitation deficit were analysed together with their preceding winter - spring transition (FMA) in the study area 47°N - 56°N; 4°E - 15°E, (i.e. Germany and adjacent areas, in this thesis referred to as Central Europe). The analysis is based on the regional mean accumulated monthly means of FMA and JJA of solar irradiation and precipitation over the study area, as well as on the seasonal anomaly of geopotential in 850 hPa over the North Atlantic and Europe. The model experiments of Fischer *et al.* 2007 and Weisheimer *et al.* 2011 for Europe and the empirical observations in southeastern Europe (Hirschi *et al.*, 2011) and southern Europe (Quesada *et al.*, 2012) could be supported: for the highly extreme events, a dominance of anticyclonic circulation regimes and the associated excess of solar irradiation and lack of precipitation (compared to the long term average values) is observed also in Central Europe.

Two out of the three of the most extreme sunny and dry summer seasons (10^{th} percentile) in Central Europe in the time period 1958 - 2011 were preconditioned in the preceding winter - spring transition seasons with highly extreme positive anomalies in solar irradiation and highly extreme negative anomalies in precipitation amount.

For the same years, a preconditioning in the preceding winter - spring transition seasons could be identified in the large-scale atmospheric circulation: a dipole in the atmospheric pressure (geopotential at 850 hPa) was found with a center of negative geopotential anomaly over southern Greenland and a center of positive geopotential anomaly over the North Sea and Fennoscandia. As a measure of the strength of this dipole, the novel Greenland - North Sea - Dipole - Index (GNDI) is introduced. In the majority of the years with highly extreme sunny and dry summers, the GNDI of the prior winter - spring transition season exceeds a value of 20. No interlink could be found between NAO / AO and extreme summers.

However, not all of the extremely sunny and dry summers in the study area and time period under consideration were preconditioned during the winter - spring transition. One of the most extreme summers under consideration was 1983. The preceding winter - spring transition was rather wet and cloudy. However, during the winter before (1982/83) an extremely strong El Niño occurred. On the other hand in 2011, an anomalously sunny and dry winter - spring transition was observed and the following summer had close to normal solar irradiation conditions and was rather wet. In the winter before (2010/11), an extremely strong La Niña occurred. This leads to the conclusion that extremely strong ENSO events can affect European climate on the seasonal scale: strong El Niño events can trigger extreme summers. Strong La Niña events can induce signals that have the potential to disturb the connection between sunny and dry winter - spring transitions and the following summer. In the context of extremely hot and dry summers in Central Europe, the results of this thesis indicate that:

- In addition to the dominance of anticyclonic systems in the atmospheric circulation and the land surface - atmosphere interactions, ENSO is another important driver of the development of extreme summers in Central Europe.

- ENSO-induced effects have the potential to disturb the interlink between winter - spring transition and the following summer concerning the interplay of atmospheric circulation and land surface - atmosphere interactions, which are responsible for the development of extremely hot and dry summers in Central Europe.

To combine both, the Greenland - North Sea - Dipole, representing the precondition in the winter - spring transition as well as La Niña as the potential disturbance of the precondition and El Niño as a potential "trigger" of extremely hot and dry summers, the Central European Drought Index (CEDI) was developed. Using the CEDI, the highly extreme (upper 10^{th} percentile) summers and one of the extreme (upper 20^{th} percentile) summers in Central Europe can be hindcast correctly.

Testing the hypothesis drawn in section 1.3 led to the following results:

- **H1** Extremely hot (and thus sunny) and dry summers in central Europe are preceded by winter - spring transitions with positive anomalies in solar irradiation and negative anomalies in precipitation.

- **H2** Extremely hot (and thus sunny) and dry summers in central Europe are preceded by characteristic atmospheric pressure patterns determining the excess of solar irradiation and the deficit of precipitation in the prior winter - spring transition season.

Both hypothesis can be confirmed, given that strong ENSO events are considered. Extreme El Niño events can lead to the development of highly extreme sunny and dry summer in Central Europe, without a preconditioning in the prior winter - spring transition season. Extreme La Niña events have the potential to disturb the connection between the winter - spring transition season and the following summer in the sense that a putative precondition is followed by a summer with average amounts of solar irradiation and precipitation.

The results of this thesis contribute to a better understanding of the developement of extreme summers in Central Europe and are thus a valuable contribution to the improvement of summer seasonal forecast for this region. The new CEDI is expected to have the potential to contribute to the development of an early warning system for extremely hot and dry summers.

6.2 Outlook

Observations of the future development of both, the GNDI and the CEDI would increase their statistical confidence. Further sensitivity studies would help us understand how severe the extreme summers that are captured by the indices are.

Both observation of the indices and sensitivity studies would help to evaluate the potential of GNDI and CEDI to serve as early warning indices for extremely sunny (hot) and dry summers in the study area.

Further studies on the relative importance of the large-scale atmospheric circulation and the land surface - atmosphere processes during the winter - spring transition season in different parts of Europe would be beneficial to further improve the understanding of the development of extreme heat events.

The validity of the solar irradiation and precipitation precursor in FMA could not be verified for a region larger than the study area, as briefly mentioned in chapter 4. However, further evaluations of the solar irradiation and precipitation precursor, as well as the GNDI and CEDI with regard to their validity in a larger region or different European regions, would still be interesting. Perhaps some modifications of the indices would improve their skill for a larger region. The analysis of different European regions would lead to a deeper understanding of the development of extremely hot and dry summers in general.

Of further interest is the question is how the winter - spring transition season and the following summer seasons in 1983 and 2011 would have developed under neutral ENSO conditions. This could be addressed by model experiments and help to support the conclusions drawn in section 5.3.3.

To gain a deeper understanding of the ENSO influence on the development of extreme summers in Europe, investigations of the "atmospheric bridge", as Lau and Nath (1996) call the atmosphere - ocean interactions presumably responsible for far distance influences of ENSO, would be helpful. An identification of the underlying processes might be possible using climate data sets that are now available from various sources (e.g. from the Satellite Application Facility on Climate Monitoring (CM SAF) and from the Global Precipitation Climatology Center (GPCC)).

