SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Integrated Simulations of the Terrestrial System over the European CORDEX Domain
Computer Project Account:	SP DE KOLL
Start Year - End Year :	2016 – 2017
Principal Investigator(s)	Stefan Kollet
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Summary of project objectives

The objective of this research project was to perform high-resolution fully coupled aquifer-to-atmosphere simulations over the European CORDEX domain to study the impact of i) groundwater dynamics, ii) human water use and iii) land use/ land cover change on regional climate, focusing on heatwaves and droughts. The simulations were performed using several configurations of the Terrestrial Systems Modeling Platform, TerrSysMP. TerrSysMP consists of the three-dimensional surface-subsurface model ParFlow, the Community Land Model CLM3.5 and the numerical weather prediction model COSMO (Shrestha et al., 2014; Gasper et al., 2014; Keune et al., 2016).

Summary of problems encountered

No major technical issues were encountered.

Experience with the Special Project framework

Our experience has been positive with all administrative aspects.

Summary of results

A large number of fully-coupled aquifer-to-atmosphere simulations were performed, which allowed us to study 1) the impact of human water use, and 2) the impact of land use/ land cover change on integrated land-atmosphere feedbacks and continental water storage. The outcome of these studies have been published and are summarized below.

1) **Human Water Use Impacts on the Strength of the Continental Sink for Atmospheric Water**

   Keune, J., Sulis, M., Kollet, S., Siebert, S., & Wada, Y. Human water use impacts on the strength of the continental sink for atmospheric water. Geophysical Research Letters, 45, doi:10.1029/2018GL077621, 2018.

   Abstract. *In the global hydrologic cycle, continental landmasses constitute a sink for atmospheric moisture as annual terrestrial precipitation commonly exceeds evapotranspiration. Simultaneously, humans intervene in the hydrologic cycle and pump groundwater to sustain, for example, drinking water and food production. Here, we use a coupled groundwater-to-atmosphere modeling platform, set up over the European continent, to study the influence of groundwater pumping and irrigation on the net atmospheric moisture import of the continental landmasses, which defines the strength of the continental sink. Four water use scenarios are constructed to account for uncertainties of water use estimates and atmospheric feedbacks. We find that human water use induces groundwater-to-atmosphere feedbacks beyond the catchment scale and potentially weakens the continental sink over arid watersheds in Southern Europe. This suggests that, regionally and over climate time scales, human water use may systematically dryout the continent, thereby raising water resources and socio-economic concerns beyond local sustainability considerations.*

2) **Land use/land cover impacts on European extreme heat and drought**

Zipper, S., Keune, J., & Kollet, S. Land use/land cover impacts on European extreme heat and drought. (in preparation)

Abstract. *Extreme heat and drought are projected to increase due to climate change over much of the globe. To project and plan for local impacts, it is critical to understand the impacts of land use/land cover (LULC) change on heat and drought. Here, we use a fully-coupled process-based bedrock-to-cloud model to assess the sensitivity of the land surface energy balance, extreme heat, and drought in Europe to LULC change datasets between 1990 and 2010, a period including the downfall of the Soviet Union and the formation of the European Union. We find that the impacts of LULC change are negligible at the local (grid-cell) scale; however, at the continental scale, there are significant regional changes in some energy balance components which are primarily driven by changes in available energy, indicating remote feedbacks through atmospheric circulation. These changes in available energy lead to spatially distributed changes in the severity of drought and extreme heat, with the largest changes in the Mediterranean, Eastern Europe, and Iberian Peninsula. Furthermore, the response of the water and energy budgets at the land surface to remote feedbacks associated with LULC change is significantly dampened where the water table is near the land surface, indicating that including groundwater in large-scale land surface-atmosphere models is essential to accurately study the effects of LULC change.*

