Master Thesis

A European heat wave hotter than 2003

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Publication Date:
2015

Permanent Link:
https://doi.org/10.3929/ethz-a-010512953

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A European heat wave hotter than 2003

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Zürich, Switzerland – May 2015
Abstract

The occurrence of heat waves is expected to increase over Europe in the future which may strongly affect society. A mechanism which contributes to hot temperature anomalies is the soil moisture-climate coupling, i.e. drying of soils in summer, leading to less evapotranspiration along with decreased latent cooling, which subsequently increase temperatures and finally enhance the drying of the soils. During summer 2003, precipitation and consequent soil moisture deficit significantly contributed to the extreme heat wave in August 2003.

Recently it was found that in 1540 there was an unprecedented lack of precipitation throughout the year. This extreme drought over Europe was very likely linked to a strong heat wave.

In this study we perform a set of regional climate simulations to examine 1540 summer conditions over Central Europe. We are able to reproduce a heat wave in 1540 with very dry soil conditions by employing reconstructed 1540 atmospheric forcing proxy conditions in the model. Summer 1540 temperatures likely exceeded 2003 temperatures in Central Europe.

We also simulate the heat wave of 2003 and prescribe very dry 1540 soil moisture conditions to assess the sensitivity of this heat wave to soil moisture. The large-scale circulation is suggested to have the major contribution to the extreme temperatures in 1540. The soil moisture-temperature coupling also contributed to the hot temperatures in this summer. For daily maximum temperatures we find stronger coupling than for mean temperatures. Furthermore we conclude that the heat wave in summer 2003 would have been even more intense with drier conditions of 1540, which underlines the importance of the soil moisture-temperature feedback to positive temperature anomalies.
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Chapter 1

Introduction

The intensity and frequency of weather extremes such as droughts and heat waves are expected to change in the future due to climate change (Meehl and Tebaldi, 2004; Alexander et al., 2006; Fischer and Schär, 2010). This is of importance for human society as extreme events severely affect ecology, human health and cause economic losses. To allow better forecasting or even mitigation of extreme events, the underlying processes and mechanisms leading to extreme conditions have to be understood. During the last decade much progress was made in understanding the development of droughts and heat waves. A main driver for temperatures in Europe is the large-scale atmospheric circulation which determines the advection of cold and warm air masses across the continent. Beyond that a number of studies show that land-climate coupling strongly influences European summer climate variability and heat waves (Seneviratne et al., 2006; Fischer et al., 2007a; Jaeger and Seneviratne, 2010; Hirschi et al., 2011; IPCC, 2012; Quesada et al., 2012). This coupling refers to the influence of the land surface on weather and climate through the impact of soil moisture (Seneviratne et al., 2010; Lorenz et al., 2012). Several observation-based as well as model-based studies highlight the importance of soil moisture as such a key variable (i.e. Hirschi et al., 2011; Orlowsky and Seneviratne, 2011).

Soil moisture is a water and energy storage and therefore linking land-surface and atmospheric processes (Seneviratne et al., 2010). In summer the partitioning of net radiation into sensible and latent heat flux may be largely controlled by soil moisture. Soil moisture-evapotranspiration coupling as well as soil moisture-precipitation coupling can play an essential role on hot extremes in summer (Seneviratne et al., 2006). Positive feedback mechanisms are operating when soils are drying and consequently evapotranspiration decreases, which leads to reduced latent cooling, enhances sensible heat flux and finally increasing surface temperatures. This may then strengthen the initial drying of the soils. Furthermore decreasing soil moisture with less evapotranspiration can also reduce precipitation which also leads to further decrease of soil moisture. On the other hand, in a negative feedback, precipitation may also be enhanced by less soil moisture as this can trigger convective instabilities (Hohenegger et al., 2009). Also soil moisture persistence can significantly enhance the influence of soil moisture on climate and can therefore also potentially improve the seasonal forecast skill for extreme events (Koster et al., 2010; Mueller and Seneviratne, 2012; Orth and Seneviratne, 2014).
In order to assess the role of these mechanisms for heat waves various studies investigated extreme events of the past, in particular the hot summer in Europe in 2003 (Schär et al., 2004; Stott et al., 2004; Andersen et al., 2005; Fischer et al., 2007b; Fischer and Schär, 2010; Weisheimer et al., 2011). Long-lasting large-scale anticyclonic conditions led to a drying of soils. The soil moisture deficit at the beginning of August then contributed to anomalously high temperatures in the first two weeks of that month. Regionally summer temperature anomalies exceeded 5 °C (Fischer et al., 2007b) and the heat wave was claimed to be the strongest in the last 500 years (Luterbacher et al., 2004).

This is under discussion as there may have been similar extreme events in the more historical past, where hardly any records exist. In particular 1540 was perhaps such an extreme warm year with very dry conditions. Recently Wetter and Pfister (2013) suggested that a heat wave occurred in 1540 in Europe that may have even exceeded the 2003 temperature anomalies. Also Schär et al. (2004) and Beniston and Diaz (2004) mention a likely warm summer in 1540, with a long-lasting high-pressure system and strong moisture deficit. Wetter et al. (2014) analyzed historical weather reports over a large Central European area, in particular grape harvest data from chroniclers, and found a significant lack of precipitation. They derived the number of precipitation days and monthly precipitation amounts at two stations, Cracow and the Swiss Plateau. These are below the 100 year minimum for spring, summer and autumn based on observational data from 1901 to 2000. This strong precipitation deficit has led to an 11-month-long mega drought over central Europe, and considering soil moisture-temperature feedback mechanisms it is suspected to be associated with a heat wave.

Unfortunately, no observational temperature records from this time exist and the influence of the drought on temperature has not been modeled yet. Hence, the overall goal of this study is to simulate temperature and soil moisture from 1540 using a regional climate model to assess if and how the dry conditions led to a heat wave. To understand the physical mechanisms of the heat wave development we specifically focus on the role of land-climate coupling on summer temperatures in 1540. In addition, we compare the event with the 2003 heat wave. We also test the sensitivity of this heat wave to 1540 soil moisture conditions.

Our objectives are, in particular to:

- Reconstruct soil moisture of the 1540 event
- Estimate temperatures of 1540
- Determine the importance of feedback mechanisms for 1540, e.g. soil moisture-temperature coupling
- Investigate if 1540 temperatures were exceeding 2003 temperatures
- Analyze the 2003 heat wave with 1540 soil conditions

The study is organized as follows. The first section reviews the importance of soil-atmosphere feedbacks on positive temperature anomalies in European summer climate. The used climate models and the experimental design to simulate the 1540 drought are described in section two. Section three presents
results from our simulations, in particular estimated temperatures. In section four the role of soil moisture for summer temperature anomalies is discussed. The final section summarizes and contextualizes the results.
Chapter 2

Methods

2.1 Model Description

In this study, we use the Community Land Model version 4 (CLM4.0) for offline Land Surface Model (LSM) simulations and the COSMO-CLM^2 model to perform coupled biosphere-atmosphere Regional Climate Model (RCM) experiments.

