The effect of soil moisture initialization in predicting the extreme 2003 heat wave and 2005 flood events in Europe

Abstract

We explored to what extent soil moisture (memory) and the associated land-atmosphere feedbacks have affected the strengths of the 2003 heat wave and 2005 flood events in central Europe. For this purpose we conducted European-scale regional climate simulations of the summer half years of 2003 and 2005 forced with satellite inferred soil moisture estimates obtained for either the same year or the transposed year. Results are presented for the 1-10 August 2003 heat wave and the 19-24 August 2005 floods. The wetter soil moisture conditions in 2005 above central Europe dampened the extreme high temperatures during 1-10 August 2003. As soil moisture and evaporation increase, the moisture transport at the edge of the persistent anticyclonic circulation strengthens leading to more precipitation in these regions. The effect of the soil moisture regime in 2003 for the floods of 19-24 August 2005 is most pronounced in places where the soil moisture was found increased relative to 2005. The wetter soil moisture regime associated with an increase in evaporation intensified and relocated the synoptic-scale circulations, which led to a shift in the position of the heaviest precipitation in the flood area. From the simulations we conclude that soil moisture is an important parameter in controlling the strength of extreme events both through local and remote effects.

5.1. Introduction

Extreme events such as droughts and floods have strong socio-economic impacts across Europe. In 2003, central Europe and the Mediterranean region were affected by a record-breaking heat wave (Schär et al., 2004; Luterbacher et al., 2004; Beniston, 2004; Black et al., 2004; Fischer et al., 2007a, 2007b), which increased mortality by around 35000 (Schär and Jendritzky, 2004), and induced crop failure and forest fire. In contrast, in August 2005 central and eastern Europe were hit by heavy floods (Jaun et al., 2008). This event caused the most catastrophic flood damage in the last 100 years with respect to loss of life and damage to infrastructure, communication routes and agriculture (Beniston, 2006; Frei et al., 2006).

Sensitivity simulations performed by Fischer et al. (2007b) demonstrated that soil moisture anomalies had a substantial impact upon the strength of the 2003 heat wave. The persistent precipitation deficit in the months between mid-February and August 2003 and the excess in total net radiation in late winter and spring 2003 strongly contributed to anomalous soil moisture deficit and persistent drought conditions during the 2003 heat wave. In flooding situations, the condition of the early spring soil moisture can be important as well. Trenberth and Guillemot (1996) showed that local evaporation was a source of the precipitation in the 1993 flood in north America and probably helped to perpetuate the wet conditions.

The positive feedback in both droughts and floods, whereby negative (positive) rainfall anomalies potentially decrease (increase) evaporation and subsequent precipitation, can potentially increase the duration and the intensity of climate extremes (e.g., Seneviratne et al., 2006). However, the uncertainties regarding the impact of soil moisture on precipitation, especially related to convective precipitation and the planetary boundary layer stability are still large (Findell and Eltahir, 2003a, 2003b; Ek and Holtslag, 2004; Koster et al., 2004, 2006; Hohenegger et al., 2009). The use of an appropriate observed soil moisture product may help to reduce these uncertainties (Bisselink et al., 2011).

The purpose of this study is to explore whether soil moisture (memory) and the associated land-atmosphere feedbacks affect the strength of heat waves and floods. We perform simulations with a regional climate model for the summer half years of 2003 and 2005, whereby the atmospheric circulation of 2003 (2005) is prescribed with the satellite inferred soil moisture of 2005 (2003), in order to obtain a large, but realistic difference in soil moisture boundary conditions.

5.2. Data and methods

5.2.1. Soil moisture and large scale synoptic conditions

Satellite observations from the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) on board of the AQUA satellite are used for soil moisture detection. The brightness temperatures are converted to soil moisture values with the Land Parameter Retrieval Model (LPRM; Owe et al., 2008). In this study we used the March-October 2003 and 2005 C-band observations from the descending mode (1:30 am) at 0.25 degree spatial resolution. Due to the limited penetration depth (0.5-2 cm), the AMSR-E data is sensitive to the very high variability of the soil moisture content. Because of this high variability, we take a 5-day moving average of the AMSR-E data set. Moreover, the AMSR-E soil moisture initially showed systematic differences with the model predicted soil moisture. For proper initialization the AMSR-E product thus needs to be rescaled within the model’s range defined through the wilting and saturation point without
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losing the full dynamical variability. Then, a mathematically equivalent formulation of the empirical method of Wagner et al. (1999) as proposed by Stroud (1999) and applied by Albergel et al. (2008) is used to retrieve a soil moisture profile of the rescaled AMSR-E soil moisture. For a more detailed description of the used methods to obtain meaningful sensitivity simulations with satellite observations see Bisselink et al. (2011).