Chapter 7

Zusammenfassung

Extreme Hitze- und Dürresommer sind eine ernste Gefahr für das menschliche Wohlbefinden, die Infrastruktur, Land- und Forstwirtschaft sowie für Ökosysteme. Frühzeitigis Wissen über ein mögliches Eintreten eines solchen Extremereignisses würde eine bessere Vorbereitung von entsprechenden Vorsorge- und Anpassungsmaßnahmen erlauben. Die Vorhersage von Hitze- und Dürreereignissen auf der saisonalen Skala ist jedoch immer noch eine Herausforderung, weil die Entwicklung dieser Ereignisse noch nicht vollständig verstanden ist.

Autoren aktueller Studien kommen zu dem Schluss, dass extreme Hitzewellen dann entstehen, wenn antizyklonale Zirkulationsmuster in der Atmosphäre im Sommer auf trockene Böden treffen. Letztere begünstigen dann die Entwicklung hoher Temperaturen, weil das Feuchtedefizit zu einer Reduktion des latenten Wärmeflusses zugunsten des sensiblen Wärmeflusses führt (Fischer *et al.*, 2007; Hirschi *et al.*, 2011; Quesada *et al.*, 2012).

Nach Kenntnis der Autorin dieser Arbeit, existiert keine Studie, welche atmosphärische Zirkulationsmuster analysiert, die zu einem Defizit der Bodenfeuchte in den Winter - Frühlings - Übergangsperioden vor extremen Sommern führen.

In der vorliegenden Arbeit werden die Eigenschaften extrem heißer und trockener Sommer in Zentraleuropa und deren vorhergehender Winter - Frühlings - Übergangsperioden analysiert, mit dem Ziel potenzielle Vorläufer extremer Sommer in der atmosphärischen Zirkulation zu identifizieren. Dabei werden sowohl Wechselwirkungen zwischen Landoberfläche und Atmosphäre als auch großräumige atmosphärische Zirkulationsregime im Zusammenhang analysiert und diskutiert. Die Analyse basiert auf in situ Beobachtungen, satellitenbasierten Fernerkundgsbeobachtungen und Re-analysedaten.

In der vorliegenden Studie werden extrem heiße und trockene Sommer nicht, anhand der Temperatur definiert, wie in früheren Studien, sondern mittels der Kombination aus solarer Einstrahlung und Niederschlag als zentralem Proxy. Dieses Vorgehen ist gerechtfertigt, weil (1) solare Einstrahlung und Landoberflächentemperaturen im Sommer in Europa eng miteinander gekoppelt sind (Makowski *et al.*, 2009) und (2) solare Einstrahlung und Niederschlag einerseits von der atmosphärischen Zirkulation bestimmt werden, andererseits selbst die atmosphärische Zirkulation durch Wechselwirkungen zwischen Landoberfläche und Atmosphäre beeinflussen.

Zur Beschreibung des Niederschlags wurden Daten des Weltzentrums für Niederschlagsklimatologie (WZN) verwendet. Aufgrund der hohen Dichte von in situ Messungen, die für die Erstellung dieses Datensatz genutzt werden, ist dieser wahrscheinlich der zur Zeit genaueste verfügbare Niederschlagsdatensatz (Schneider *et al.*, 2014).

Für die solare Einstrahlung wird der satellitenbasierte Datensatz MAGICSOL verwendet. Die hohe Genauigkeit dieses Datensatzes wird in Kapitel 3 gezeigt. Weil die zeitliche Abdeckung des MAGICSOL Datensatzes (1983 - 2005), für die Zwecke der hier durchgeführten Analysen nicht ausreicht, wird er mit Re-analyse Daten ergänzt. Dafür kommen ERA-40 und ERA-interim Daten in Betracht. Andere Re-analyse Datensätze scheiden aufgrund mangelnder Genauigkeit bzw. mangelnder zeitlicher Abdeckung von vornherein aus. Auf Basis der Evaluierung der Solarß-strahlungsdatensätze aus diesen beiden Re-analysen, wurde entschieden die Solarstrahlungsdaten aus ERA-40 für den von dieser Re-analyse abgedeckten Zeitraum zu verwenden. Die bleibende Lücke wurde mit ERA-interim Daten und operationellen Daten des CM SAF gefüllt.

Die extremsten Sommer (JJA) hinsichtlich des Solarstrahlungsüberschusses und des Niederschlagsdefizites wurden gemeinsam mit den jeweils vorhergehenden Winter - Frühlings - Übergangsperioden (FMA) im Untersuchungsgebiet 47°N - 56°N; 4°E - 15°E (Deutschland und angrenzende Gebiete, in dieser Arbeit als Zentraleuropa bezeichnet) analysiert. Die Analyse basiert auf regionalen Mitteln der akkumulierten Monatsmittel von FMA und JJA von Solarstrahlung und Niederschlag im Untersuchungsgebiet und auf der Analyse der saisonalen Anomalien des Geopotentials in 850 hPa über dem Nordatlantik und Europa. Die Modellexperimente von Fischer *et al.* 2007 und Weisheimer *et al.* 2011 für Europa und die Beobachtungen von Hirschi *et al.* 2011 in Südosteuropa und von Quesada *et al.* 2012 Südeuropa wurden bestätigt: Für die extremsten Hitzesommer wurde auch für Zentraleuropa eine Dominanz von antizyklonalen Zirkulationsregimen mit dem damit verbundenen Solarstrahlungsüberschuss und dem Niederschlagsdefizit (im Vergleich zum langjährigen Mittel) beobachtet.

Zwei der drei extremsten sonnigen und trockenen Sommer (obere 10% Perzentile) in Zentraleuropa im Zeitraum 1958 - 2011 wurden bereits in der jeweils vorhergehenden Winter - Frühlings - Übergangsperiode mit extrem großen positiven Solarstrahlungsanomalien und extrem großen negativen Niederschlagsanomalien präkonditioniert.