2.1.1 Land Model

We are studying the influence of land parameters of the terrestrial ecosystem on climate using CLM4.0 (Oleson et al., 2010; Lawrence et al., 2011), which was developed to understand the effect of natural and human changes in vegetation on climate. It is the land surface component of the Community Earth System Model (CESM; Meehl et al., 2013). The model accounts for biogeophysics, the hydrological cycle, biogeochemistry and vegetation. It includes related processes like vegetation composition, energy exchange and soil hydrology. Five primary sub-grid land cover types represent the land-surface in each grid cell. The vegetated parts are further divided into plant functional types. For each subgrid land cover type and plant functional type patch energy and water calculations are done separately. The soil is divided into 15 layers, with depth increasing exponentially from top to bottom. The first three layers represent the top 10 cm of the soil, which strongly exchange with the atmosphere. The first seven layers constitute the top meter of the soil. To the lowest soil level is coupled to a prognostic groundwater model. Lawrence et al. (2011) provide a detailed description of CLM4.0. The documentation is available from http://www.cgd.ucar.edu/tss/clm/.

2.1.2 Regional Climate Model

To investigate how land processes and in particular soil moisture are affecting air temperature we perform simulations using the biosphere-atmosphere regional climate model COSMO-CLM^2 (Davin et al., 2011; Davin and Seneviratne, 2012). COSMO-CLM^2 couples the non-hydrostatic regional atmospheric model COSMO-CLM (COnsortium for Small-scale Modelling in Climate Mode; Rockel et al., 2008) to CLM4.0 (Oleson et al., 2010) using the OASIS3-MCT coupler to communicate between the models.
Land surface processes are represented by CLM4.0 instead of the simpler native land surface parametrization of COSMO-CLM, which lead to a reduction of biases over Europe in mean climate, climate variability and extremes (Davin et al., 2011; Davin and Seneviratne, 2012; Lorenz et al., 2012). In contrast to the COSMO-CLM² version described by Davin and Seneviratne (2012) we employ a newer version of the land model (CLM4.0) and the atmospheric model (COSMO5.0).

The model has a horizontal resolution of 0.44° (≈ 50 km) with 32 vertical atmospheric levels. The model runs on the CORDEX EU domain (Kotlarski et al., 2014) which includes the entire European continent and parts of Russia and Northern Africa. We use the Runge-Kutta scheme for the time integration. Vertical turbulent mixing is parametrized using turbulent kinetic energy as a prognostic variable (Mellor and Yamada, 1982). The mass flux scheme of Tiedtke (1989) is applied to moist convection.

2.2 Experimental design

We simulate the climate of the year 1540, in particular temperatures and soil moisture, as it was stated to be an extreme dry year (Wetter et al., 2014). Note that Wetter et al. (2014) is referred to as W14 in the following. W14 provide precipitation estimates from a central European domain, which they inferred from weather reports. For consistency we perform our analysis over the same domain, from 45° to 55° N and from 5° to 20° E (Figure 2.1).

Apart from the reconstructed precipitation data from W14 there are no observational records over this domain from 1540. Hence, we employ the following approach in this study: We first construct 1540 atmospheric forcing that emulate precipitation amounts from W14 to perform uncoupled CLM

![Figure 2.1: a) The CORDEX domain where COSMO-CLM² simulations are performed. b) The Central European study domain (45° to 55° N, 5° to 20° E), with Cracow and the Swiss Plateau where historical precipitation records are available.](image-url)
simulations. From these simulations, we can infer reconstructed 1540 soil moisture. Then we perform coupled COSMO-CLM\textsuperscript{2} simulations using the reconstructed boundary conditions and reconstructed soil moisture from CLM.

2.2.1 Construction of 1540 atmospheric forcing proxy

W14 provide information about precipitation amounts and the number of days with precipitation over the W14 domain and particular at two stations, Cracow and the Swiss Plateau. Based on this information we construct the 1540 atmospheric forcing proxy. We reproduce precipitation amounts for the 1540 event of W14 across the domain by using gridded observation data for Europe (EOBS) covering the period from 1979 to 2013 \cite{Haylock2008}. From this period all relevant climate variables to force the model are available. We compared driest half-monthly periods from EOBS data over the study domain with the 1540 precipitation records from W14, which are in good agreement. Consequently the 1540 proxy year is constituted of 24 driest half-monthly periods from the 34 year long EOBS dataset. The selected years are shown in Table \ref{tab:2.1}. The actual length of a half-monthly period changes according to the length of the month. The first half consists always of the first 15 days of a month whereas the second half is either 13 days for February, 15 days for all months with 30 days and 16 days for months with 31 days.

Finally to force CLM, we apply two datasets. One 1540 forcing proxy is based on EOBS with precipitation, temperature and surface pressure expanded by WFDEI meteorological forcing data which includes radiation, humidity, wind and surface pressure \cite{Weedon2014}. Furthermore, to derive an alternative forcing we also selected the respective 24 half-monthly periods from ERA-Interim reanalysis data, which includes all relevant climate variables necessary for the boundaries of the model \cite{Dee2011}.

By selecting half-monthly periods from different years we also change atmospheric forcing conditions after each half-month. Sharp transitions in the atmospheric conditions between half-monthly periods evolve, but during the half-monthly periods the patterns are consistent.

Note that in 1540, radiation, temperature and CO\textsubscript{2} were at pre-industrial levels with no influence of anthropogenic climate change. The EOBS and ERA-Interim data is impacted by current emissions, radiation and temperature. Therefore, we adjusted temperature and incoming radiation in our 1540 forcing proxy according to pre-industrial levels for the offline CLM runs \cite{IPCC2013}. Temperatures where uniformly reduced by 0.8 K, incoming longwave radiation by 2.6 W m\textsuperscript{-2} and incoming shortwave radiation was augmented by 1 W m\textsuperscript{-2}. This adjusted 1540 forcing proxy is used to perform the model simulations are described in the following.

2.2.2 Modeling of 1540 soil moisture

In order to estimate 1540 soil moisture conditions we perform uncoupled CLM runs using the constructed 1540 forcing proxy. We employ both gridded observation data from EOBS and ERA-Interim reanalysis data. This allows to identify the impact of different forcing data sets. As we do not know the initial soil moisture conditions of 1540, we sample the present-day range of initial conditions using pre-computed
Table 2.1: Selected half-monthly periods of the 1540 forcing proxy. The half-monthly periods are chosen from the gridded observation EOBS dataset as they minimize precipitation amounts over the W14 domain.

