Proposal

for a doctoral thesis at the
Swiss Federal Institute of Technology Zürich (ETHZ)

Regional Climate Modelling of European Summer Heatwaves

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presented by

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1 Introduction and Motivation

A record-breaking heatwave affected the European continent in summer 2003. With mean summer temperatures (June, July and August) exceeding the 1961–90 mean by about 3°C over large areas (Schär et al. 2004), it was very likely the hottest European summer over the past 500 years (Luterbacher et al. 2004, Beniston 2004, Black et al. 2004, Schönwiese et al. 2004). In Central and Southern Europe the socio-economic implications of this extraordinary heatwave were disastrous (Schär and Jendritzky 2004). Estimations by the World Health Organization (WHO) and the Earth Policy Institute indicate a statistical excess over the mean mortality of between 22,000 and 35,000 heat-related deaths accross Europe (Larsen 2003, Vandentorren et al. 2004, Hémon and Jougla 2004, Koppe and Jendritzky 2004). During the maximum heatwave, in the two first weeks of August, the mortality rate in France increased by 54% (Hémon and Jougla 2004). The financial loss due to crop failure over southern, central and eastern Europe is estimated at 12.3 billion US$ by the reinsurance Swiss RE. Forest fires in Portugal alone resulted in total damage of 1.6 billion US$ (Zanetti et al. 2004).

An event like that of summer 2003 is statistically extremely unlikely, even when the observed warming is taken into account (Schär et al. 2004). However, Schönwiese et al. (2004), using statistical time series analysis on German surface temperature series, reveal an increasing probability of hot summers taking place along with a warming trend observed especially within the recent decades. Stott et al. (2004) point out that the increasing probability can be partly attributed to past human influence, which has more than doubled the risk of European mean summer temperatures as hot as 2003. Schär et al. (2004) using regional climate models show that this risk of extreme summers is further increasing in future, associated with pronounced increase in year-to-year variability in response to greenhouse-gas forcing. These results are in good agreement with a GCM study by Meehl and Tebaldi (2004) suggesting that future heat waves over Europe and North America will become more intense, more frequent and longer lasting.

The physical processes involved in the formation of a heatwave are still not fully understood. The sequence of feedbacks involves substantial uncertainties due to large-scale anticyclonic forcing, radiation, soil hydrology and other processes, which are difficult to represent in climate models (Schär et al. 2004). Vidale et al. (2003) demonstrate that the predictability of the regional climate varies strongly between different seasons and regions, being weakest during summer and over continental regions.

This PhD thesis aims to identify the key processes of an evolving heatwave in order to get a better scientific understanding of the summer climate variability and extreme events. In this study we use the regional climate model CHRM (Climate High-Resolution Model) to simulate summer heatwave formation over Europe. Sensitivity experiments for the summer 2003 are performed by manipulating different variables in order to determine their influence on the formation of a heatwave. We emphasize on the role of circulation changes, evapotranspiration, their interactions and the related feedback processes by conducting experiments with varying initial conditions.

2 The Scientific Basis and State of the Research

2.1 The European Summer Heatwave 2003

Heatwaves are generally associated with specific atmospheric circulation patterns represented by large-scale anticyclonic forcing (Black et al. 2004). These patterns are often characterised by semistationary 500-hPa positive height anomalies that dynamically produce subsidence, clear skies, light winds, warm-air advection, and prolonged hot conditions at the surface (Kunkel et al. 1996, Palecki et al. 2001, Meehl and Tebaldi 2004). This was the case for both recent heat waves in Chicago 1995 and Central Europe 2003. The response to this circulation anomaly is nonlinearly amplified by a positive feedback due to suppressed evapotranspiration owing to the lack of soil moisture (Hartmann 1994, Schär et al. 2004, Lakshmi et al. 2004). Black et al. (2004) suggest that the exceptionally high temperatures in summer 2003 were mainly the consequence of the atmospheric circulation enabling a dominance of the local heat balance over Europe. The anomalously clear skies and the extremely strong radiative anomalies in June contributed to a rapid loss of soil water. This resulted in negative latent heat flux anomalies due to the lack of moisture and positive sensible heat fluxes due from the extremely hot land surface in August (Black et al. 2004).

2.2 Summer Climate Variability

The positive average temperature anomaly of about 3°C over Europe in summer 2003 corresponds to an excess of locally up to 5 standard deviations (Schär et al. 2004). It was preceded by an exceptionally strong, unprecedented warming starting in 1978 (a linear trend of 0.7°C ± 0.20°C per decade) that featured very likely the hottest summer decade 1994 to 2003 (Luterbacher et al. 2004). This results compares well with the even stronger trends observed by Schönwiese et al. (2004) over Germany, which turn out to be most pronounced in August. At Swiss stations the heatwave 2003 reached its maximum in June (+6.8°C wrt 1864–2000) and August (+5.7°C), whereas July was less extreme. Schär et al. (2004) found a shift of the summer temperature distribution 1941–2000 by a mean warming of 0.8°C with respect to the period 1864–1923.