In Fig. 5-1 the difference between the rescaled AMSR-E soil moisture of 2003 and 2005 is presented. At 1 March (Fig. 5-1a), the difference between the soil moisture content is shown. The soil moisture content in 2003 is higher compared to the soil moisture content at 1 March 2005 in eastern Europe and Iberia these regions. For Iberia, the 2004/05 hydrological year (October 2004 to September 2005) was characterized by intense dry conditions (Garcia-Herrera et al., 2007).

![Figure 5-1. Mean difference (m$^3$ m$^{-3}$) between the rescaled AMSR-E soil moisture of 2003 and 2005 (2003 minus 2005) for (a) 1 March, (b) April, (c) 1-10 August, and (d) 19-24 August.](image)

For central and eastern Europe, the soil moisture content at the start of 2003 was relatively high due to anomalously high precipitation in summer and autumn 2002 over central and eastern Europe (Rudolf et al., 2003; Christensen and Christensen, 2003). After a wetter than normal start of 2003 in central and eastern Europe, the rainfall deficit in 2003 increased towards the summer which resulted in a negative difference in the soil moisture content between April 2003 and 2005, except for Iberia (Fig. 5-1b). For Iberia, the soil moisture in April 2003 was higher than in April 2005.

In August 2003, a persistent strong high pressure zone dominated central Europe, which inhibited the intrusion of moisture advection from the Atlantic into central Europe. This in addition to the dry conditions inherited from the spring and early summer season of 2003 resulted in the large negative difference in soil moisture at 1-10 August (Fig. 5-1c) and 19-24 August 2003 (Fig. 5-1d) compared to 2005.
5.2.2. Model and experiments

The Royal Netherlands Meteorological Institute (KNMI) regional atmospheric climate model RACMO2 (Lenderink et al., 2003; van Meijgaard et al., 2008) has been used to produce 50 km resolved model integrations for the European domain at the seasonal time scale. The land surface processes are described by the hydrology revised version of the Tiled ECMWF Scheme for Surface Exchanges over Land (Hydrology-TESSEL; Balsamo et al., 2009).

This experiment includes four simulations. From those, two control (CTL) simulations are prescribed with the circulation and the soil moisture of March-October 2003 and 2005, labelled CTL2003 and CTL2005, respectively. In addition, two other sensitivity simulations are performed. The simulation labeled as SM2005 is driven by the atmospheric circulation from 2003, but forced at the land surface with soil moisture from 2005. The SM2003 simulation is driven by the circulation from 2005, but forced at the land surface with soil moisture from 2003.

The four experiments are each performed as a 2-member ensemble in which the initialized time of the AMSR-E soil moisture was varied. One run is started at initial time 1 March (CTL2003, CTL2005, SM2005, and SM2003). After the initialization, the soil moisture evolves freely until the simulations end in October. In the other runs the model soil moisture is replaced with daily satellite inferred soil moisture (CTL2003d, CTL2005d, SM2005d and SM2003d) between March until October to obtain interactions between the land and the atmosphere directly originating from the AMSR-E soil moisture product.

5.3. Results

5.3.1. Temperature

In Fig. 5-2 the temperature difference of the SM2005 and SM2003 simulations with respect to the CTL simulations for 1-10 August 2003 and 19-24 August 2005 are presented. The initialization with the soil moisture of 1 March 2005 resulted in a positive difference in Spain and eastern Europe and a negative difference in the Balkan region (Fig. 5-2a). These differences are caused by the difference in soil moisture between 1 March 2003 and 2005 as presented in Fig. 5-1a. In other words, if soil moisture of 1 March 2003 had been at the level of 1 March 2005, the temperature in the period 1-10 August 2003 would have been higher in Spain and eastern Europe and lower in the Balkan region. Daily replacement of model soil moisture in the 2003-simulation with observed soil moisture from 2005 produces a decrease of temperature in central Europe, Italy and the Balkan region and an increase north of the Black Sea (Fig. 5-2c). Note that these differences represent a substantial portion of the 1-10 August temperature difference in the CTL2005d-CTL2003d (not shown). These findings suggest that 1-10 August 2003 temperatures over parts of central Europe and the Balkans would have been cooler given the same large scale circulation pattern when using the soil moisture evolution of 2005.