Für dieselben Jahre konnte auch eine Präkonditionierung in der Winter - Frühlings - Übergangsperiode in der Atmosphäre identifiziert werden: ein Dipol in der Druckanomalie (Anomalie des Geopotenzials in 850 hPa), mit einem Zentrum negativer Anomalie über Südgrönland und einem Zentrum positiver Anomalie über der Nordsee und Fennoskandien. Als ein Maß für die Stärke dieses Dipols wurde der neue Grönland - Nordsee - Dipol - Index (GNDI) eingeführt. In der Mehrzahl der Jahre mit extremst sonnigen und trockenen Sommern, überschreitet der GNDI der vorhergehenden Winter - Frühlings - Übergangsperiode einen Wert von 20. Es wurde weder ein Zusammenhang mit der NAO noch mit der AO und den extremen Sommern gefunden.

Jedoch wurden nicht alle extremst sonnigen und trockenen Sommer im Untersuchungsgebiet und dem analysierten Zeitraum in der vorhergehenden Winter - Frühlings - Übergangsperiode präkonditioniert. Einer der extremsten Sommer im Beobachtungszeitraum war der Sommer 1983. Die vorhergehende Winter - Frühlings - Übergangsperiode war aber eher feucht und bewölkt. Jedoch trat im Winter vor diesem Ereignis (1982/83) ein extrem starkes El Niño Ereignis auf. Auf der anderen Seite gab es in 2011 eine ungewöhnlich sonnige und trockene Winter - Frühlings - Übergangsperiode, auf die aber ein eher feuchter Sommer mit durchschnittlicher solarer Einstrahlung folgte. Im Winter zuvor (2010/11) trat ein extrem starkes La Niña Ereignis auf. Dies führt zu der Schlussfolgerung, dass extrem starke ENSO Ereignisse das europäische Klima auf der saisonalen Skala beeinflussen können: Starke El Niño Ereignisse können extreme Sommer verursachen. Starke La Niña Ereignisse können Signale erzeugen, die das Potential haben, die Verbindung zwischen sonnigen und trockenen Winter - Frühlings - Übergangsperioden und den darauffolgenden Sommern zu stören. Im Kontext extrem heißer und trockener Sommer in Zentraleuropa zeigen diese Ergebnisse Folgendes:

- Zusätzlich zur Dominanz antizyklonaler Drucksysteme in der atmosphärischen Zirkulation und den Wechselwirkungen zwischen Landoberfläche und Atmosphäre, ist ENSO ein weiterer wichtiger Faktor für die Entwicklung extremer Sommer in Zentraleuropa.

- Durch ENSO ausgelöste Effekte haben das Potenzial die Verbindungen zwischen der Winter - Frühlings - Übergangsperiode und dem darauf folgenden Sommer bezüglich des Zusammenspiels von atmosphärischer Zirkulation und Wechselwirkungen zwischen Landoberfläche und Atmosphäre, welche für die Entwicklung extrem heißer und trockener Sommer verantwortlich sind, zu zerstören.

Mit dem in dieser Arbeit entwickelten Zentraleuropäischen Dürreindex (CEDI) werden der Grönland - Nordsee - Dipol, der die Präkonditionierung in der Winter - Frühlings - Übergangsperiode repräsentiert, und La Niña, als Ursache für die potenzielle Störung dieser Präkonditionierung, bzw. El Niño, als ein weiterer potenzieller Auslöser für extrem heiße und trockene Sommer, kombiniert. Mithilfe des CEDI können die extremst heißen und trockenen Sommer (obere 10% Perzentile) und einer der extremen Sommer (obere 20% Perzentile) in Zentraleuropa richtig "nachhergesagt" werden.

Die Tests der in Abschnitt 1.3 aufgestellten Hypothesen führt also zu folgenden Ergebnissen:

- **H1** Extrem heißen (und damit sonnigen) und trockenen Sommer in Zentraleuropa gehen oft Winter - Frühlings - Übergangsperioden voraus, die eine positive Solarstrahlungsanomalie und eine negative Niederschlagsanomalie aufweisen.

- **H2** Extrem heißen (und damit sonnigen) und trockenen Sommer in Zentraleuropa gehen charakteristische atmosphärische Muster der Druckanomalie voraus, die den Solarstrahlungsüberschuss und das Niederschlagsdefizit in der vorhergehenden Winter - Frühlings - Übergangsperiode bestimmen.

Beide Hypothesen können also bestätigt werden, unter der Voraussetzung dass, starke ENSO Ereignisse berücksichtigt werden. Extrem starke El Niño Ereignisse können, zur Entwicklung von extremst sonnigen und trockenen Sommern in Zentraleuropa führen, welche nicht in der vorhergehenden Winter - Frühlings - Übergangsperiode präkonditioniert wurden. Extrem starke La Niña Ereignisse haben das Potenzial die Verbindung zwischen Winter - Frühlings - Übergangsperioden und dem folgenden Sommer zu stören. Und zwar in dem Sinne, dass einer vermeintlichen Präkonditionierung ein Sommer mit durchschnittlicher Solarstrahlung und durchschnittlichen Niederschlagsmengen folgt.

Die Ergebnisse dieser Arbeit tragen zu einem besseren Verständis der Entwicklung extremer Sommer in Zentraleurope bei und sind daher ein wertvoller Beitrag zur Verbesserung der sommerlichen Jahreszeitenvorhersage für dieses Gebiet. Weiterhin kann aufgrund der Ergebnisse erwartet werden, dass der neu entwickelte CEDI einen wesentliche Beitrag zur Entwicklung eines Frühwarnsystems für extrem heiße und trockene Sommer leisten kann.

Bibliography

Allan, R., Ringer, M. A., Pamment, J. A., and Slingo, A. (2004). Simulation of the earth's radiation budget by the European Centre for Medium-Range Weather Forecasts 40-year reanalysis (era40). *J. Geophys. Res.*, **109**.

Babst, F., Müller, R., and Hollmann, R. (2008). Verification of NCEP Reanalysis Shortwave Radiation with Mesoscale Remote Sensing Data. *Geosciences and Remote Sensing Letters*, **5**(1).

