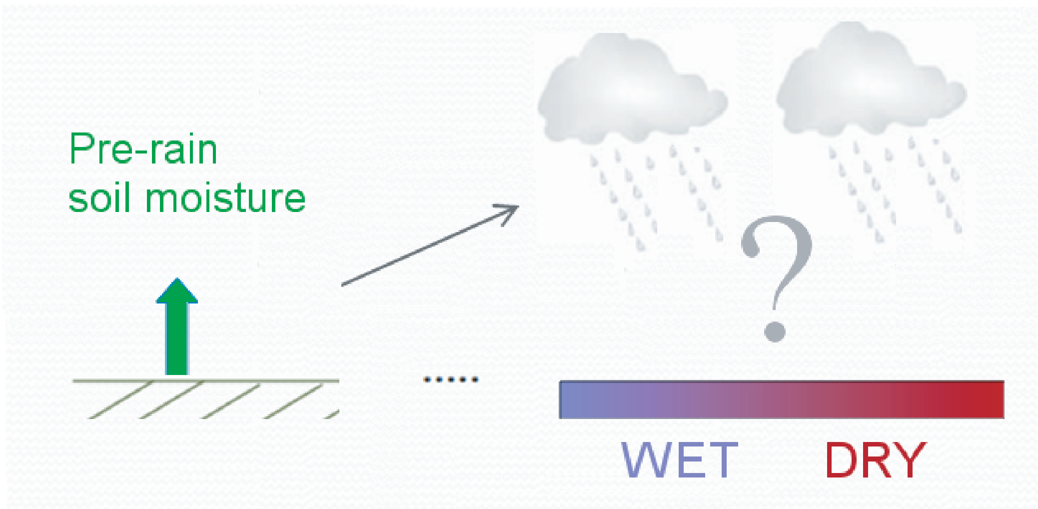
Max-Planck-Institut
für Meteorologie

MAX-PLANCK-GESELLSCHAFT

International Max Planck Research School
on Earth System Modelling

Understanding Soil Moisture - Precipitation Coupling on Mesoscales Using Observations over North Africa



Irina Yurievna Petrova

Hamburg 2017

Berichte zur Erdsystemforschung
Reports on Earth System Science

191
2017

Hinweis

Die Berichte zur Erdsystemforschung werden vom Max-Planck-Institut für Meteorologie in Hamburg in unregelmäßiger Abfolge herausgegeben.

Sie enthalten wissenschaftliche und technische Beiträge, inklusive Dissertationen.

Die Beiträge geben nicht notwendigerweise die Auffassung des Instituts wieder.

Die "Berichte zur Erdsystemforschung" führen die vorherigen Reihen "Reports" und "Examensarbeiten" weiter.

Anschrift / Address

Max-Planck-Institut für Meteorologie
Bundesstrasse 53
20146 Hamburg
Deutschland

Tel./Phone: +49 (0)40 4 11 73 - 0
Fax: +49 (0)40 4 11 73 - 298

name.surname@mpimet.mpg.de
www.mpimet.mpg.de

Notice

The Reports on Earth System Science are published by the Max Planck Institute for Meteorology in Hamburg. They appear in irregular intervals.

They contain scientific and technical contributions, including Ph. D. theses.

The Reports do not necessarily reflect the opinion of the Institute.

