General introduction

1.1. Land-atmosphere interaction

Water on earth is constantly in motion through the hydrological cycle (Fig. 1-1a). The hydrological cycle is driven by incoming solar radiation, supplying the energy for evaporation from land surfaces and the ocean. As moist air is lifted, it cools and water vapour condenses to form clouds. Moisture is transported around the globe until it returns to the surface as precipitation. Once the water reaches the ground, it either infiltrates into the soil and becomes groundwater or remains on the earth’s surface and seeps its way into the oceans, lakes, rivers and streams.

![Figure 1-1. Schematic of the land water balance (a) and land energy balance (b) for a given surface soil layer (adapted from Seneviratne et al., 2010).](image)

Evaporation consists of plant transpiration, direct evaporation of water from the soil surface, canopy-intercepted evaporation from precipitation or dew. To a large extent, the amount of water that evaporates from the land surface is determined by the characteristics of the land surface such as vegetation, soils, geology and topography (Beven, 2001). In addition, the surface energy balance (Fig. 1-1b) is important for the evaporation of water. The solar energy that is not reflected and absorbed by clouds, back-scattered by air and reflected by the surface reaches the surface (shortwave). This incoming energy is balanced by outgoing long wave radiation, sensible heat flux, latent heat flux and to a smaller extent by ground heat flux. A large part of the outgoing long wave radiation is absorbed by the atmosphere, which in turn emits longwave radiation both upwards and downwards. The latter is absorbed by the land surface again. The state of the land surface and the availability of water and energy play a major role in the partition of net radiation into sensible, latent and ground heat flux. Modifications in the surface characteristics, due to land use change in river basins or climate change, will affect both water and energy balance. Therefore, it is crucially important to have an improved understanding of land-surface atmosphere exchanges and possible feedbacks involving the soil moisture reservoir.
1.2. Impact of soil moisture on weather and climate

Soil moisture is a key parameter controlling several land-atmosphere exchanges and feedback mechanisms within the climate system, which involve in particular air temperature, boundary layer stability and in some instances precipitation (Seneviratne et al., 2010). Local feedbacks between the soil and the atmosphere have been subject of several studies. An important soil moisture-precipitation feedback mechanism is precipitation recycling, i.e. the quantification of the ratio that consists of the contribution of local evaporation to local precipitation (e.g., Burde and Zangvil, 2001). A positive feedback mechanism is generally understood as an evaporation-precipitation coupling, where positive rainfall anomalies result in high soil water content that can enhance evaporation and subsequent precipitation (Betts et al., 1996; Eltahir, 1998; Savenije, 1995; Schär et al., 1999). In contrast, a negative feedback enhances precipitation recycling during periods of lower precipitation. Drier atmospheric conditions lead to higher sensible heat flux and deep boundary layer growth that may promote precipitation through enhanced convection (Findell and Eltahir, 2003a; Ek and Holtslag, 2004).

In models, local feedback mechanisms are found in regions where evaporation is directly dependent on soil moisture (Seneviratne et al., 2010). Koster et al. (2004) calculate the strength of the land-atmosphere feedback with 12 models, expressed as a coupling factor. They found with the 12-model average that most regions with high land-atmosphere coupling named “hotspots” are found in the transient zones. In the transition zones evaporation is suitably high but still sensitive to soil moisture.

Evidence is building that human-induced climate change, “global warming”, will increase evaporation and precipitation, leading to an intensification of the hydrological cycle, in particular extreme events (Huntington, 2006; Trenberth, 2011). However, at a global level, a limit to the acceleration of the hydrological cycle on land may already have been reached (Jung et al., 2010). For Europe, simulations driven by increasing greenhouse gas concentrations predict considerable enhancement of interannual (year-to-year) variability of the European summer climate, both for temperature and precipitation, associated with higher risks of heat waves (Mehl and Tebaldi, 2004; Schär et al., 2004), droughts (Milly et al., 2005) and heavy precipitation events (Pal et al., 2004; Frei et al., 2006). This means that the risk of extreme heat waves like summer 2003, is likely to increase in the future (Beniston, 2004; Mehl and Tebaldi, 2004; Schär et al., 2004; Fischer and Schär, 2010). Analyses of the 2003 European heat wave have highlighted the importance of the soil moisture feedback to both the persistency and intensity of the heat wave (Fischer et al., 2007a, 2007b). Recently, observational evidence was found between soil moisture deficit and summer hot extremes in southeast Europe (Hirschi et al., 2010). Seneviratne et al. (2006) shows that land-atmosphere coupling in the form of soil-moisture temperature and soil-moisture precipitation feedbacks are the most important mechanisms contributing to current and future heat wave events. However, the impact of soil moisture on precipitation, especially related to convective precipitation and the planetary boundary layer stability are still uncertain (Findell and Eltahir, 2003a, 2003b; Ek and Holtslag, 2004; Koster et al., 2004, 2006; Hohenegger et al., 2009).