In this study, we used TerrSysMP to study the sensitivity of extreme heat and drought to LULC change in a physically- and spatially-consistent manner over all of Europe, with an additional focus on the role of groundwater in controlling land surface and atmospheric response to LULC change. Unlike previous studies which compare modern to pre-settlement LULC, we focus on historically observed LULC change between 1990 and 2010 associated with two major geopolitical changes occurring in the early 1990s: the formation of the European Union and the collapse of the Soviet Union (Kuemmerle et al., 2016; Prishchepov et al., 2012). Specifically, we address the questions:

- What impact does LULC change have on extreme heat and drought in Europe, and how do impacts vary across spatial scales (grid cell, regional, continental)?
- To what degree does shallow groundwater mitigate or enhance the response of the land surface and atmosphere to LULC change?

In order to evaluate the response of the water/energy balances, extreme heat, and drought to historically realistic LULC change over the European continent, we developed two new land surface input datasets covering the CORDEX domain. These data sets correspond to land use and land cover for the years 1990 and 2010.

Our new LULC datasets document substantial, spatially heterogeneous LULC change between 1990 and 2010 over Europe. Net LULC change is primarily characterized by a reduction in overall cropland area which is balanced by an increase in other LULCs (Figure 1). In 1990, 38.2% of the land grid cells in the focus domain were crop, 21.6% evergreen tree, 19.6% deciduous tree, 18.8% grass, and 1.7% bare/urban. In 2010, the proportions were 35.6% crop (-2.6 percentage points [pp] from 1990), 22.1% evergreen tree (+0.5pp), 20.2% deciduous tree (+0.6pp), 20.3% grass (+1.5pp), and 1.8% bare/urban (+0.1pp). Overall, 8.4% of grid cells (n=4250) changed LULC between 1990 and 2010, with the dominant LULC trajectories being crop to grassland (CtoG; agricultural abandonment; 30.5% of changed cells), grass to deciduous or evergreen tree (reforestation; 16.9% of changed cells); and grass to crop (GtoC; 7.7% of changed cells).

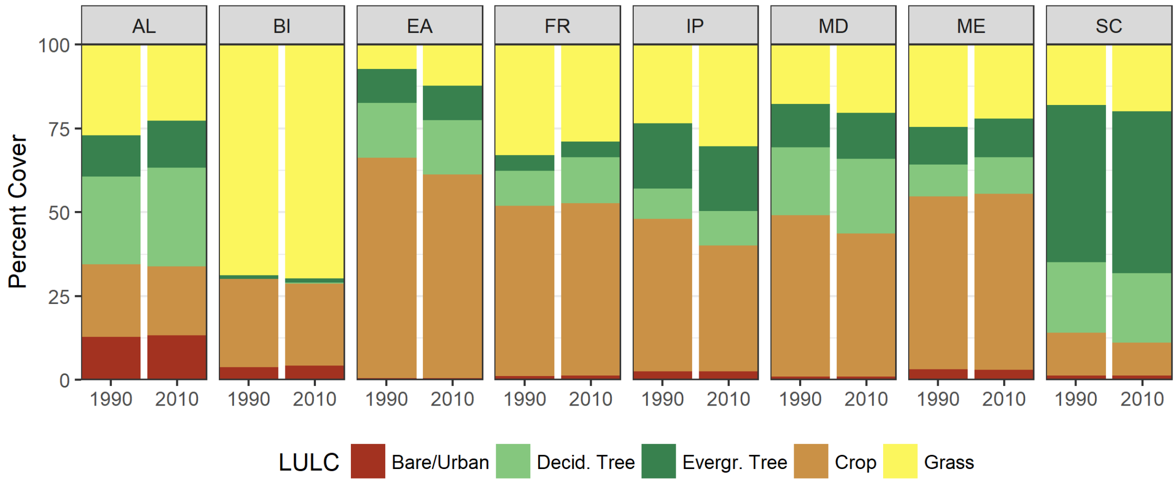

Figure 1. Comparison of major LULC categories between 1990 and 2010 for all European PRUDENCE regions (AL: Alps, BI: British Islands, EA: Eastern Europe, FR: France, IP: Iberian Peninsula, MD: Mediterranean, ME: Mid-Europe, SC: Scandinavia).