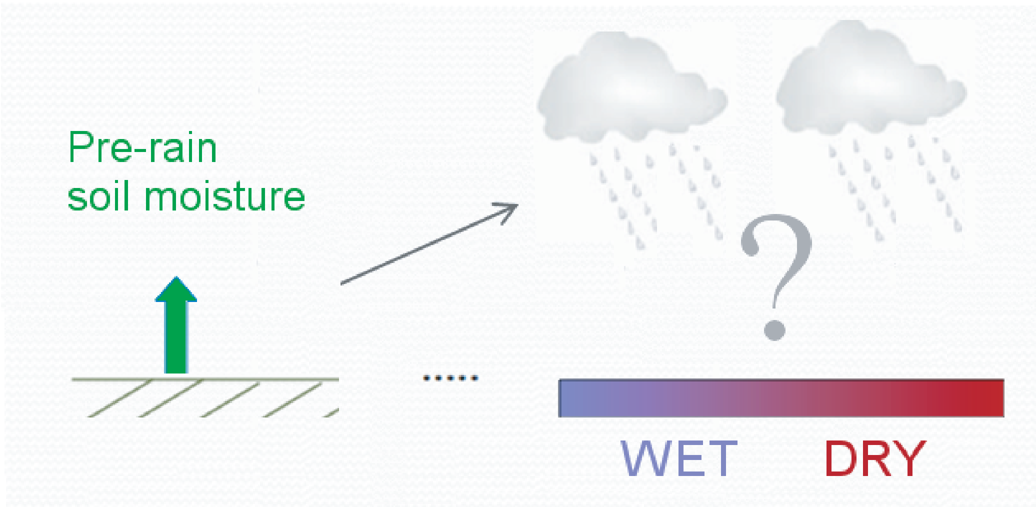
The "Reports on Earth System Science" continue the former "Reports" and "Examensarbeiten" of the Max Planck Institute.

Layout

Bettina Diallo and Norbert P. Noreiks
Communication

Copyright

Understanding Soil Moisture - Precipitation Coupling on Mesoscales Using Observations over North Africa



Dissertation with the aim of achieving a doctoral degree
at the Faculty of Mathematics, Informatics and Natural Sciences
Department of Earth Sciences of Universität Hamburg
submitted by

Irina Yurievna Petrova

Hamburg 2017

Irina Yurievna Petrova

Max-Planck-Institut für Meteorologie
Bundesstrasse 53
20146 Hamburg

Tag der Disputation: 01.02.2017

Folgende Gutachter empfehlen die Annahme der Dissertation:

Prof. Dr. Martin Claußen
Dr. Chiel C. van Heerwaarden

Berichte zur Erdsystemforschung / Max-Planck-Institut für Meteorologie 191
Reports on Earth System Science / Max Planck Institute for Meteorology 2017

ISSN 1614-1199

Abstract

Soil moisture is a main driver of land-atmosphere interactions. On the meso-scale (10-100 km), soil moisture influences the formation and development of rainfall systems, with attendant consequences for the hydrological, agricultural and social-economic sectors. Understanding of the strength and the sign of the soil moisture – precipitation coupling (SMPC) has a number of relevant implications for the present and future climates. To date, there is significant uncertainty in how soil moisture affects rainfall, owing largely to the lack of observational evidence. In this thesis, analysis of 10 years of satellite soil moisture and precipitation records using a common analysis framework is done to advance our understanding of the SMPC from an observational perspective in the North African region.

The present study reproduces, evaluates and applies the statistical method of Taylor et al. (2012), which links the probability of afternoon rainfall occurrence to the preceding soil moisture conditions. The results of this evaluation indicate that the estimated coupling relationship largely relies on the set up of introduced assumptions and limitations. A number of assumptions used by the method maximize the probability of the negative spatial SMPC in the region. The sensitivity tests identify the following major conditions which maximize the likelihood of negative coupling: (i) - the afternoon accumulated precipitation (AAP) threshold value used in the method to define a rainfall event should be between 1 and 15 mm/ 9hrs, (ii) - the areal distribution of the AAP should be taken into account, and (iii) - events with smaller AAP area should be selected. The latter condition is not considered in the current set up. Except for that, the original framework is found to be optimal for its purposes. The preference of rainfall to occur over spatially drier soils in the region is found to be robust. The above findings together with the simplicity of the framework can be identified as a key for its applicability and further improvement.