Since soil moisture directly controls fluxes of water and energy at the land surface and maintain/amplify subsequent extreme events such as droughts, floods or summer heat waves, a good representation of soil moisture in models is required. Accurate estimates of surface soil moisture are often difficult to obtain, especially at larger spatial scales. The main reason is that it is a very difficult variable to measure, not at a point in time, but on a consistent and spatially comprehensive basis (Leese et al., 2001).
Satellite remote sensing can be an ideal tool for obtaining soil moisture data at global scales. Despite the limitations, such as the shallow sensing (e.g., Wagner et al., 2007) depth and the difficult measurements under dense vegetation cover (e.g., de Jeu et al., 2008), major advances have taken place in the field of soil moisture measurement in recent years (Schmugge et al., 2002; Tapley et al., 2004; Wagner et al., 2007; Kerr, 2007; de Jeu et al., 2008; Robinson et al., 2008; Vereecken et al., 2008). Research progress in this area will lead to better forecasting skills of soil moisture and the associated land-atmosphere coupling.

1.3. Aims and outline

The main objective of this study was to assess the effect and understand the underlying mechanisms which involve the land-surface and the overlying atmosphere with respect to processes of extreme events (both wet and dry conditions) and future climate.

The aim of the first study was to apply the dynamical precipitation recycling model of Dominguez et al. (2006) to determine which areas in Europe are susceptible to land-atmosphere interactions by calculating a dynamic recycling ratio, which investigates this feedback at all relevant meteorological time scales. Regions with a large “precipitation recycling” are potentially susceptible to land cover and/or land use change (Chapter 2).

During extreme dry or wet periods the hydroclimatology of a large region can change abruptly. However, most precipitation recycling studies that have been performed to define the role of land surface-atmosphere interactions focus on monthly or longer time scales. Long time scales, however, mask key relationships between precipitation recycling and other variables involving the feedback process that occur at shorter time scales. The advantage of the dynamical precipitation recycling model is that it can be used on a daily time scale. Therefore, the second aim was to perform temporal and spatial analysis of the process of precipitation recycling in a dry and wet year on a daily time scale (Chapter 3).

A good representation of soil moisture is required to improve simulations of the interactions between the surface and atmosphere, and thus ultimately, to improve the forecast skills. A third aim was to explore the applicability of remotely sensed near-surface soil moisture over Europe and to initialize a regional climate model to investigate whether the predictions of temperature and precipitation are improved (Chapter 4).

Given the inferred impacts of soil moisture for temperature and precipitation, modifying the soil moisture initial conditions can be relevant for the amplifying of heat waves and floods. Accordingly, the aim of the last study was to explore to what extent soil moisture (memory) and the associated land-atmosphere feedbacks might affect the strengths of the 2003 heat wave and 2005 flood events in central Europe (Chapter 5).

This thesis is structured in six chapters. After this introduction (Chapter 1), the formulated four research aims are addressed in subsequent chapters with two different approaches. Firstly, we applied an analytical model driven with data from a land surface model (Chapter 2) and from a regional climate model (Chapter 3). Secondly, we used remotely sensed near-surface soil moisture to initialize a regional climate model to examine the underlying mechanisms which involve the land-surface and the overlying atmosphere (Chapter 4 and Chapter 5). These chapters have already been published or submitted in international peer reviewed journals. This means that the chapters have their own introduction and final remarks. Finally, the last chapter (Chapter 6) details the overall conclusions of this thesis and provides an outlook over possible future research directions in this field.