2.3 Future Summer Climate

Stott et al. (2004) estimate that past human influence has more than doubled the risk of European mean summer temperatures as hot as 2003. They expect that the likelihood will rapidly increase in future. Regional climate model simulations show an increase in summer temperature variability in response to increased greenhouse gas forcing (Schär et al. 2004). Intercomparisons with other models support this result (Vidale et al., in prep). Schär et al. (2004) suggest that towards the end of the 21st century, under the given scenario assumptions, about every second summer could be as warm or warmer (and as dry or dryer) than 2003. Beniston (2004) show that the period during which exceedance of a maximum temperature of 30°C can be expected, will be extended by close to one month at the end of the century. These results compare reasonably well with a GCM study by Meehl and Tebaldi (2004) suggesting that future heat waves over Europe and North America will become more intense, more frequent and longer lasting. They show that present-day heatwaves over these regions coincide with a specific atmospheric circulation pattern that is intensified by the ongoing increases in greenhouse gas concentration.

3 Proposed Research

3.1 Objectives

The over-all objective of this PhD thesis is:

- Improving the scientific understanding of the different processes involved in the formation of summer heatwaves over the midlatitudes in order to estimate their intensity, frequency and length in a present and future climate.

This general objective can be subdivided in specific objectives which induce the following research questions subsumed under different topics. The analyses will reveal strengths and weaknesses of the approach, and will allow to focus on key processes. At present, some possible lines of further investigations are given here as options:

Summer Heatwave 2003

- Can the regional climate model CHRM represent the magnitude and regional distribution of the extreme temperature anomalies during the summer heatwave 2003?
- What was the range of the soil water content in spring and summer 2003 with respect to the ERA-40 period (1958–2001)?
- How did the soil water content influence the sensible and latent heat fluxes before and during the heatwave?

Formation of Summer Heatwave (Physical Processes)

- How sensitive is the formation of a heatwave to soil water under a given atmospheric circulation? What is the role of soil water? Is it part of a feedback process or a key factor, that drives the development and provides predictability?
- What is the interaction between soil water content and atmospheric circulation? How does reduced summer soil water content drive atmospheric circulation?
- Option 1: Is there another summer period in the instrumental period with a similar anticyclonic forcing as summer 2003 (e.g. summer 1947 (cf. Beniston and Diaz 2004))? In which way is it different from summer 2003?
- Option 2: What is the evolution of surface and top-of-atmosphere net radiation fluxes before and during a summer heatwave?

Future Summer Climate

- Option 3: How will frequency, intensity and length of summer heatwaves change in a future climate?

- Option 4: Are there any isolated key factors, which will become more important for the formation of a summer heatwave in a future climate?

3.2 Data and Tools

Regional Climate Model CHRM

The regional climate model (RCM) used in this study is the Climate High-Resolution Model (CHRM). The CHRM is a climate version of the former mesoscale weather forecasting model of the German and Swiss meteorological services known as the HRM (High-Resolution Model) or formerly EM (Europa-Modell) (Majewski 1991, Majewski and Schrodin 1994). The model has been modified by Lüthi et al. (1996) for application as a regional climate model. The computational domain covers Europe and the North-eastern Atlantic with a horizontal resolution of 56km, 20 vertical levels and three active soil layers. The CHRM has been validated regarding its ability to represent natural variability on different timescales (Vidale et al. 2003). A similar model set-up has previously been used for sensitivity studies by Schär et al. (1999), Heck et al. (2001), and Hohenegger and Vidale (2004) and a study on heavy precipitation processes in a warmer climate by Frei et al. (1998). In this study, simulations are mainly driven (using the relaxation boundary technique of Davies (1976)) by assimilated lateral boundary conditions and sea surface temperatures from the ECMWF operational analysis and the ECMWF re-analysis project ERA-40.

Data Overview

The ECMWF operational analysis data, used as initial and lateral boundary conditions, is available at a resolution of T_L511 (corresponding to about 40km) produced in near real-time. In order to determine the model bias, the model output is compared to observational data by the Climate Research Unit (CRU) (New et al. 1999, New et al. 2000, Mitchell et al. 2004), and precipitation data by the Global Precipitation Climatology Centre GPCC available since 1986 (Rudolf et al. 1994, Rudolf et al. 2003) and by the Global Precipitation Climatology Project (GPCP) available since 1979 (Huffman et al. 1997). The reference data set used as climatology is represented by the long-term 44-year CHRM run (1958–2001) performed by Vidale et al. (personal communication) using the same model set-up driven by ERA-40 boundary conditions. The ERA-40 reanalysis data has a spectral horizontal resolution of T_L159 (corresponding to about 120km) and covers the period 1958–2002 (Simmons and Gibson 2000). The variations of the soil water content represented in the CHRM will be compared to a diagnostic data set of monthly variations in terrestrial water storage by Seneviratne et al. (2004) and Hirschi et al. (2005).