<table>
<thead>
<tr>
<th>half-monthly period</th>
<th>original year</th>
<th>half-monthly period</th>
<th>original year</th>
</tr>
</thead>
<tbody>
<tr>
<td>01-15 January</td>
<td>1990</td>
<td>01-15 July</td>
<td>2010</td>
</tr>
<tr>
<td>16-31 January</td>
<td>1989</td>
<td>16-31 July</td>
<td>1990</td>
</tr>
<tr>
<td>01-15 February</td>
<td>1993</td>
<td>01-15 August</td>
<td>2003</td>
</tr>
<tr>
<td>16-28 February</td>
<td>2003</td>
<td>16-31 August</td>
<td>1984</td>
</tr>
<tr>
<td>01-15 March</td>
<td>1996</td>
<td>01-15 September</td>
<td>1999</td>
</tr>
<tr>
<td>16-31 March</td>
<td>2003</td>
<td>16-30 September</td>
<td>1997</td>
</tr>
<tr>
<td>01-15 April</td>
<td>2007</td>
<td>01-15 October</td>
<td>1986</td>
</tr>
<tr>
<td>16-30 April</td>
<td>2007</td>
<td>16-30 October</td>
<td>1985</td>
</tr>
<tr>
<td>01-15 May</td>
<td>1988</td>
<td>01-15 November</td>
<td>1984</td>
</tr>
<tr>
<td>15-31 May</td>
<td>1992</td>
<td>16-30 November</td>
<td>1993</td>
</tr>
<tr>
<td>01-15 June</td>
<td>1996</td>
<td>01-15 December</td>
<td>2004</td>
</tr>
<tr>
<td>16-30 June</td>
<td>1986</td>
<td>16-31 December</td>
<td>2007</td>
</tr>
</tbody>
</table>

fields from each year between 1984 and 2010 (27 years). This provides an estimate of the uncertainty due to initialization of the model. Consequently, we perform 2x27=54 simulations to derive 1540 soil conditions.

2.2.3 Coupled Model experiments

We finally perform four model runs with the coupled COSMO-CLM\(^2\), where we modify boundary conditions and soil moisture. This allows us to differentiate between the influence of atmospheric forcing and prescribing soil moisture (i.e. turning off land-atmosphere interactions) in the model.

In two experiments we employ boundary conditions of the constructed 1540 atmospheric forcing proxy in COSMO-CLM\(^2\). In one of these experiments we prescribe soil moisture which we computed with the CLM offline simulations, referred to as BC1540_SM1540. In the other 1540 experiment soil moisture is computed interactively and the experiment is called BC1540_SM1540. Furthermore, we perform two experiments where we employ the boundary conditions of 2003. Using 2003 boundary conditions, soil moisture is computed interactively (BC2003_INT) or prescribed to 1540 conditions (BC2003_SM1540).

The naming of the experiments and the setup are summarized in Table 2.2.

Table 2.2: Simulation setup

<table>
<thead>
<tr>
<th>boundary conditions</th>
<th>soil moisture</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>interactive</td>
<td>BC2003_INT</td>
</tr>
<tr>
<td>2003</td>
<td>1540</td>
<td>BC2003_SM1540</td>
</tr>
<tr>
<td>1540</td>
<td>interactive</td>
<td>BC1540_INT</td>
</tr>
<tr>
<td>1540</td>
<td>1540</td>
<td>BC1540_SM1540</td>
</tr>
</tbody>
</table>
Chapter 3

Results

3.1 Validation of 1540 forcing proxy

3.1.1 Precipitation

In order to compare precipitation amounts from our proxy with data from W14 we calculate seasonal precipitation means for spring (MAM), summer (JJA) and autumn (SON) at the location of Cracow (47.25°N, 8.25°E) and the Swiss Plateau (50.25°N, 19.75°E). W14 provide seasonal precipitation amounts including uncertainty estimates at the two stations from historical records using statistical models. As reference we calculate the distribution of EOBS seasonal precipitation amounts at the same locations (Figure 3.1). Precipitation amounts of the 1540 forcing proxy are generally in good agreement with data from W14, showing also very low precipitation amounts. At the two stations EOBS precipitation amounts for all three seasons are higher than precipitation of 1540. At the Swiss Plateau precipitation amounts of both the 1540 data from W14 and from the constructed 1540 proxy are lower than all EOBS data in all considered seasons. However, constructed 1540 precipitation amounts are higher than in W14. Only in autumn the amount is contained in the range of the distribution. In spring and in particular in summer, the amounts are outside the distribution. In Cracow the agreement is better but also the total variance of precipitation amounts is smaller. The 1540 proxy precipitation is close to the median from W14 in particular in summer and within the distribution. Note that the tails of the distributions of precipitation from EOBS and W14 are overlapping in summer and autumn.

3.1.2 Temperature

The reconstructed 1540 proxy year consists of 24 half-monthly periods, which implies that there also 24 different circulation patterns. The sharp transitions between the different periods are constructed artificially. To examine the impact of these sharp transitions on our results, we test here if we can find remarkable changes in temperatures between these transitions from one half-monthly period to the other. We calculate the mean of the 23 temperature differences from the last day of any half-month and the first day of the following half-monthly period at every grid box of the CORDEX domain and divide them by the mean temperature changes from one day to another within the half-monthly periods. The results
Figure 3.1: Seasonal precipitation amounts at the Swiss Plateau (a) and Cracow (b). The red stars indicate precipitation amounts from the 1540 forcing proxy. The boxplots show precipitation distributions from EOBS data (grey) and from 1540 data of W14 (white). The precipitation amounts are shown for March, April, May (MAM), June, July, August (JJA) and September, October, November (SON).

are shown in Figure 3.2. Most of the regions show values close to one, meaning the changes between the periods are of the same magnitude as day to day variability. There is no pattern which shows that there are larger jumps at grid boxes close to boundaries, where we prescribed the forcing. This gives us some confidence that the impact of the sharp transitions between the half-monthly periods are of minor relevance for the analysis in this study.

We also perform a spectral analysis where we estimate the spectral density of daily temperatures at each grid box (Venables and Ripley, 2002). In case there would be significant changes every 15 days we would expect a larger spectrum at scaling of 1/15, where 15 is the frequency. Our half-monthly periods change after 15 days and therefore we checked for frequencies of 14, 15, 16 days. We could not detect any remarkable periodicity around the scaling of 1/15 (also 1/14, or 1/16). Consequently we assume that our setup is suitable to investigate temperatures in 1540.

3.2 Reconstructed 1540 soil moisture

We computed 1540 soil moisture with CLM where we employed 27 different initial conditions from 1984 to 2010 and two 1540 forcing datasets (ERA-Interim and EOBS) with very low precipitation as described in Section 2.2. We furthermore computed soil moisture for each year between 1984 and 2010
Figure 3.2: Relative change of mean temperature of BC1540_INT from the last day of any half-monthly period to the first day of the next one, divided by mean temperature change from any day to the next day in the 1540 proxy year.

using CLM and ERA-Interim or EOBS data at the boundaries. The resulting present-day climatologies serve as reference to assess the soil moisture from the 1540 CLM experiments. In Figure 3.3 daily means over the study domain for all simulations are shown, the year 2003 is highlighted since this was very dry over central Europe (Fischer et al., 2007b).

We find that all 1540 simulations show much lower soil moisture than the climatology from 1984 to 2010. This indicates that the 1540 proxy forcing with a persistent precipitation deficit contributed to the drought development in 1540. This is of interest as low soil moisture can potentially contribute to positive temperature anomalies in summer. (Seneviratne et al., 2010; Fischer et al., 2007a; Hirschi et al., 2011).