Baccini, M., Biggeri, A., Accetta, G., Kosatsky, T., Katsouyanni, K., Analitis, A., Anderson, H., Bisanti, L., D'Ippoliti, D., Danova, J., Forsberg, B., Medina, S., Paldy, A., Rabczenko, D., Schindler, C., and Michelozzi, P. (2008). Heat Effects on Mortality in 15 European Cities. *Epidemiology*, **19**(5), 711 – 719. DOI:10.1097/EDE.0b013e318176bfcd.

Barnston, A. and Livezey, R. (1987). Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Monthly Weather Review*, **115**, 1083–1126.

Barriopedro, D., Fischer, E., Luterbacher, J., Trigo, R., and García-Herrera, R. (2011). The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe. *Science*, **332**, 222–224. DOI:10.1126/science.1201224.

Behera, S., Ratnam, J., Masumoto, Y., and Yamagata, T. (2013). Origin of extreme summers in Europe: the Indo-Pacific connection. *Climate Dynamics*, **41**, 663 – 676. DOI:10.1007/s00382-012-1524-8.

Bendix, J. (1998). Ein neuer Methodenverbund zur Erfassung der klimatologisch-lufthygienischen Situation in Nordrhein-Westfalen. Untersuchunge mit Hilfe boden- und satellitengestÃ$\frac{1}{4}$tzter Fernerkundung und numerischer Modellierung. In *Bonner Geographische Abhandlungen*, volume 98.

Bendix, J. (2002). A satellite-based climatology of fog and low-level stratus in Germany and adjacent areas. *Atmosph. Res.*, **64**, 3–18.

Bendix, J., Thies, B., T., N., and Cermak, J. (2006). A feasibility study of daytime fog and low stratus detection with TERRA/AQUA-Modis over land. *Meteorol. Appl.*, **13**, 111–125.

Beniston, M. and Diaz, H. (2004). The 2003 heat wave as an example of summers in a greenhouse climate? Observations and climate model simulations for Basel, Switzerland. *Global and Planetary Change*, **44**, 73–81. DOI:10.1016/j.gloplacha.2004.06.006.

Berrisford, P., Dee, D., Fielding, K., Fuentes, M., Kållberg, P., Kobayashi, S., and Uppala, S. (2009). The ERA-Interim Archive. Technical report, ERA Report Series No. 1, ECMWF: Reading, UK. available at `www.ecmwf.int/publications`.

Betts, A. and Ball, J. (1999). Basin scale surface water and energy budgets for the Mississipi from the ECMWF reanalysis. *Journal of Geophysical Research*, **104**, 19293–19305.

Betts, A. K., Ball, J. H., Bosilovich, M., Viterbo, P., Zhang, Y., and Rossow, W. B. (2003). Intercomparison of water and energy budgets for five mississippi subbasins between ECMWF re-analysis (ERA-40) and NASA Data Assimilation Office fvGCM for 1990-1999. *J. Geophys. Res.*, **108**. DOI: 10.1029/2002JD003127.

Beyer, H., Drews, A., and Rindelhardt, U. (2006). Irradiance Maps Applied for the Performance Assessment of PV Systems - A Case study for the German Federal State of Saxony. In *21 European Photovoltaic Solar Energy Conference, 4-8 September 2006, Dresden, Germany*.

Bissolli, P. and Dittmann, E. (2001). The objective weather type classification of the German Weather Service and its possibilities of application to environmental and meteorological investigations. *Meteorologische Zeitschrift*, **10**(4), 253–260.

Black, E., Blackburn, M., Harrison, G., Hoskins, B., and Methven, J. (2004). Factors contributing to the summer 2003 European heatwave. *Weather*, **59**(8).

Bowen, I. (1926). The ratio of heat losses by conduction and by evaporation from any water sources. *Physical Rev.*, **27**, 779–787.

Broennimann, S. (2007). Impact of El Niño - Southern Oscillation on European Climate. *Reviews of Geophysics*, **45**, RG3003. DOI:10.1029/2006RG000199.

Bundesanstalt für Gewässerkunde (Ed.) (2004). Jahresbericht 2003. Technical Report ISSN 0170 - 5156, Bundesanstalt für Gewässerkunde.

BUWAL, BWG, M. (2004). Auswirkungen des Hitzesommers 2003 auf die Gewässer. *Schriftenreihe Umwelt Nr. 369*, page 174 p. Bundesamt für Umwelt, Wald und Landschaft, Bern.

Carril, A., Gualdi, S., Cherchi, A., and Navarra, A. (2008). Heatwaves in Europe: areas of homogeneous variability and links with the regional to large-scale atmospheric and SSTs anomalies. *Climate Dynamics*, **30**, 77 – 98. DOI:10.1007/s00382-007-0274-5.

Cassou, C., Terray, L., and Phillips, A. (2005). Tropical Influence on European Heat Waves. *Journal of Climate*, **18**, 2805–2811.

Cermak, J. and Bendix, J. (2008). A novel approach to fog / low stratus detection using Meteosat 8 data. *Atmosph. Res.*, **87**, 279–292.

Cermak, J., Eastman, R. M., Bendix, J., and Warren, S. G. (2009). European climatology of fog and low stratus based on geostationary satellite observations. *Q.J.R. Meteorol. Soc.*, **135**, 2125–2130. DOI:10.1002/qj503.

Chang, F.-C. and Wallace, J. (1987). Meteorological conditions during heat waves and droughts in the united states great plains. *Monthly Weather Review*, **115**, 1253–1269.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J., Sanz, M., Schulze, E., Vesela, T., and Valtenini, R. (2005). Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, **437**, 529–533. DOI:10.1038/nature03972.

Czaja, A., Robertson, A., and Huck, T. (2003). The role of atlantic ocean-atmosphere coupling in affecting north atlantic oscillation variability. *In: Hurrell,J.W., Kushnir,Y., Ottersen, G., Visbeck,M. (Eds.), The North Atlantic Oscillation, Climatic Significance and Envrionmental Impact. AGU Geophys. Monogr.*, **134**, 147–172. DOI:10.1029/GM134.