The method is then applied to investigate the strength and spatial variability of the SMPC, as well as the temporal effects of soil moisture on moist convection. The analyses show that the negative spatial and the negative temporal coupling relationships co-exist and are not independent of one another. Regional application of the method at a higher than before horizontal resolution of 1° reveals previously averaged effects of wetland and irrigated land areas on the SMPC measure, and identifies regions, where surface effects on rainfall can be expected to be particularly strong. These are the south-western part of the domain with the most robust negative SMPC signal, and the South Sudan. In the latter region, the spatial coupling is found to be modulated by the presence of wetlands and is susceptible to the amount of long-lived propagating convective systems. In the drier northern latitudes the low-level atmospheric moisture variability is suggested to be more decisive than the soil moisture state.

The results of this thesis provide the first insight into the regional variability and potential "hot-spots" of the SMPC in North Africa with further implications for the hydrological, agricultural, economical sectors, as well as climate change analyses and planning of future measurement campaigns. Though focused on North Africa, the results of this study are relevant and are likely to be applicable to other semi-arid climates.

Zusammenfassung

Die Bodenfeuchte ist einer der Hauptantriebe für Wechselwirkungen zwischen der Landoberfläche und der Atmosphäre. Auf der Mesoskala (10-100 km) beeinflusst die Bodenfeuchte die Bildung und Entwicklung von Niederschlagssystemen mit Auswirkungen auf die Hydrologie sowie agrarwirtschaftliche und sozio-ökonomische Bereiche. Das Verständnis um die Intensität und das Vorzeichen der Richtung der Bodenfeuchte—Niederschlag Kopplung (SMPC für soil moisture – precipitation coupling) hat eine Reihe von relevanten Auswirkungen für das gegenwärtige und künftige Klima. Wie die Bodenfeuchte den Niederschlag beeinflusst ist bis heute mit großen Unsicherheiten behaftet, was im Wesentlichen an fehlenden Beobachtungsdaten liegt. Um die SMPC besser zu verstehen, liegen dieser Arbeit daher zehnjährige Satellitendatenzeitreichen der Bodenfeuchte und des Niederschlags zugrunde. Diese Beobachtungsdaten werden in einem einheitlichen Rahmen mit Fokus auf die nordafrikanische Region analysiert.

Diese Arbeit reproduziert, evaluiert und wendet die statistische Methode von Taylor et al. (2012) an, die die Wahrscheinlichkeit zwischen nachmittäglichem Niederschlag und vorausgehender Bodenfeuchte in Relation stellt. Die Evaluierung dieser Zusammenhänge zeigt, dass die Kopplungsbeziehungen stark von den gewählten Annahmen und deren Limitierungen abhängig sind. Die Annahmen der Methode maximieren die Wahrscheinlichkeit einer negativen räumlichen SMPC in der Region. Durchgeführte Sensitivitätsstudien identifizieren die folgenden Bedingungen für eine maximale negative Kopplung: (i) – der akkumulierte nachmittägliche Niederschlag (AAP für afternoon accumulated precipitation) sollte zwischen 1 und 15 mm/ 9 Stunden liegen, (ii) – die räumliche Verteilung des AAP sollte berücksichtigt werden, und (iii) - Ereignisse mit kleineren AAP sollten ebenfalls berücksichtigt werden. Letztere Bedingung ist in der derzeitigen Konfiguration nicht berücksichtigt. Abgesehen davon ist diese Konfiguration optimal auf ihren Zweck abgestimmt. Die Präferenz für Niederschlagsereignisse über räumlich trocknerem Boden ist in dieser Region robust. Die oben genannten Ergebnisse und die einfache Anwendbarkeit der Methode sind der Schlüssel für ihre Anwendbarkeit und künftige Verbesserungen.