In the situation of 19-24 August 2005, the effect of driving the large scale circulation of 2005 with the soil moisture of 1 March 2003 produces a positive temperature response in Russia and a small negative temperature response in eastern Europe (Fig. 5-2b). However, the temperature response in the period 19-24 August 2005 initialized with 1 March 2003 soil moisture is less pronounced (SM2003-CTL2005) than the effect of the mirror experiment (SM2005-CTL2003) as seen in Fig. 5-2a. Daily replacement of model soil moisture in the 2005-simulation with observed soil moisture evolution from 2003 results in a positive temperature difference in central Europe, Italy and the Balkan region and a negative temperature difference north of the
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Black Sea (Fig. 5-2d). Again the strongest difference is found in the Balkan regions where soil moisture is responsible for a substantial part of the temperature increase.

Figure 5-2. Mean change in temperature (K) for the period 1-10 August 2003 and 19-24 August 2005 due to soil moisture initialization at 1 March with the soil moisture of (a) 2005 (SM2005i-CTL2003i) and (b) 2003 (SM2003i-CTL2005i) and due to daily initialization with the soil moisture of (c) 2005 (SM2005d-CTL2003d) and (d) 2003 (SM2003d-CTL2005d).

5.3.2. Precipitation

In Fig. 5-3 we present the effect of forcing the regional climate simulations of the summer seasons of 2003 and 2005 with observed soil moisture from either of the years to the amount of precipitation during the 1-10 August 2003 drought and 19-24 August flood period, respectively. Initialization of the 2003-run with observed soil moisture inferred at 1 March 2005 is found to have a limited effect on precipitation during the period 1-10 August 2003 (Fig. 5-3a). Owing to the substantial soil moisture difference between 2005 and 2003 between April and August (Figs. 5-1b,d) we might expect a larger response from a daily replacement of model soil moisture in the 2003-run with observed soil moisture from 2005. It is indeed found that this run results in higher evaporation, and consequently higher relative humidity and enhanced cloud cover (not shown). However, it does not have a large effect on the precipitation (Fig. 5-3c), with the exception of the Adriatic Sea and parts of Russia.

Initialization of the 2005-run with observed soil moisture inferred at 1 March 2003 results in both negative and positive differences in precipitation in those areas that were influenced by the low pressure system, which gave rise to the heavy floods during the period 19-24 August 2005 (Fig. 5-3b). If soil moisture at 1 March 2005 had been at the level of 1 March 2003, the precipitation in the period 19-24 August 2005 would have been lower on the western edge and higher on the eastern edge of the low pressure system. Daily replacement of soil moisture in the 2005-run with observed soil moisture from 2003 results in a response with an opposite pattern, i.e.
a decrease in precipitation in the area east and an increase in the area west of the low pressure system (Fig. 5-3d).

Figure 5-3. Mean change in precipitation (mm) for the period 1-10 August 2003 and 19-24 August 2005 due to soil moisture initialization at 1 March with the soil moisture of (a) 2005 (SM2005_i-CTL2003_i) and (b) 2003 (SM2003_i-CTL2005_i) and due to daily initialization with the soil moisture of (c) 2005 (SM2005_d-CTL2003_d) and (d) 2003 (SM2003_d-CTL2005_d).

These findings suggest that precipitation during 19-24 August 2005 over parts of central Europe would have been lower when using the soil moisture evolution of 2003 as expected. However, the simulations also show that a substantial part of central Europe would have been wetter during the flood periods when the drier soil moisture conditions of 2003 would have prevailed.