Dee, D. P. and Uppala, S. (2009). Variational bias correction of satellite radiance data in the ERA-interim reanalyis. *Quarterly Journal of the Royal Meteorological Society*, **135**, 1830–1841. DOI:10.1002/qj493.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars,

A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Holm, E. V., Isaksen, L., Kållberg, P., Koehler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thepaut, J. N., and Vitart, F. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, **137**(656), 553–597. DOI:10.1002/qj.828.

Della-Marta, P., Luterbacher, J., von Weissenfluh, H., Xoplaki, E., Brunet, M., and Wanner, H. (2007). Summer heat waves over western Europe 1880-2003, their relationship to large-scale forcings and predictability. *Climate Dynamics*, **29**, 251–275. DOI:10.1007/s00382-007-0233-1.

Deutscher Wetterdienst (1976). Monatlicher Witterungsbericht, Amtsblatt des Deutschen Wetterdienstes, Juni 1976; Juli 1976; August 1976. Technical report, Deutscher Wetterdienst.

Deutscher Wetterdienst (2003). Witterungsreport, Juni 2003; Juli 2003; August 2003. Technical report, Deutscher Wetterdienst.

Drews, A. (2007). Preparation of a global radiation data set based on the Heliosat method. Final report on the DWD-contract 30112583/07-HEL. available at: `www.cmsaf.eu`.

Drews, A., Beyer, H., and Rindelhardt, U. (2008). Quality of performance assessment of PV plants based on irradiance maps. *Solar Energy*, **82**, 1067–5841.

Dürr, B. and Zelenka, A. (2009). Deriving surface global irradiance over the Alpine region from METEOSAT Second Generation data by supplementing the HELIOSAT method. *International Journal of Remote Sensing*, **30**, 5821–5841. DOI: 10.1080/014311160902744829.

Dyck, S. and Peschke, G. (1989). *Grundlagen der Hydrologie*. Verlag für Bauwesen, Berlin. 2. Auflage.

Ebi, K., Teisber, T., Kalkstein, L., Robinson, L., and Weiher, R. (2004). Heat watch/warning systems save lives. *Bulletin of the American Meteorological Society*, **85**(8), 1067 – 1073. DOI:10.1175/BAMS-85-8-1067.

Eoportal.org (2002). Meteosat first generation (MFG)s spacecraft. `http://events.eoportal.org/presentations/204/11737.html`. last visited: 5 October 2011.

Fink, A., Brücher, T., Leckebuch, G., Pinto, J., and Ulbrich, U. (2004). The 2003 European summer heatwaves and drought - synoptic diagnosis and impacts. *Weather*, **59**(8), 209 – 216. DOI:10.1256/wea.73.04.

Fischer, E., Seneviratne, S., Lüthi, D., and Schär, C. (2007). Contribution of land-atmosphere coupling to recent European summer heat waves. *Geophysical Research Letters*, **34**. DOI:10.1029/2006GL029068.

Förster, H. and Lilliestam, J. (2010). Modeling the thermoelectronic power generation in view of climate change. *Regional Environmental Change*, **10**, 327–338. DOI:10.1007/s10113-009-0104-x.

Frädrich, K. (1990). European Grosswetter during the warm and cold extremes of the El Niño/Southern Oscillation. *International Journal of Climatology*, **10**, 21–31.

Frädrich, K. (1994). An ENSO impact on Europe? *Tellus*, **46A**, 541–552.

Frädrich, K. and Müller, K. (1992). Climate anomalies in Europe associated with ENSO extremes. *International Journal of Climatology*, **12**, 25–31.

GCOS (2009). GCOS Essential Climate Variables. `http://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables`, last modified: 26 May 2009.

GPCC (2012). GPCC Product Infor. `http://gpcc.dwd.de`, last visited 20 September 2012.

Graf, H.-F. and Zanchetin, D. (2012). Central Pacific El Nino, the "subtropical bridge," and Eurasian climate. *Journal of Geophysical Research*, **117**. DOI:10.1029/2011JD016493.

Gruber, S., Hölzel, M., and Häberli, W. (2004). Permafrost thaw and destabilization of Alpine rock walls in the hot summer of 2003. *Geophysical Reseach Letters*, **31**. DOI:10.1029/2004GL020051.

Gupta, S., Stackhouse Jr., P., Cox, S., Mikovitz, J., and Zhang, T. (2006). Surface radiation budget project completes 22-year data set. *GEWEX News*, **16**(4), 12–13.

Hammer, A. (2001). *Anwendungsspezifische Solarstrahlungsinformationen aus Meteosat-Daten*. Ph.D. thesis, Universität Oldenburg, Uhlhornsweg 49-55, 26129 Oldenburg.

Hammer, A., Heinemann, D., Hoyer, C., Kuhlemann, R., Lorenz, E., Müller, R., and Beyer, H. (2003). Solar Energy Assessment Using Remote Sensing Technologies. *Remote Sensing of the Environment*, **86**, 423–432.

Hatzianastassiou, N., Matsoukas, C., Drakakis, E., Stackhouse, Jr., P. W., Koepke, P., Fotiadi, A., Pavlakis, K. G., and Vardavas, I. (2007). The direct effect of aerosols on solar radiation based on satellite observations, reanalysis datasets, and spectral aerosol optical properties from Global Aerosol Data Set (GADS). *Atmospheric Chemistry and Physics*, **7**, 2585–2599.

Heck, P., Zanetti, P., Enz, R., Green, J., and Suter, S. (2004). Natural catastrophes and man made disasters in 2003. Technical Report Sigma Report No. 1/2004, Swisse Re.

Herceg Bulic, I. and Kucharski, F. (2012). Delyed ENSO impact on spring precipitation over North/Atlantic European region. *Climate Dynamics*, **38**, 2593–2612. DOI:10.1007/s00382-011-1151-9.

Hirschi, M., Seneviratne, S., and Schaer, C. (2006). Seasonal Variations in Terrestrial Water Storage for Major Midlatitude River Basins. *Journal of Hydrometeorology*, **7**, 39–60.

Hirschi, M., Seneviratne, S., Alexandrov, V., Bober, F., Boroneant, C., Christensen, O., Formayer, H., Orlowksy, B., and Stepanek, P. (2011). Observational evidence of soil-moisture impact on hot extremes in southeastern Europe. *Nature Geoscience*, **4**, 17–21. DOI:10.1038/NGEO1032.