Mit dieser Methode wird einerseits die Intensität und Variabilität der SMPC untersucht und anderseits die zeitliche Auswirkung der Bodenfeuchte auf die atmosphärische Konvektion analysiert. Die Ergebnisse zeigen, dass die negativen räumlichen und zeitlichen Kopplungen koexistieren und nicht unabhängig voneinander sind. Regionale Anwendungen der Methode auf einer höheren horizontalen Auflösung von 1° zeigen Effekte auf die SMPC, die von Feuchtgebieten oder bewässerten Böden herrühren, und vormals wegen der Mittelung in der gröberen Auflösung erkennbar waren. Zudem identifiziert die höhere Auflösung Regionen, in denen die Bodeneffekte auf den Niederschlag besonders stark sind. Dies betrifft den Südwesten der Region mit dem robustesten negativen SMPC Signal sowie den südlichen Sudan. Dort wird die räumliche Kopplung von den vorhandenen Feuchtgebieten moduliert und ist zudem von der Anzahl der langlebigen Konvektionssysteme beeinflusst. In den trockeneren Bereichen ist dagegen die Vari-

abilität der atmosphärischen Feuchte in den bodennahen Schichten ausschlaggebender als die Bodenfeuchte.
Die Ergebnisse dieser Arbeit geben einen ersten Einblick in die regionale Variabilität und die potentiellen kritischen Regionen der SMPC in Nordafrika sowie ihre Auswirkungen und Einflüsse auf die Hydrologie, Landwirtschaft, Ökonomie und den dortigen Klimawandel, sowie die Planung künftiger Messkampagnen. Obwohl der Fokus der Arbeit auf Nordafrika liegt, sind die Ergebnisse dieser Arbeit ebenso relevant und anwendbar für andere semi-aride Klimate.

Contents

Chapter 1

Introduction

The objective of the present work is to improve our understanding of how soil moisture affects the development of new convective rainfall events and related precipitation variability in the real world. Specifically, this study contributes to a still scarce observational evidence of the soil moisture – precipitation coupling (SMPC) relationship in the North African region by using state-of-the-art multi-year microwave satellite data. The soil moisture - precipitation coupling is a fundamental part of a broader concept of land-atmosphere interaction with considerable relevance for the climate system, including socio-economical aspects.

1.1 Motivation

The land and the atmosphere are two closely coupled systems. Various combinations of land surface properties, including those caused by human activity, continuously affect the state of the atmosphere through a complex system of hydrological, radiative and turbulent processes. Soil moisture has been identified as being one of the key parameters, which drives the interaction between the land and the atmosphere, as it represents a main source of moisture and heat for the lower atmosphere on land (Seneviratne et al. (2010), a review).

The effects of soil moisture on the atmosphere cover a wide range of spatial and temporal scales (Nicholson, 2015). Accordingly, a large number of climate and weather phenomena is influenced by these effects, while understanding of these interactions is highly relevant for a broad variety of fields. The latter include e.g. socio-economical and agricultural sectors (e.g. Taylor and Lambin, 2002; Alter et al., 2015), extreme weather forecast and monitoring (e.g. Hirschi et al., 2010), operational meteorology and climate change (e.g. van den Hurk et al., 2012; Dirmeyer and Wang, 2014). The role of land-atmosphere coupling in the projected climate variability was studied e.g. by Seneviratne et al. (2006); Dirmeyer et al. (2012, 2013a,b); Dirmeyer and Wang (2014) on a regional and global scales and e.g. by Lauwaet et al. (2012); Thiery et al. (2016)