For most of the year the 1540 runs show even lower soil moisture than 2003. We find a strong decrease in soil moisture in the beginning of August for both, the 2003 and 1540 simulations. This was when the heat wave of 2003 was occurring and we use the half-monthly period from August 2003 for the 1540 atmospheric forcing proxy (see Table 2.1). Consequently a similar behavior can be expected. 1540 soil moisture is still lower during this time, which is notable as 2003 was then already extremely. Only at the end of August, 2003 shows similarly low or partly lower soil moisture than the 1540 simulations.

The spread of the 1540 simulations resulting from the different initialization of the simulations diminishes throughout the year. The decreasing variance indicates that the impact from the initial conditions is rather small for the further evolution of the year and in particular in summer. After summer we find again an increase of soil moisture variance towards autumn, which might indicate a soil moisture memory effect. The differences between simulations forced with EOBS and ERA-Interim are small for both, the reference simulations and the 1540 simulations. We conclude that the uncertainty from forcing data set is relatively
small. However, the CLM simulations with ERA-Interim forcing seem to be slightly wetter and show a larger spread than simulations forced with EOBS.

We calculate the ensemble means of the CLM simulations for 1540 using either EOBS data or ERA-Interim reanalysis data as forcing. They are very similar. In the following we use the soil moisture ensemble mean of 27 different initialized, uncoupled CLM simulations forced with ERA-Interim as a robust soil moisture estimate for 1540. It might be more realistic to use soil moisture output of CLM simulations forced with observation data from EOBS, which used to select precipitation minima for the 1540 proxy. However, we decided to use mean soil moisture of simulations forced with ERA-Interim to be consistent with the coupled COSMO-CLM\textsuperscript{2} simulations, where we also use ERA-Interim data at the boundaries.

Note that we generally consider top 10 cm soil moisture in this study as this strongly linked to atmospheric exchange.

**Figure 3.3:** Mean soil moisture of CLM offline runs in top 10 cm averaged over the W14 domain. The red lines show CLM simulations from 1984 to 2010 forced with gridded observation from EOBS data (EOBS), black lines show soil moisture from CLM simulations forced with ERA-Interim reanalysis data (ERA). The 1540 CLM simulations are forced with the constructed 1540 atmospheric proxy forcing. Blue lines show 1540 soil moisture from CLM using EOBS data at the boundaries and initial conditions from 1984 to 2010. Green lines show 1540 CLM output using ERA-Interim at the boundaries and again initial conditions from 1984 to 2010. The black solid line indicates 2003 soil moisture.
3.3 Analysis of coupled model experiments

We perform coupled COSMO-CLM$^2$ experiments as described in Section 2.2 in order to derive temperatures. Our analysis focuses on summer (June, July and August) and when considering 1540 conditions we here refer to the \textit{BC1540\_INT} experiment, since results for both 1540 experiments are very similar.

3.3.1 Spatial structure of the 1540 event

To analyze the spatial pattern and extent of the 1540 event, we here analyze the model results for the full CORDEX domain, i.e. Europe including our Central European study domain and investigate how summer climate is behaving there.

We calculate summer temperature anomalies of daily mean temperatures normalized with the standard deviation of the climatology at every grid box. This allows to better compare anomalies between the different simulations (Figure 3.4) and also to relate the simulations to climatological summers of the past. The mean summer temperatures of the COSMO-CLM$^2$ simulations from 1979 to 2010 serve as climatology. Overall we find strong summer temperature anomalies in all simulations and in particular over Central Europe from three to six standard deviations. This confirms that all experiments lead to above-average European summers which are possibly related to soil moisture deficits. We consider these findings as indication that there was a heat wave in 1540. Note that we define a heat wave as a periods of anomaly high temperatures in summer and do not apply a specific threshold or index.

For \textit{BC2003\_SM1540} we can see a signal around four standard deviations from mean temperature, which is stronger than for \textit{BC2003\_INT}. We conclude that dry 1540 soil conditions would have led to an even stronger heat wave in 2003. Furthermore, the location of the heat wave is slightly larger in \textit{BC2003\_SM1540} than for \textit{BC2003\_INT}. We see the strongest signal over France, Switzerland and Northern Italy. In addition, we also observe a strong signal over the Mediterranean Sea which is likely related to the large-scale circulation.

For 1540 (\textit{BC1540\_INT}) we find a much stronger signal of temperature anomalies (up to six standard deviations from the mean) than for 2003 experiments. This indicates that based on the precipitation deficit COSMO-CLM$^2$ is able to produce strong temperature anomalies and potentially confirming the impact of the drought on temperatures. We also detect a clear shift in the location of the summer temperature anomalies compared to 2003. Interestingly, we observe the largest anomalies in Northern France, Belgium and Western Germany which is located south-west from the W14 domain, where we were actually minimized precipitation. This might indicate that the heat wave did not only occur over the study domain but also over Western Europe. The extension of the heat wave is limited to Central and Western Europe which could suggest that heat waves are generally limited to a region and not occurring over the whole continent. In addition we infer that we can reproduce strong 1540-like temperature anomalies with COSMO-CLM$^2$ even if atmospheric boundary conditions of 1540 are employed far away from the target area. When considering anomalies of autumn we still detect positive anomalies over the study domain.
RESULTS

but the signal is less than three standard deviations for all experiments (Figure A.1). This indicates that the persisting soil moisture deficit in autumn does not influences temperatures in autumn as much as in summer.

![Temperature anomalies of BC2003_INT, BC2003_SM1540, and BC1540_INT for the CORDEX domain.](image)

**Figure 3.4**: Temperature anomalies of a) BC2003_INT, b) BC2003_SM1540 and c) BC1540_INT for the CORDEX domain. Anomalies are calculated by subtracting the mean summer temperatures of the experiment by the mean summer temperature from 1979 to 2010 and dividing by the standard deviation of the anomaly.

Beside temperature anomalies we also investigate summer soil moisture, radiation, precipitation and evapotranspiration of the simulations to better understand the physical mechanisms leading to these temperature anomalies. We focus on the differences between the simulations, to assess the sensitivity of the 2003 heat wave on 1540 soil conditions and to compare summer 1540 with the 2003 heat summer.

Differences in summer means for specific variables for the full CORDEX domain between BC2003_SM1540 and BC2003_INT (Figure 3.5) as well as BC1540_INT and BC2003_INT (Figure 3.6) are calculated. We find mean summer temperature differences of around 1°C over the study domain between BC2003_INT and BC2003_SM1540. Net radiation is around 20 W m⁻² (Figure 3.5b), which can be partly assigned to larger, incoming shortwave radiation of up to 10 W m⁻² over central Europe (Figure 3.5c). Longwave radiation is very similar in both simulations and there are only very small differences (Figure 3.5d). Top 10 cm soil moisture is up to 10% lower for BC2003_SM1540 than for BC2003_INT, whereas differences are
RESULTS

less pronounced for 1 m soil moisture. Note that the top layers of the soil are dominating the atmospheric exchange from land. Latent heat flux is strongly decreased over the study area where we have lower soil moisture (Figure 3.5g). The drier soils coincide with a reduced latent heat flux and higher temperatures (Figure 3.5a). The precipitation differences are only around 1 mm d$^{-1}$, with the strongest signal over Switzerland. BC2003_SM1540 tends to have slightly lower precipitation than BC2003_INT over the study domain. However, differences are varying locally and we do not find a clear pattern for precipitation.