5.4. Discussion and conclusions

5.4.1. 1-10 August 2003 heat wave

We have shown that the (spring) soil moisture conditions have a local effect on the temperature in the heat wave of August 2003 due to a change in the partitioning of available energy at the surface between sensible and latent heat flux. The Balkan region is more sensitive than the rest of Europe, as indicated by the large temperature response to soil moisture perturbations. In other words, the soil moisture deficit in 2003 contributed significantly to the evolution of the heat wave of 1-10 August 2003 due to land atmosphere interactions, consistent with the findings of Fischer et al. (2007a, 2007b).

The persistent strong anticyclonic circulation anomaly over central Europe played a crucial role during the 2003 summer heat wave (Black et al., 2004; Ogi et al., 2005). The radiative cooling with the soil moisture evolution of 2005 resulted in a higher air density and in an increase of the surface pressure in central Europe (not shown). Figure 5-4a shows the change in vertically
integrated moisture flux during 1-10 August 2003 when soil moisture is replaced daily with observed soil moisture from 2005. The different pressure gradient and evaporation regimes compared to the control run for 2003 resulted in a positive difference of the moisture transport at the edge of the persistent anticyclone. Note that the positive rainfall differences as seen in Fig. 5-3e are located in the areas with an increase in moisture advection. As soil moisture and evaporation increase, the moisture transport at the edge of the persistent anticyclonic circulation strengthens which potentially leads to more precipitation in these regions.

Figure 5-4. Mean change in vertically integrated moisture flux (kg m s\(^{-1}\)) for the period 1-10 August 2003 and 19-24 August 2005 due to daily initialization with the soil moisture of (a) 2005 (SM2005\(_d\)-CTL2003\(_d\)) and (b) 2003 (SM2003\(_d\)-CTL2005\(_d\)).

5.4.2. 19-24 August 2005 flood

Analysis of the 19-24 August 2005 flood period shows that the effects of forcing the 2005-run with different soil moisture regimes are most pronounced in places where the soil moisture perturbation relative to the control run was positive. The shift in precipitation as derived from Fig. 5-3b suggests a more eastward position of the low pressure system in the SM2003\(_i\) run. The soil moisture on 1 March 2003 is higher in the flood area compared to 1 March 2005 (Fig. 5-1a), implying enhanced evaporation in the SM2003\(_i\) run relative to the CTL2005\(_i\) run in that region in the period past 1 March 2005. Consequently, the moisture transport associated with the cyclonic low pressure cell positioned over central Europe and originating from the gulf of Genoa strengthens and penetrates more eastwards (not shown). Thus, if soil moisture of 1 March 2005 had been at the level of 1 March 2003, the wetter soil moisture regime associated with an increase in evaporation would have had the effect of intensifying and relocating the low pressure cell and the precipitation in central Europe.

The impact of the daily replacement of soil moisture in the 2005-run with observed soil moisture from 2003 is more pronounced. The shift in precipitation as derived from Fig. 5-3b suggests a more westward position of the low pressure system in the SM2003\(_d\) run. The replacement of the soil moisture evolution of 2005 with the soil moisture evolution of 2003 results in a drier regime in a large part of Europe with the exception of Russia (Fig. 5-1d). The soil moisture in the western part of Russia increases when using the soil moisture evolution of 2003. Figure 5-4b shows the change in moisture transport when using the soil moisture evolution of 2003. In response to the different soil moisture evolution of 2003 and the associated increase of evaporation in Russia the air captured more moisture of evaporative origin resulting in an increase of the moisture transport. The strengthened moisture transport prevented the low pressure system...
above central Europe to penetrate more land inwards, which resulted in a more westward precipitation peak. Thus, when the soil moisture of 2005 had been at the level of 2003 between March until October, the effect of the drier soil moisture regime in the flood area is overwhelmed by the increase in soil moisture in Russia. The wetter soil moisture regime in Russia and the associated increase in evaporation would have had the effect of intensifying the moisture transport to central Europe, which would have led to a relocation of the position of the heaviest precipitation in the flood area.

We have demonstrated the importance of accurate soil moisture initialization in regional climate predictions. The effect of soil moisture on the atmosphere is achieved through both local and remote atmospheric pathways and in both dry and wet synoptic scale conditions which can potentially strengthen or dampen the extremes.