Two fully-coupled simulations were performed, covering the heatwave year in 2003: 1) using a land use/land cover corresponding to 1990; and 2) using a land use/land cover corresponding to LULC 2010. The simulation differences are evaluated, focusing on heat and drought, and the role of groundwater for mitigating the response of LULC change.

The response of extreme and average air temperature to LULC varied. We calculated differences in total summer (June-August) degree days with a base temperature of 10 °C between the two scenarios, in order to identify whether there are small but persistent differences which may have an important cumulative effect over the course of the growing season (Figure 2a-c). We find that the total degree days are lower with 2010 LULC compared to 1990 LULC over most of the domain: 19,260 grid cells (38.3% of the terrestrial portion of the domain) had a decrease of at least 10 °C-days, while only 3806 (7.6%) had an increase of that magnitude. Total differences range from -163 °C-days to +124 °C-days, with an average difference of -8 °C-days. Areas with higher degree day totals in 2010 tend to be located in the northern parts of the domain, including along the northern coast of France and Germany, most of the United Kingdom, and the Baltic States. In contrast, areas with the largest decreases in degree days in 2010 tend to be located in the southern portion of the domain, particularly along the northern and western edges of the Black Sea. The observed differences in degree days do not appear to be associated with local LULC change. For example, the Baltic States (where degree days increased) and Romania (where degree days decreased) are both among the areas with the greatest amount of agricultural abandonment between 1990 and 2010 (Figure 1).

Compared to summer degree days, mean air temperature during the period of most extreme heat (August 1-14) exhibits increased spatial coherence (Figure 2d-f). Air temperature decreased by $\leq$ 1 °C in 17.5% of the land domain, most along a north-south swath through central Europe including Italy, France, Western Germany, and the United Kingdom. These areas, particularly France, were among the regions hardest hit by extreme heat in 2010 (García-Herrera et al., 2010; Stefanon et al., 2014a; Zaitchik et al., 2006), and experienced an expansion of grassland between 1990 and 2010. In contrast, air temperature increased by $\geq$ 1 °C in 56.7% of the domain, including the Iberian Peninsula but with the strongest changes in northeastern Scandinavia and northwestern Russia, with local changes were up to 15 °C. Given that these changes occur in northwestern Russia where there was no difference in the LULC input datasets, temperature changes in this region may be associated with LULC change occurring over Europe more broadly, as atmospheric fluxes over Europe tend to move from southwest to northeast (Keys et al., 2012; Van der Ent et al., 2010).