Comparing BC1540_INT and BC2003_INT we find higher summer temperatures in 1540 than in 2003 in Western Central Europe, in particular in the West of Germany, the Netherlands, Belgium and Northern France (Figure 3.6a). The differences in summer mean temperatures are more than 3 $^\circ$C. Net radiation differences show a similar pattern as temperature differences (Figure 3.6b). We find strongest differences of radiation of up to 60 W m$^{-2}$ which directly affect temperatures. The incoming longwave radiation shows also large difference of up to 50 W m$^{-2}$, which suggests that net radiation differences are driven by higher incoming shortwave radiation in 1540 (Figure 3.6c). The incoming longwave radiation has an effect close to zero and even a slight negative contribution to the positive anomaly of net radiation (Figure 3.6d). Mean summer latent heat flux is of more than 20 W m$^{-2}$ lower for 1540 than 2003 over the study domain and even expanded to Spain, France, Great Britain, the Netherlands, Belgium and Poland (Figure 3.6g). Also soil moisture is about 15% lower in BC1540_INT than BC2003_INT over larger parts of our study domain (Figure 3.6e). Note that the differences in the top soil moisture are larger than soil moisture within the first 1 m (Figure 3.6f). We find a precipitation deficit for 1540 in the study domain, which we expected because we constructed our 1540 experiment with minimal precipitation in this area (Figure 3.6h). The difference in precipitation is only around 2 mm d$^{-1}$ which is also in agreement with very small precipitation amounts in 2003. However, the little precipitation can be seen as one driver of very low soil moisture in 1540.

3.3.2 Temperatures in Central Europe

In order to examine the temperature evolution during the year we present daily mean temperature anomalies averaged over the W14 domain for the experiments (Figure 3.7). Daily mean temperatures of the COSMO-CLM$^2$ simulations from 1979 to 2010 serve as climatology to calculate temperature anomalies. Generally we find large summer temperature anomalies in all simulations. The two 2003 experiments evolve similarly during the year, which is very likely related to the the same atmospheric boundary conditions. For BC2003_INT we find large negative anomalies in winter and autumn of up to $-8^\circ$C and large positive anomalies of up to $8^\circ$C in summer. Similar results are found for BC2003_SM1540, whereas negative anomalies are less pronounced and positive temperature anomalies in summer are slightly stronger.

Daily mean temperatures from BC1540_INT, where we employed the 1540 atmospheric proxy at the boundaries, show a different evolution than 2003 experiments. Overall negative temperature anomalies are less frequent in BC1540_INT and we find higher temperatures than in the 2003 experiments. We observe highest anomalies in summer from mid June to mid July. Then daily anomalies averaged over the study domain are more than 9 $^\circ$C. Also in August, where the heat wave of 2003 was occurring the
RESULTS

1540 temperatures anomalies exceed both 2003 experiments. In the beginning of August the temperature evolution is very similar in all experiments. This coincides with the employment of the same boundary conditions during this two weeks in all experiments, as we selected the first half of August 2003 for the 1540 atmospheric forcing proxy (see Table 2.1).

To better compare the simulations in summer we calculated differences of daily mean temperatures for June, July and August between the experiments (b).

The differences between BC2003_INT and BC2003_SM1540 fluctuate around 1 °C and differences are getting larger during the course of the summer. BC2003_SM1540 tends to exceed the summer peaks in BC2003_INT, especially in the first half of August temperatures of BC2003_SM1540 are up to 3 °C higher than the BC2003_INT. Interestingly in the end of November we find a strong positive anomaly for the 2003 experiments, BC2003_INT exceeds BC2003_SM1540 around 3 °C.

Differences between BC1540_INT and BC2003_INT range from −6 °C to nearly 10 °C averaged over the study domain. We find highest differences from mid June to mid July, which coincides with strongest temperature anomalies in the 1540 experiment. In the first weeks of August BC1540_INT temperatures are still larger than 2003 temperatures, even tough this was the time of the 2003 heat wave. Since summer peak temperatures of 2003 are even exceeded by BC1540_INT, we reveal that 1540 a heat wave occurred.

In the beginning of June, the end of July, the middle and the end of August BC2003_INT temperature anomalies exceed temperatures in BC1540_INT by more than 5 °C. This confirms again that 2003 was an extreme warm summer.

To relate the temperatures to a typical summer climatology of this region we calculate the distribution of mean summer temperature over the study domain (using again COSMO-CLM from 1979 to 2010) and compare this with the mean summer temperatures of our experiments (Figure 3.8). The reference heat wave of 2003 is already 1 °C warmer than two standard deviations. All summer mean temperatures of the experiments are outside two standard deviations of the climatological mean summer temperature. For BC2003_SM1540 temperature is getting on average around 0.3 °C warmer compared to reference 2003 experiment. This could confirm that drier soils enhance summer temperature anomalies. BC1540_INT show on average warmer temperatures than the two 2003 experiments. This confirms that 1540 summer was likely a warmer summer than 2003.

However, the differences between the experiments are changing considering monthly mean temperatures (instead of summer mean temperatures) over our domain. But we always find that in summer months BC2003_SM1540 shows warmer mean temperatures than BC2003_INT. Considering mean autumn temperatures where we still have a soil moisture deficit in 1540, mean temperatures are very similar and within the range of the climatology (not shown).

Analysis of hottest temperatures

The model experiments show above-average warm summers and according to the high temperatures BC1540_INT a heat wave occurred in summer. In order to investigate extreme conditions we examine daily maximum temperatures beside daily means. These are the maximum temperatures simulated within a day.
and they are potentially strongly linked to soil moisture (i.e. Fischer et al. 2007a; Jaeger and Seneviratne 2010; Hirschi et al. 2011; Seneviratne et al. 2013). We can find similar strong anomalies for maximum temperatures and larger differences between the experiments than looking at daily mean temperatures. The spatial pattern is very similar (Figure A.3).

Another indicator for extremes are the number of hot days (NHD), defined as the days where the maximum temperature is larger than the 90th percentile of a reference climatology. To compute the NHD in summer 1540 we use the output from COSMO-CLM from 1979 to 2010 as reference. A single day needs to exceed the 90th percentile of the same day in the climatology and also the 90th percentile of two days before and afterwards. This moving five day window should assure more robust results and is based on the approach of Lorenz et al. (2012). The 1540 experiment has more hot days than the experiments using 2003 boundary conditions (Table 3.1). The highest number of 43 days shows BC1540_INT, which generally has the warmest daily mean and maximum temperatures. BC2003_SM1540 has one more hot day than BC2003_INT. By changing the number of days to calculate the 90th percentile threshold i.e. three day window or seven day window, the NHD is changing by ±1 day but the ranking remains the same.