3.3 Relevance of Research – Benefits and Risks

The representation of processes and feedbacks during summer heatwaves involves substantial uncertainties (Schär et al. 2004). The predictability of the regional climate is weakest during summer and over continental regions (Vidale et al. 2003). Furthermore, the representation of extreme events is still a challenge to climate models. A better scientific understanding of the different processes involved in the formation of a heatwave and their interactions in the chain of feedbacks would allow to overcome some of these deficiencies. Extended knowledge on the sensitivity of summer climate to different variables would allow to increase the reliability of the estimation of summer variability in a future climate. A potential benefit of this project is the improvement of predictability of summer climate in seasonal forecasting.

It should be stated that parameterisation of soil processes and soil types in the CHRM are relatively simple. This could result in a non-optimal representation of some processes, a problem addressed in Hagemann et al. (2004). However, recent changes in the depth of soil layers by Vidale et al. (2003) have allowed overcome some of these problems. The CHRM has been used in several previous studies and has been validated regarding its ability to represent reasonable variability on different timescales.

3.4 Research Plan and Time Schedule

The PhD project will require three years time and can be subdivided into the following (closely interrelated) parts:

1. Familiarisation with the regional climate model, the computational environment at CSCS in Manno, and the statistical analysis tools (6 months).
2. Determining a realistic range of different variables by analysing the 44-year CHRM run driven by ERA-40 reanalysis data in order to set-up a sensitivity experiment.

Performing and analysing ensemble sensitivity experiments by manipulating spring soil water content (8 months).

3. Sensitivity experiments in other summer periods (e.g. 1983 or 1994) with similar anticyclonic forcing using similar methodology as for summer 2003 (8 months).

4. Option 1–2: Focusing on the simulation and parameterisation of soil moisture hydrology, surface fluxes and radiation budgets in order to implement improvements in the parameterisation schemes (16 months).

5. Option 3–4: Simulating summer climate variability in a future climate using GCM simulations for different greenhouse scenarios as lateral boundary conditions. Analysis of simulations with respect to observations and simulations of the present and past climate (16 months).

Detailed Time Schedule

2004	
May 2004	**Beginning of PhD project**
	Familiarisation with the CHRM
Jun 2004	Performing CHRM test simulations
	Familiarisation with statistical analysis software (NCL, NCO)
Jul 2004	Preparing of observational reference data sets (CRU, GPCP) for the use in the same resolution as CHRM output data.
	Setting up of first sensitivity test experiment for summer 2003
Aug 2004	First soil moisture sensitivity experiments with arbitrary range of soil moisture variations
Sep 2004	Participation in the NCCR Climate Summer School: "Climate Variability. From Observation to Prediction" (poster participation: "Regional Climate Modelling of the European summer heatwave 2003")
	Familiarisation with the computational environment at CSCS
Oct 2004	Extracting and analysing 44-year CHRM run in order to determine realistic range of soil water content
	Establishing reference data set
Nov 2004	CHRM multi-ensemble sensitivity experiment with realistic soil water range
Dec 2004	Statistical analysis of sensitivity experiment
2005	
Jan 2005	Concept of first paper
Spring 2005	**First paper** on the role of soil water in the formation of a summer heatwave
	Conference contribution on results of first paper at EGU 05 Vienna
Summer 2005	Start working on option 1 or 3
2006	
Spring 2006	Conference contribution and **second paper** on options 1 or 3
Summer 2006	Start working on option 2 or 4

2007

Spring 2007	**Final paper** on options 2 or 4 and results of thesis
May 2007	Completion of PhD Thesis: *Intensity and frequency of European summer heatwaves in present and future climate* (exam).

3.5 Cooperations

ETH

- Intense collaboration is expected with other CHRM users in our work group, namely Daniel Lüthi, Pier-Luigi Vidale (former user), Sonja Seneviratne (future user) and Reinhard Schiemann.
- Collaboration is expected with Martin Hirschi working on seasonal changes in terrestrial water storage for major river basins in order to quantify a realistic range of soil water content.
- A potentially useful link could be established with Mischa Croci-Maspoli in order to identify periods of similar anticyclonic forcings in the recent past.
- For option 3 a link is expected to the global climate modelling group, led by Martin Wild.

National

- Strong collaboration is expected within the NCCR Climate work package 2 "Future Climate - Processes and Forecasting".
- Collaboration is expected with Paul Della-Marta (PhD student at University of Bern) working on variability of anticylonicity over the past 50 years.

International

- Links are expected with Pedro Viterbo and Laura Ferranti (ECMWF) working on similar sensitivity experiments using the ECMWF model.
- Links are expected with the group of Randall Koster (Global Modeling and Assimilation Office (GMAO)) at NASA Goddard Space Flight Center.

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4 Acceptance of Research Plan

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