Howard, L. (1833). *The Climate of London, Vols. I-III*. London.

Hurrell, J. and Deser, C. (2010). North atlantic climate variability: The role of the north atlantic oscillation. *Journal of Marine Systems*, **79**, 231–244. DOI:10.1016/j.jmarsys/2009.11.002.

Hurrell, J. *et al.* (2013a). The climate data guide: Hurrell wintertime slp-based northern annular mode (nam) index). Retrieved from `https//climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based/`, last modified: 08 Oct 2013.

Hurrell, J. *et al.* (2013b). The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (PC-based). Retrieved from `https//climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based/`, last modified: 08 Oct 2013.

Ionita, M., Lohmann, G., Rimbu, N., and Scholz, P. (2012). Dominant modes of diurnal temperature range variability over europe and their relationships with large-scale atmospheric circulation and sea surface temperature anomaly patterns. *Journal of Geophysical Research*, **117**. DOI:10.1029/2011JD016669.

IPCC (2013). Summary for policy makers. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change: Stocker, T.F. and Qin, D. and Plattner, G.-K. and Tignor, M. and Allen, S.K. and Boschung, J. and Naules, A. and Xia, Y. and Bex, V. and Midgley, P.M. (eds)*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jendritzky, G., Fiala, D., Havenith, G., Koppe, C., Laschewski, G., Staiger, H., and Tinz, B. (2007). Thermische Umweltbedingungen (The Termal Environment). *Promet*, **33**(3/4), 83 – 90.

Jones, W. P. (2009). First- and second-order conservative remapping schemes for grids in spherical coordinates. *Monthly Weather Review*, **127**, 2204–2210.

Journée, M. and Bertrand, M. (2010). Improving the spatio-temporal distribution of surface solar radiation data by merging ground and satellite measurements. *Remote sensing of the Environment*, **114**, 2692–2704. DOI:10.1016/j.rse.2010.06.010.

Kållberg, P., Simmons, A., Uppala, S., and Fuentes, M. (2005). The ERA-40 Archive, ECMWF 2005. Technical report, ERA-40 Project Report Series No.17. available at `http://www.ecmwf.int/publications/library/do/references/list/192`.

Koster, R., Dirmeyer, P., Zhichang, G., Bonan, G., Chan, E., Cox, P., Gordon, C., Kanae, S., Kowalczyk, E., Lawrence, D., Liu, P., Lu, C., Malyshev, S., McAvaney, B., Mitchell, K., Mocko, D., Oki, T., Oleson, K., Pitman, A., Sud, Y., Taylor, C., Verseghy, D., Vasic, R., Xue, Y., and Yamada, T. (2004). Regions of strong coupling between soil moisture and precipitation. *Science*, **305**, 1138–1140. DOI:10.1126/science.1100217.

Kunkel, K., Changnon, S., Reike, B., and Arritt, R. (1996). The july 1995 heat wave in the midwest: A climatic perspective and critical weather factors. *Bulletin American Metereological Society*, **77**, 1507–1518.

Lau, N.-C. and Nath, M. (1996). The Role of the "Atmospheric Bridge" in Linking Tropical Pacific ENSO Events to Extratropical SST Anomalies. *Journal of Climate*, **9**, 2036–2056. DOI:.

Lobinger, G. (2004). "Der "Käfersommer". *LWF (Bayerische Landesanstalt für Wald und Forstwirtschaft) aktuell*, **43**, 26–27. http://www.waldwissen.net/waldwirtschaft/schaden/insekten/lwf_kaefersommer/index_DE,lastvisited31.01.2011.

Lüst, R. (1992). Remote sensing from space: the European Space Agency's achievements and current programmes. *International Journal of Remote Sensing*, **13**(6-7), 1023–1034.

Makowski, K., Jaeger, E., Chiacchio, M., and Wild, M. (2009). On the relationship between diurnal temperature range and surface solar radiation in Europe. *Journal of Geophysical Research*, **114**. DOI:10.1029/2008JD011104.

Markovic, M., Jones, C., Winger, K., and Paquin, D. (2009). The surface radiation budget over North America: gridded data assessment and evaluation of regional climate models. *International Journal of Climatology*. DOI: 10.1002/joc.1860.

Mc Cutcheon, S., Martin, J., and Barnwell, T. (1992). Water quality. *Maidment, D.R. (ed): Handbook of Hydroloy*. McGraw-Hill, Inc.

Meehl, G. and Tebaldi, C. (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, **305**(5686), pp.994 – 997. DOI:10.1126/science.1098704.

Muecke, H.-G. and Becker, P. (2008). Klimawandel und Gesundheit - Informationen zu den gesundheitlichen Auswirkungen sommerlicher Hitze und Hitzewellen und Tipps zum vorbeugenden Gesundheitsschutz. http://www.umweltbundesamt.de/publikationen/ratgeber-klimawandel-gesundheit.

Mühr, B., James, D., Khazai, B., Köbele, D., Kunz, M., Kunz-Plapp, T., Leyser, A., and Vannieuwenhuyse, M. (2012). Analysis of U.S. extreme drought and record heat 2012. Technical report, Center for Disaster Management and Risk Reduction Technology CEDIM. https://www.cedim.de/download/20120921usa_drought_no2.pdf.

Müller, R., Matsoukas, C., Gratzki, A., Behr, H., and Hollmann, R. (2009). The CM-SAF operational scheme for the satellite based retrieval of solar surface irradiance - A LUT base eigenvector hybrid approach. *Remote Sensing of the Environment*, **113**, 1012–1024. DOI:10.1016/j.rse.2009.01.012.

Munich Re Group (2004). Geschäftsbericht der Münchener-Rück Gruppe 2003. p. 54 ff.

Nemani, R., Keeling, C. D., Hashimoto, H., Jolly, W., Piper, S., Tucker, C., Myneni, R., and Running, S. W. (2003). Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science*, **300**, 1560 – 1563. DOI:10.1126/science.1082750.