Table 3.1: Number of hot days (NHD) in summer (JJA)

<table>
<thead>
<tr>
<th>simulation</th>
<th>NHD</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC2003_INT</td>
<td>31</td>
</tr>
<tr>
<td>BC2003_SM1540</td>
<td>32</td>
</tr>
<tr>
<td>BC1540_INT</td>
<td>43</td>
</tr>
</tbody>
</table>

3.3.3 Soil moisture evolution

We consider the evolution of mean daily soil moisture in the different experiments averaged over the W14 domain in addition to mean temperatures. Soil moisture from CLM offline runs for 1540 and 2003 and soil moisture of coupled COSMO-CLM\(^2\) for 1540 and 2003 is presented in Figure 3.9. Note that we did not perform experiments where we prescribe soil moisture of 2003. We find differences of soil moisture within the same year. This might be caused by different atmospheric forcing conditions applied in CLM and COSMO-CLM\(^2\). Soil moisture from both 1540 simulations is generally considerably drier than 2003 soil moisture. In the beginning of June we have slightly drier conditions for the 1540 experiments, soil moisture is decreasing in all simulations until the end of June except for BC2003_SM1540 where we prescribe 1540 soil moisture. There, daily mean soil moisture is even partly exceeding 2003 soil moisture. In July we find a different behavior in all experiments, in particular 2003 soil moisture is much wetter. We find differences of more than 10 % between 2003 and 1540 soil conditions especially in the beginning of July. The drier 1540 experiment shows higher temperatures at this time (Figure 3.7). Note that soil moisture from SM1540 deviates from BC1540_INT. Soils in BC1540_INT are drier in the beginning of July and wetter in the end of July, where its peak is nearly reaching 2003 soil moisture. There is a steep decrease of soil moisture in all simulations including the 2003 simulation which can be assigned to
the same forcing conditions in the first half of August (Table 2.1). The decrease of soil moisture in the BC2003_INT is even more pronounced as the drier soils of 1540 cannot dry as much as the wetter soils of 2003. After the soil moisture minimum in August, soils are getting wetter in all simulations. There is a strong increase of the 2003 soil moisture and the difference with the 1540 forcing exceeds 15 % in October. BC1540_INT soil moisture is increasing more than the 1540 soil moisture from CLM and stays wetter until the end of the year.

Figure 3.9: Daily mean top 10 cm soil moisture averaged over the W14 domain. Interactively computed soil moisture from COSMO-CLM² for BC2003_INT (black) and BC1540_INT (red) and soil moisture from uncoupled CLM for 2003 (green) and 1540 (blue). Note that we are prescribing 1540 soil moisture (blue) in BC2003_SM1540, whereas we do not perform simulations using 2003 soil moisture.
Figure 3.5: Differences between mean summer in 2003 with 1540 soil moisture (BC2003_SM1540) and 2003 (BC2003_INT). The maps are showing differences for a) temperature, b) net radiation, c) incoming shortwave (SW) radiation, d) incoming longwave (LW) radiation, e) top 10 cm soil moisture, f) top 1 m soil moisture, g) latent heat flux and h) precipitation.
Figure 3.6: Differences between mean summer in 1540 (BC1540_INT) and 2003 (BC2003_INT). The maps are showing differences for a) temperature, b) net radiation, c) incoming shortwave (SW) radiation, d) incoming longwave (LW) radiation, e) top 10 cm soil moisture, f) top 1 m soil moisture, g) latent heat flux and h) precipitation.
**Figure 3.7:** a) Daily temperature anomalies averaged over the W14 domain for BC2003_INT (red), BC2003_SM1540 (black), and BC1540_INT (green). b) Daily mean temperature differences for summer between BC2003_SM1540 and BC2003_INT (black) and BC1540_INT and BC2003_INT (green).

**Figure 3.8:** Distribution of summer mean temperatures between 1979 and 2010 averaged over the W14 domain (grey). The dashed line indicates the double standard deviation. The colored lines show summer mean temperatures of BC2003_INT (red), BC2003_SM1540 (black) and BC1540_INT (green).
Chapter 4

Discussion

4.1 Soil moisture-temperature coupling in Central Europe

In order to better understand how summer temperature anomalies develop we here investigate the underlying mechanisms. In particular we focus on the impact of soil moisture on temperatures in summer, because then feedback mechanisms are relevant and a soil moisture deficit potentially leads to strong temperature anomalies (i.e. Fischer et al., 2007b; Jaeger and Seneviratne 2010; Seneviratne et al., 2010; Fischer et al., 2007a; Hirschi et al., 2011).

Comparing BC2003_SM1540 and BC2003_INT we suggest that a feedback loop is likely to enhance hot temperatures in summer. Temperatures anomalies over the study area coincide with drier soils and a strongly decreased latent heat flux (Figure 3.5). We find that during the course of the summer temperature differences are getting larger (Figure 3.7b), which indicates that soil moisture is likely a more important driver for positive temperature anomalies under drier conditions. BC2003_SM1540 exceeds BC2003_INT in August by up to 3°C. This is remarkable as in August 2003 there were regionally extreme temperature anomalies up to 5°C in Europe (Schär et al., 2004). Note that the heat wave during August 2003 had the largest magnitude over France which is not included in our study domain.

The BC2003_SM1540 summer temperature anomalies are very likely enhanced by a positive feedback initiated by drier soils. This is in agreement with studies showing that drier soils can lead to higher summer temperatures (i.e. Fischer et al., 2007a; Seneviratne et al., 2013). The soil moisture deficit can be partly driven by the less precipitation in 1540 (Figure 3.5).

Also the strong temperature anomalies in 1540 are very likely to some extent related to the extreme dry soils, which are linked to the persistent lack of precipitation (Figure 3.6). We suggest that the hot temperatures in summer of 1540 can be partly explained by a positive feedback mechanisms, where a soil moisture deficit is leading to less evapotranspiration and a decreased latent cooling, enhancing temperatures and the drying of the soils (Figure 3.6). In July the drier 1540 experiment shows higher temperatures (Figure 3.7), which indicates that soil moisture deficit drives hotter temperatures in the 1540 experiments. Beside soil moisture other mechanisms are controlling temperature anomalies and we cannot exclude that the strong anomalies are caused by large-scale atmospheric circulation.

A strong contribution of the circulation on summer temperatures in 1540 may be suggested when consid-
erating the different evolution of the 2003 and 1540 experiments. Our results show that in the beginning of June, the end of July, the middle and the end of August temperatures of BC2003_INT where higher than BC1540_INT despite much wetter soils (Figure 3.7b). In particular in the middle of July temperatures were up to 5 °C cooler although we find a soil moisture deficit in the 1540 experiment. Considering different regions also reveal that weather regimes contribute to temperature anomalies. For example, we detect strong soil moisture differences over Northern Finland where we do not have positive temperature anomalies (Figure 3.6). For autumn we find mean temperatures within the range of the climatology for all experiments, even if we still have a strong soil moisture deficit for 1540. This suggest that in autumn drier soils are likely not the controlling mechanism for temperature anomalies in Europe. In the end of November we find a strong positive anomaly in BC2003_INT, even though soils are wetter than in the other experiments (Figure 3.7b and Figure 3.9), which again underlines the importance of other temperature drivers.