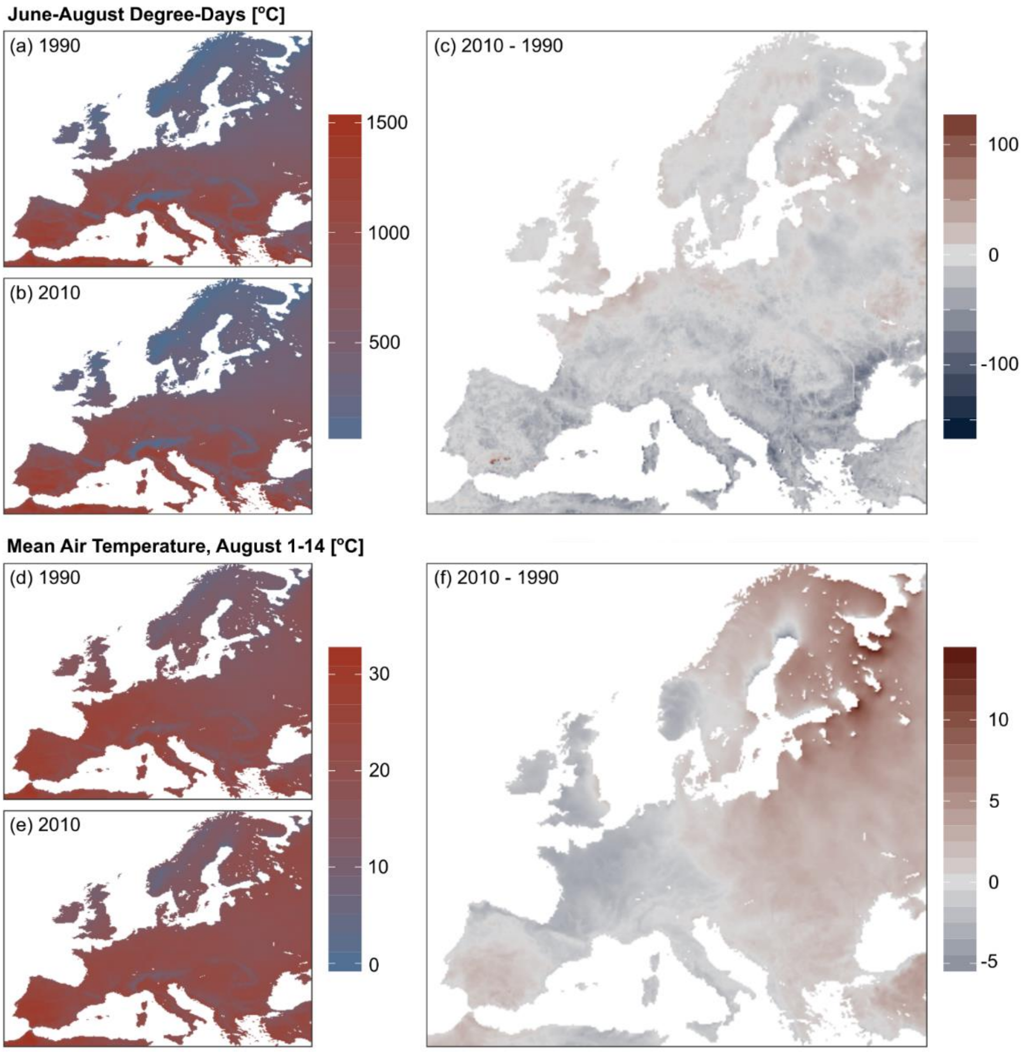

Figure 2. Maps showing two indicators of summer heat: **(a-c)** cumulative summer degree days; and **(d-f)** mean 2m air temperature for August 1-14, the most severe portion of the heat wave. **(a)** and **(d)** simulation output with 1990 LULC. **(b)** and **(e)** simulation output with 2010 LULC. **(c)** and **(f)** difference between simulation 2010 and 1990 LULC.

Water table depth (WTD) varies over the domain, from a minimum of ~0 m in groundwater convergence zones (e.g. river valleys) and northern latitudes to a maximum of ~100 m, which is the total thickness of the soil column (Figure 3a). We find that changes in the energy balance, extreme heat, and drought between the 1990 and 2010 LULC scenarios are more sensitive to variability in WTD than the trajectory of LULC change, particularly at very shallow WTD (< 1 m). Comparing nearby CtoC (Crop to Crop) and CtoG (Crop to Grass) pixels, the difference in both latent heat flux (Figure 3b) and precipitation deficit (Figure 3d) between LULC scenarios is significantly lower in locations with WTD $\leq$ 1 m compared to locations with WTD > 1 m; however, with a given WTD bin, there is no statistically significant difference between land use change trajectories. Similarly, there are no statistically significant differences in air temperature among LULC trajectories for a given WTD (Figure 3c). However, unlike the latent heat flux and precipitation deficit, differences between 1990 and 2010 LULC scenarios are significantly higher at locations where WTD $\leq$ 1 m compared to most locations where WTD > 1 m.