NOAA (2010). El-Niño / Southern Oscillation Indicators. `http://www.ncdc.noaa.gov/teleconnections/enso/indicators/`. last visited: 21 August 2012.

Norris, J. R. and Wild, M. (2007). Trends in aerosol radiative effects over Europe inferred from observed cloud cover, solar "dimming" and solar "brightening". *Journal of Geophysical Research-Atmospheres*, **112**(D8).

Ogi, M., Tachibana, Y., and Yamazaki, K. (2003). Impact of the winterteime North Atlantic Oscillation (NAO) on the summertime atmospheric circulation. *Geophysical Research Letters*, **30**(13), 37–1 – 37–4. DOI:10.1029/2003GL017280.

Ogi, M., Tachibana, Y., and Yamazaki, K. (2004a). The Connectivity of the Winter North Atlantic Oscillation (NAO) and the Summer Okhotsk High. *Journal of the Meteorological Society of Japan*, **82**, 905–9012. DOI:10.2151/jmsj.2044.905.

Ogi, M., Yamazaki, K., and Tachibana, Y. (2004b). The summertime annular mode in the Northern Hemisphere and its linkage to the winter mode. *Journal of Geophysical Research*, **109**. DOI:10.1029/2004JD004514.

Ohmura, A., Dutton, E., Frogan, B., Fröhlich, K., Gilgen, H., Hegner, H., Heimo, A., König-Langlo, G., McArthur, B., Müller, G., Philipona, R., Pinker, R., Whitlock, C., Dehne, K., and Wild, M. (1998). Baseline Surface Radiation Network (BSRN/WCRP): New precision radiometry for climate research. *Bulletin of the American Meteorological Society*, **79**, 2115–2136.

Oke, T. (1982). The energetic basis of urban heat island. *Quarterly Journal of the Royal Meteorological Society*, **108**(455), 1–24. DOI:.

Orth, R. and Seneviratne, S. (2012). Analysis of soil moisture memory from observations in Europe. *Journal of Geophysical Research*, **117**. DOI:10.1029/2011JD017366.

Palecki, M., Changnon, S., and Kunkel, K. (2001). The nature and impacts of the july 1999 heat wave in the midwestern united states: Learning from the lessoons of 1995. *Bulletin American Metereological Society*, **82**, 1353–1367.

Posselt, R., Müller, R., Stöckli, R., and Trentmann, J. (2011). Spatial and temporal homogeneity of solar surface irradiance across satellite generations. *Remote Sensing*, **3**, 1029–1046. DOI:10.3390/rs3051029.

ProClim(Ed.) (2005). Hitzesommer 2003 - Synthesebericht. Technical report, ProClim - Forum for Climate and Global Change, Platform of the Swiss Academy of Sciences. ISBN: 978-3-907630-16-7.

Quesada, B., Vautars, R., Yiou, P., Hirschi, M., and Seneviratne, S. (2012). Asymmetric European summer heat predictability from wet and dry southern winter and springs. *Nature climate change*, **2**. DOI:10.1038/NCLIMATE1536.

Ratcliffe, R. (1978). Meteorological aspects of the 1975 - 76 drought. *Proceedings of the Royal Society of London, Series A*, **363**, 355–357.

Robine, J., Cheung, S., Le Roy, S., van Oyen, H., Griffiths, C., Michel, J., and Hermann, F. R. (2007). Death toll exceeded 70000 in europe during the summer of 2003. *Comptes Rendus Biologies*, **331**, 171–178. DOI:10.1016/j.crvi.2007.12.001.

Robinson, P. (2001). On the definiton of a heat wave. *Journal of applied meteorology*, **40**, 762 – 775.

Rodwell, M. (2003). On the predictability of the north atlantic climate. *In: Hurrell,J.W., Kushnir,Y., Ottersen, G., Visbeck,M. (Eds.), The North Atlantic Oscillation, Climatic Significance and Envrionmental Impact. AGU Geophys. Monogr.*, **134**, 173–192.

Rudolf, B. and Schneider, U. (2005). Calculation of gridded precipitation data for the global land-surface using in-situ gauge observations. In *2nd Workshop of the International Precipitation Working Group*.

Sarachik, E. S. and Cane, M. (2010). *The El Niño-Southern Oscillation Phenomenon*. Cambridge University Press.

Sardeshmukh, P. and Smith, C. (2012). Bivariate ENSO Time Series or the "BEST" ENSO Index. `http://www.esrl.noaa.gov/psd/people/cathy.smith/best/#values`, last visited: August 2012.

Schär, C. and Jendritzky, G. (2004). Hot news from summer 2003. *Nature*, **432**, 559–560.

Schneider, U., Becker, A., Meyer-Christoffer, M., Ziese, A., and Rudolf, B. (2011). Global Precipitation Ananlysis Products of the GPCC. Technical report, DWD Internet Publication, 1-13. available at `www.gpcc.dwd.de`.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Ziese, M., and Rudolf, B. (2014). Gpcc's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle. *Theoretical and Applied Climatology*, **115**, 15 – 40. DOI:10.1007/s00704-013-0860-x.

Schönwiese, C.-D. (1994). *Klimatologie*. Ulmer, Stuttgart.

Seneviratne, S., Lüthi, D., Litschi, M., and Schär, C. (2006). Land-atmosphere coupling and climate change in Europe. *Nature*, **443**, 205–209. DOI:10.1038/nature05095.

Smith, C. and Sardeshmukh, P. (2000). The Effect of ENSO on the Intraseasonal Variance of Surface Temperature in Winter. *International Journal of Climatology*, **20**, 1543–1557.

Teixera, J. (1999). Simulation of fog within the ECMWF prognostic cloud scheme. *Q.J.R. Meteorolog. Soc.*, **125**, 529–552.

Teuling, A., Hirschi, M., Ohmura, A., Wild, M., Reichstein, M., Ciais, P., Buchmann, N., Ammann, C., Montagnani, L., Richardson, A., Wohlfahrt, G., and Seneviratne, S. (2009). A regional perspective on trends in continental evaporation. *Geophysical Research Letters*, **36**. DOI:10.1029/2008GL036584.