In order to finally quantify the influence of a soil moisture deficit on positive temperature anomalies we relate differences in soil moisture between BC2003_INT and BC2003_SM1540 as well as BC2003_INT and BC1540_INT to differences in temperature. Overall we find a large scatter, but also a (weak) relationship (Figure 4.1 a & b). Drier soils in BC2003_SM1540 than in BC2003_INT partly contribute to stronger temperature anomalies in summer (Figure 4.1 a). The linear regression is shown in red and the explained fraction of variance is only 11%. Note that highest temperature differences between BC2003_SM1540 and BC2003_INT do not show highest soil moisture differences. This can be explained as in these cases actual soil moisture is very low and consequently temperature is likely more sensitive to small soil moisture differences. For BC1540_INT and BC2003_INT soil moisture-temperature coupling tends to be stronger. Drier soil moisture in BC1540_INT tends to lead to warmer temperatures and wetter soils lead to colder temperatures in 1540. The linear regression is shown in red, the explained fraction of variance is 23%. This is not a very strong signal but underlines again that soil moisture is one (but not the only) driver for temperature anomalies. When considering daily maximum temperatures we find a stronger relation, with an explained fraction of variance of 30% (Figure A.4).

Overall these results confirm that the strong 1540 temperature anomalies, which exceed 2003 temperatures, can be partly explained by a strong soil moisture deficit. We detect the largest soil moisture contribution during periods where temperatures (anomalies) are very high. This illustrates the asymmetric impact of soil moisture, which has a stronger influence on hotter temperatures (i.e. [Jaeger and Seneviratne] 2010; [Hirschi et al.] 2011).
4.2 Constraining soil moisture in the 1540 simulation

In order to disentangle the impacts soil moisture and the large-scale circulation on temperature we perform an additional simulation for 1540. We prescribe the CLM-derived 1540 proxy soil moisture (BC1540_SM1540), as in BC2003_SM1540, where land-atmosphere interactions are mainly turned-off. Soil moisture is very low in both experiments, but BC1540_INT is partly even drier than BC1540_SM1540 (Figure 3.9). We find the strongest differences from June to September albeit a fluctuating signal. In the beginning BC1540_INT tends to be drier and in September BC1540_SM1540 shows lower soil moisture. The differences might originate from the different forcing conditions in CLM and COSMO-CLM². Precipitation patterns and amounts in BC1540_INT and BC1540_1540SM vary locally and likely contribute to different soil moisture. However, we cannot determine whether the differences in soil moisture constitute a robust signal or arise due to variability of COSMO-CLM². This could be tested with sensitivity experiments, where initial conditions are slightly disturbed, which was not done in this study.

These soil moisture differences consequently impact temperatures which we investigate in the following. Wetter soils in summer (+10%) in BC1540_SM1540 result in higher evapotranspiration in the according areas and finally lead to stronger latent cooling and lower temperatures (Figure A.5). Beside this direct evapotranspiration-temperature feedback we also detect an indirect feedback mechanism. More evapotranspiration supports cloud formation and therefore reduces incoming shortwave radiation and consequently also temperature. Incoming longwave radiation is also lower in BC1540_SM1540 as generally lower temperatures lead to reduced emission of radiation.

Figure 4.1: Soil moisture-temperature coupling in summer. a) The soil moisture difference between BC2003_SM1540 and BC2003_INT is plotted against the respective temperature difference. b) The soil moisture difference between BC1540_INT and BC2003_INT is plotted against the respective temperature difference. Each point corresponds to a daily mean from June to August averaged over the study domain. The least-squares regression is shown in red.
The same mechanisms can be observed considering June and September, where soil moisture differences are very high (Figure A.6 and Figure A.7). Drier soils are generally associated with positive temperature differences and wetter soils with negative temperature differences., which underlines again the importance of soil moisture on temperatures.

Timeseries of daily mean temperatures are well aligned for both 1540 experiments but show differences in particular for the highest anomalies (Figure 4.2a). This gives us more confidence that the large-scale atmospheric circulation is the dominant driver of the high temperatures in 1540 (Figure 4.2a). This is in agreement with Quesada et al. (2012), who also highlight the importance of specific weather regimes of initially dry conditions for summer temperature anomalies.

However, BC1540_INT shows higher temperatures in the middle of June and the beginning of August, where soils were drier. To quantify the contribution of soil moisture to the hotter summer temperatures in BC1540_INT compared to BC1540_SM1540 we investigate the soil moisture-temperature coupling in these experiments. We find a relationship, the explained fraction of variance is 32% (Figure 4.2b). This indicates that the soil moisture-temperature feedback can partly explain higher temperatures in addition to large-scale atmospheric forcing with its major contribution to summer temperature anomalies in 1540.

\[ R^2 = 0.32 \]

![Figure 4.2](image)

**Figure 4.2:** Comparison of 1540 experiments. a) Mean daily temperature anomalies for BC1540_INT and BC1540_SM. b) Summer soil moisture-temperature coupling. The soil moisture difference between BC1540_INT and BC1540_SM is plotted against the respective temperature difference. Each point corresponds to a daily mean from June to August averaged over the study domain. The least-squares regression is shown in red.

### 4.3 Validating 1540 temperatures

The analysis reveals that temperatures in 1540 were likely exceeding 2003 temperatures over the central European study domain as earlier suggested by Wetter and Pfister (2013).
Wetter and Pfister (2013) estimated spring-summer temperature anomalies of about 4.7 °C to 6.8 °C in Switzerland. We find a mean spring-summer temperature anomaly over the Swiss domain (46.25° to 47.25° N, 6.25° to 10.25° E) of around 3 °C with local differences ranging between 1.9 °C to 3.5 °C (not shown). Our results are lower than the estimates of Wetter and Pfister (2013) for Switzerland, but we confirm that the dry 1540 summer was likely anomalously hot across central Europe. However, we use a reference climatology of the last 30 years whereas Wetter and Pfister (2013) calculate anomalies to a reference period from 1901 to 2000. Furthermore they consider a Swiss domain north of the Alps, whereas we look at entire Switzerland as we cannot detect a gradient north and south of the Alps. Note that August and also September are not included in the estimated temperatures of Wetter and Pfister (2013), where we find anomaly high temperatures. Furthermore the center of the heat wave where we find strongest temperature signals in our simulations is shifted north-west of Switzerland, meaning that there are higher temperature anomalies outside Switzerland.
Chapter 5

Conclusions and Outlook

5.1 Conclusion

In this study we perform a set of regional climate simulations to examine the 1540 drought over central Europe. We investigate underlying physical mechanisms such as the role of soil moisture-temperature coupling and the importance of the large-scale circulation. On the basis of 1540 precipitation data which show a strong precipitation deficit, we reconstruct an estimate of 1540 forcing conditions using EOBS gridded observations from the recent past. Based on this forcing, we compute soil moisture using the CLM land model. Generally, the estimated 1540 soil moisture is very dry over Central Europe compared to the climatology from 1984 to 2010, and even drier than in 2003. This illustrates that the persistent lack of precipitation in 1540 has significantly contributed to drying of soils.

Employing 1540 atmospheric forcing conditions and corresponding estimated soil moisture, we perform coupled COSMO-CLM simulations to infer the influence of the 1540 drought on temperature. We also analyze the heat wave of 2003 and prescribe 1540 soil moisture conditions in 2003 to assess the sensitivity of this heat wave to soil moisture conditions.