Given the strong body of literature documenting the key role of groundwater in controlling land surface processes (Hain et al., 2015; Kollet and Maxwell, 2008; Lowry and Loheide, 2010; Maxwell and Kollet, 2008), particularly during dry periods (Fang et al., 2017; Taufik et al., 2017; Zipper et al., 2015; Zipper and Loheide, 2014), these results suggest that WTD more strongly affects extreme heat and drought than LULC change over the conditions simulated here. Studying the same domain, Keune et al. (2016) showed that the representation of groundwater flow processes and hydrostratigraphy was more important to simulated outcomes than initial model conditions. While groundwater impacts on land surface process are often thought of as a local process occurring at relatively small spatial scales (e.g. in zones of groundwater convergence), we demonstrate that explicit representation of groundwater in a process-based manner is required to accurately simulate land surface and atmospheric processes at the continental scale, even at large spatial scales (Fan, 2015).

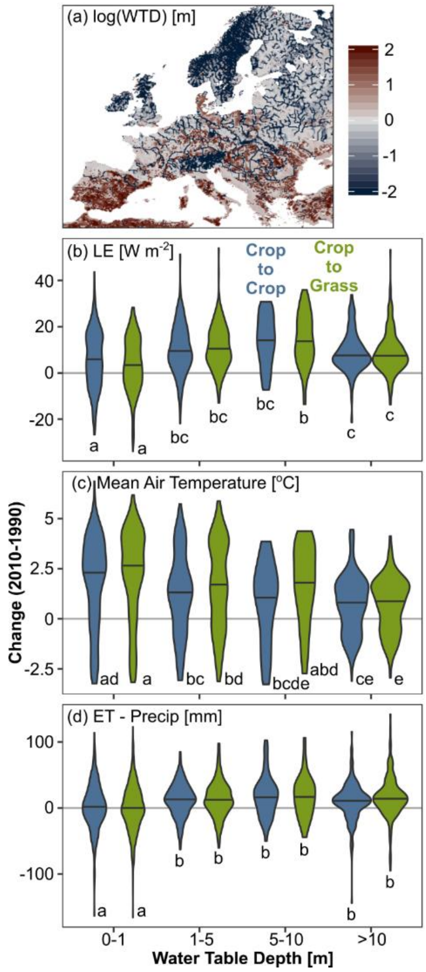

Figure 3. (a) 2010 water table depth; pixels where WTD=0 m are displayed as 0.01 m. Change between 1990 and 2010 LULC scenarios for **(b)** mean latent heat flux, August 1-14; **(c)** mean air temperature, August 1-14; **(d)** precipitation deficit, June-August; as a function of water table depth and change trajectory. Within each plot, the same letter denotes no statistically significant difference between the means of the two samples ($p > 0.05$, Tukey Honest Significant Difference).

List of publications/reports from the project with complete references

Keune, J., Gasper, F., Goergen, K., Hense, A., Shrestha, P., Sulis, M. and Kollet, S.: Studying the influence of groundwater representations on land surface-atmosphere feedbacks during the European heat wave in 2003, J. Geophys. Res. Atmos., 121(22), 2016JD025426, doi:10.1002/2016JD025426, 2016.

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Zipper, S., Keune, J., & Kollet, S. Land use/land cover impacts on European extreme heat and drought. (*in preparation*).

Future plans

We are pursuing a continuation of this projects, focusing on two aspects:

1) Feedback pathways: to assess major atmospheric feedback pathways a Lagrangian particle trajectory model is applied to the output of existing simulations. This allows to identify remote land-atmosphere feedbacks induced by human water use and land use/land cover change.
2) Climate feedbacks: to assess long-term climate feedbacks of human water use, extended simulations of the fully coupled aquifer-to-atmosphere system, including human water use, are planned.

A continuation of this special project has been requested, focusing on the identification of atmospheric feedback pathways to human water use.

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