Thompson, D. and Wallace, J. (1998). The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Journal of Climate*, **25**, 1297–1300.

Träger-Chatterjee, C., Müller, R. W., Trentmann, J., and Bendix, J. (2010). Evaluation of ERA-40 and ERA-interim re-analysis incoming surface shortwave radiation datasets with mesoscale remote sensing data. *Meteorologische Zeitschrift*, **19**(6), 631–640. DOI:10.1127/0941-2948/2010/0466.

Träger-Chatterjee, C., Mueller, R., and Benidx, J. (2013). Analysis of extreme summers and prior late winter/spring conditions in central europe. *Natural Hazards and Earth System Sciences*, **13**, 1243–1257. DOI:10.519/nhess-13-1243-2013.

Trenberth, K. (1991). General characteristics of El Nino-Southern Oscillation. *in: Glant, M.H. et al (Eds.) Teleconnections linking worldwide climate anomalies*, pages 13–42.

Trentmann, J., Träger-Chatterjee, C., Müller, R., Posselt, R., and Stöckli, R. (2010). Evaluation of three climatological data sets of the surface longwave downwelling radiation. Poster presented at the 13th Conference on Atmospheric Radiation, 28 June - 2 July 2010, Portland, Oregon, US.

Undine, I. (2014). Das Niedrigwasser des Rheins im Sommer und Herbst 2003. `http://undine.bafg.de/servlet/is/19472/`, last visited 23 April 2014.

Uppala, S., Kållberg, P., Simmons, A., Andreae, U., Da Costa Bechtold, V., Firino, M., Gibson, J., Haseler, J., Hernandez, A., Kelly, G., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R., Andersson, E., Arpe, E., Balmaseda, M., Beljaars, A., Van de Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Holm, E., Hoskins, B., Isaksen, L., Janssen, P., Jenne, R., McNally, A., Mehfouf, J.-F., Morcrette, J.-J., Rayner, N., Saunders, R., Simon, P., Sterl, A., Trenberth, K., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J. (2005). The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society*, **131**, 2961–3012.

Utschig, H., Bachmann, M., and Pretzsch, P. (2004). "Das Trockenjahr 1976 bescherte langjährige Zuwachseinbrüche". *LWF (Bayerische Landesanstalt für Wald und Forstwirtschaft) aktuell*, **43**, 17 – 18. DOI:.

Vautard, R., Yiou, P., D'Andrea, F., de Noblet, N., Cassou, C., Polcher, J., Ciais, P., Kageyama, M., and Fan, Y. (2007). Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit. *Geophysical Research Letters*, **34**. DOI:10.1029/2006GL028001.

Walker, G. and Bliss, E. (1932). World weather v. *Memoirs of the Royal Meteorological Society*, **IV**(36), 53–85.

Walter, K. and Graf, H.-F. (2005). The north atlantic variability structure, storm tracks, and precipitation depending on the polar vortex strength. *Atmopspheric Chemistry and Physics*, **5**, 239–248.

Wang, G., Dolman, A., and Alessandri, A. (2011). A summer climate regime over Europe modulated by the North Atlantic Oscillation. *Hydroloy and Earth System Sciences*, **15**, 57–64.

Weisheimer, A., Doblas-Reyes, F., Jung, T., and Palmer, N. (2011). On the predictability of the extreme summer 2003 over Europe. *Geophysical Research Letters*, **38**. DOI:10.1029/2010GL046455.

WHO (2013). Protecting the publicj and minimizing health effects from heat: towards the developemtn of a heat-health action framework for the prefecture of hyogo, japan. Technical report, World Health Organization, Center for Health Development. available at `http://www.who.int/kobe_centre/publications/hyogo_health_heat_2013/en/`.

Wilks, D. (2006). *Statistical Methods in the Atmospheric Sciences*. Elsevier Academic Press.

WMO (2014). Climate Risk Management. `http://www.wmo.int/pages/themes/climate/risk_management.php`, last visited 06 May 2014.

World Health Organization (WHO) (2010). The solid facts on climate change an health. `http://www.euro.who.int/__data/assets/pdf_file/0010/95815/FS_ParmaClosure.pdf`, last visited: 15 April 2014.

Yang, S.-K., Hou, Y.-T., Miller, A., and Campana, K. (1999). Evaluation of the Earth Radiation Budget in NCEP-NCAR Reanalysis with ERBE. *Journal of Climate*, **12**, 477–493.

Zampieri, M. and D'Andrea, F. (2009). Hot European Summers and the Role of Soil Moisture in the Propagation of Mediterranean Drought. *Journal of Climate*, **22**, 4747–4758. DOI:10.1175/2009JCLI2568.1.

Zhang, Y., Rossow, W., Lacis, A., Oinas, V., and Mishchenko, M. (2004). Calculation of radiative fluxes from the surface to top of atmosphere based on ISCCP and other global data sets: Refinements of the radiative transfer model and the input data. *J. of Geophysical Research*, **109**. DOI: 10.1029/2003JD004457.

Erklärung

Ich versichere, dass ich die vorliegende Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Die Dissertation wurde in der jetzigen oder einer ähnlichen Form noch bei keiner anderen Hochschule eingereicht und hat keinen sonstigen Prüfungszwecken gedient.

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Träger-Chatterjee, C., Müller. R.W., Bendix, J. (2013), Analysis of extreme summers and prior late winter / spring conditions in central Europe, *Natural Hazards and Earth System Sciences* 13: 1243 - 1257, DOI:10.5194/nhess-13-1243-2013.

Müller. R.W., Trentmann, J., Träger-Chatterjee, C., Posselt, R., Stöckli, R. (2011), The role of the effective cloud albedo for climate monitoring and analysis, *Remote Sensing* 11: 2305 - 2320, DOI:10.3390/rs3112305.

Träger-Chatterjee, C., Müller. R.W., Bendix, J., Trentmann, J. (2010), Evaluation of ERA-40 and ERA-interim re-analysis incoming surface shortwave radiation datasets with mesosclae remote sensing data. *Metorologische Zeitschrift* 19: 631 - 640, DOI:10.1127/0941-2948/2010/0466.