The analysis reveals that the 1540 drought has led to a heat wave over Europe and that temperatures in 1540 were likely exceeding 2003 temperatures over the central European study domain. We find lower temperature anomalies for spring-summer temperature anomalies in Switzerland than the estimates of Wetter and Pfister (2013), but we confirm that the dry 1540 summer was likely anomalously hot across central Europe.

From our model experiments we conclude that circulation effects are the main drivers for the large temperature anomalies in 1540, in particular in the beginning of the summer. Soil moisture-temperature coupling also contributed to the high temperatures in summer. When looking at maximum daily temperatures we find stronger coupling. This confirms a more prominent role of soil moisture during heat wave extremes compared to average conditions. In autumn where we still observe a large soil moisture deficit the role of soil moisture is less important. Furthermore, we observe strong regional temperature anomalies in the 1540 and 2003 simulations but not over the entire CORDEX domain, which suggests
CONCLUSIONS AND OUTLOOK

that heat waves are generally unlikely to extend over the whole European continent. The simulations show that August 2003 could have been warmer if there were very dry soils as in 1540. This is in agreement with various studies that show that soil moisture-temperature feedback has its strongest influence in summer, where soil moisture content is lowest in Europe. Since we expect an increasing number of extreme events over Europe in the future this might be relevant as the 2003 benchmark can be exceeded again with a 1540-like event.

We are able to simulate more extreme heat waves than 2003 with COSMO-CLM$^2$ when applying extreme dry soil moisture conditions.

5.2 Outlook

We prescribe mean soil moisture from CLM which is forced with ERA-Interim data, but we could extent our experimental design to constrain soil moisture in COSMO-CLM$^2$ with mean soil moisture derived of CLM forced with EOBS data. Soil moisture would be then slightly lower. Another idea for further experiments would be to prescribe the median instead of the mean of CLM soil moisture ensembles which would also lead to slightly drier. This would consequently allow to assess the sensitivity of prescribing different soil moistures in the model.

Regarding the experimental design it would be useful to construct different 1540 forcing proxies, e.g. taking the second driest half-monthly periods from the EOBS data, to test the sensitivity of temperatures and also the location of the heat wave.

We consider a relatively small study area whereas COSMO-CLM$^2$ is run on the CORDEX domain, which includes entire Europe and also parts of Northern Africa. The 1540 forcing is applied at the boundaries of the CORDEX domain, which is far away from our target area. This possibly adds uncertainties to the climate in the target area. To have confidence that forcing conditions are determining the climate in the study area it might be useful to perform the simulations on a smaller domain so that the boundary conditions are closer to the study area.

Another interesting effect arise as we prescribed soil moisture in COSMO-CLM$^2$. The model output show very low soil moisture for simulations where we employ 1540 boundary conditions. However, the interactively computed soil moisture and the 1540 soil moisture from CLM differ, in particular in summer interactively computed soil moisture is partly even drier. This might be related to different precipitation amounts and different atmospheric forcing conditions applied in CLM and COSMO-CLM$^2$. A comprehensive analysis would be useful to understand these differences.

Future studies may consider, that in 1540, CO$_2$, radiation and temperature were at pre-industrial levels. In COSMO-CLM$^2$ current levels of CO$_2$, radiation and temperature are applied, which have to be adjusted to even better reproduce realistic and robust 1540 conditions.
Acknowledgement

I hereby want to thank René Orth for supervising me and leading me reliably through my thesis. I am grateful for the very good, uncomplicated cooperation and I appreciate his constructive ideas and feedback. I thank Mathias Hauser who patiently helped me particularly with technical questions (modeling and latex) and always found time to support me. Furthermore many thanks to Edouard Davin for guiding me safely through COSMO-CLM\(^2\) and all his constructive advise. I also want to thank Sonia I. Seneviratne for providing me the opportunity to work on this interesting subject and for taking time for all the discussion about my thesis. In addition I am thanking the office colleagues from my supervisors who I was potentially disrupting during regular visits and who also gave me input. Overall I could benefit from the very good land-climate dynamics group working environment and always felt welcome in the group. Thanks to Johannes Werner from TU Darmstadt who provided me with the 1540 precipitation data.
Declaration of Originality

With my signature, I hereby declare: I hereby declare that the written work I have submitted entitled

*A European heat wave hotter than 2003*

is original work which I alone have authored and which is written in my own words, with the exclusion of proposed corrections.

**Author**
Martha-Marie Vogel

**Supervising Lecturer**
Prof. Dr. Sonia I. Seneviratne

With my signature, I hereby declare:

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- I have not manipulated any data.

- I have identified all persons who have substantially supported me in my work in the acknowledgments.

- I understand the rules specified above.

I understand that the above written work may be tested electronically for plagiarism.

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*Place and Date*                  *Signature*

Appendix A

Figures

Figure A.1: Temperature anomalies in autumn (SON) of a) BC2003_INT, b) BC2003_SM1540 and c) BC1540_INT for the CORDEX domain. Anomalies are calculated by subtracting the mean summer temperatures of the experiment by the mean summer temperature from 1979 to 2010 and dividing by the standard deviation of the anomaly.
Figure A.2: Temperature anomalies in September of a) BC2003_INT, b) BC2003_SM1540 and c) BC1540_INT for the CORDEX domain. Anomalies are calculated by subtracting the mean summer temperatures of the experiment by the mean summer temperature from 1979 to 2010 and dividing by the standard deviation of the anomaly.
Figure A.3: Anomalies of daily maximum temperatures of a) BC2003_INT, b) BC2003_SM1540 and c) BC1540_INT for the CORDEX domain. Anomalies are calculated by subtracting the maximum summer temperatures of the experiment by the maximum summer temperature from 1979 to 2010 and dividing by the standard deviation of the anomaly.
Figure A.4: Soil moisture-maximum temperature coupling in summer 2003 and 1540. The soil moisture difference between BC1540_INT and BC2003_INT is plotted against the respective maximum temperature difference. Each point corresponds to a daily maximum/mean from June to August averaged over the study domain. The least-squares regression is shown in red.
Figure A.5: Differences of mean summer between the two 1540 experiments (BC1540_INT - BC1540_SM1540). The maps are showing differences for a) temperature, b) net radiation, c) incoming shortwave (SW) radiation, d) incoming longwave (LW) radiation, e) top 10 cm soil moisture, f) top 1m soil moisture, g) latent heat flux and h) precipitation.
Figure A.6: Differences of mean June between the two 1540 experiments (BC1540_INT - BC1540_SM1540). The maps are showing differences for a) temperature, b) net radiation, c) incoming shortwave (SW) radiation, d) incoming longwave (LW) radiation, e) top 10 cm soil moisture, f) top 1m soil moisture, g) latent heat flux and h) precipitation.
Figure A.7: Differences of mean September between the two 1540 experiments (BC1540_INT - BC1540_SM1540). The maps are showing differences for a) temperature, b) net radiation, c) incoming shortwave (SW) radiation, d) incoming longwave (LW) radiation, e) top 10 cm soil moisture, f) top 1m soil moisture, g) latent heat flux and h) precipitation.
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