on a local scale. All the studies agree that the land-atmosphere coupling through the variability in soil moisture can explain a significant part of projected changes in the atmospheric state. Soil moisture conditions have been also indicated to influence amplitude and duration of warm temperature extremes, like heat waves (e.g Fischer et al., 2007a,b; Hirschi et al., 2010) and droughts (e.g. Lare and Nicholson, 1994; Atlas et al., 1993; Sud et al., 2003). At the local scale, soil moisture variability have shown to have a pronounced impact on formation and development of intense rain storms (e.g. Clark et al., 2004; Taylor, 2010; Birch et al., 2013). Other studies indicate that soil moisture state inter alia may contribute to severity of tornadoes (Cheresnick and Basara, 2005) and re-intensification of tropical cyclones (Evans et al., 2011; Laureano Bozeman et al., 2012). In association with the above mentioned weather and climate phenomena, vulnerability of social-economical and agricultural sectors is actively discussed and studied on regional and global scales. These include such acute topics as development of early-warning systems and predictability, water and food security, population mortality and decease outbreaks, population migration, as well as climate adaptation strategies (e.g. Kandji et al., 2006; García-Herrera et al., 2010).

In the future, an increase in the strength of land-atmosphere coupling is expected (e.g. Dirmeyer, 2011), and the regions with strong coupling will likely expand (Seneviratne et al., 2006; Dirmeyer et al., 2013a). As a consequence, enhanced controls of soil moisture variability on atmospheric dynamics, and hence on the climate change related variability and mentioned above socio-economical aspects, are likely to be observed in the future (Dirmeyer et al., 2012). Accordingly, an advance in the understanding of the mechanisms and interactions involved in the soil moisture - atmosphere coupling is highly required.

Most of the research in the area, as well as the physical understanding gained from it, is based on the analysis of numerical model results. Large scale models are usually used to investigate the role of soil moisture in climate variability (Koster et al. (2004); Guo et al. (2006); Dirmeyer et al. (2013b)), while cloud resolving schemes allow examining the response of the lower atmosphere to the variability of surface moisture and related heat and moisture fluxes (e.g. Avissar and Schmidt, 1998; van Heerwaarden and Guerau de Arellano, 2008; Couvreux et al., 2012). Yet, uncertainties in both remain large (e.g. Koster et al., 2004; Dirmeyer et al., 2006; Hohenegger et al., 2009; Zeng et al., 2010). Moreover, the understanding of soil moisture effects on atmospheric dynamics and climate from models is heavily underscored by the contradictory findings between the models (e.g. Orlowsky and Seneviratne, 2010), as well as between the models and existing observational evidence (Taylor et al., 2012).

One of the least understood and most controversial aspects of land - atmosphere interaction is related to the effect of soil moisture on subsequent precipitation operating on 10-100 km scales, namely soil moisture - precipitation coupling (SMPC, Seneviratne et al. (2010); Nicholson (2015)). Analyses of large-scale models and observations result in opposite sign of the SMPC (Taylor et al., 2012). Multiple convection-resolving model based studies mostly agree on the sign, yet they are not consistent in the magnitude of the coupling and are restricted to the convection scheme applied, resolution and various model assumptions (e.g. Hohenegger et al., 2009; Taylor et al., 2013). Fewer studies utilizing exclusively or mostly observational data exist. The majority of them represent case studies of measurement campaigns, meaning a short time-period of collected data, poor spatial variability estimates and lack of statistical evidence. Considering inability of the ground measurements nowadays to provide the required spatial and temporal coverage, exploration of extensive long-term satellite-based products is highly beneficial.

Following the current needs and relevance of the topic, the present work utilizes 10 years of state-of-the-art satellite microwave estimates of soil moisture and precipitation parameters to evaluate the link between soil moisture conditions and subsequent precipitation occurrence, i.e. SMPC. Thereby, this study contributes to a still scarce observational evidence of the SMPC built on the long-term satellite data.

For the present study, the Northern African region, mainly the Sahel area, is selected for a number of reasons. First of all, the land surface controls on atmospheric dynamics is known to be particularly strong in this region (Dirmeyer, 2011; Miralles et al., 2012; Gallego-Elvira and Taylor, 2016), while the future projections of rainfall remain being the most uncertain (IPCC, 2007). Secondly, the region provides a very poor in situ data network, which considerably limits observational evidence of the soil moisture - precipitation coupling, and therefore validation of model results in the area. Last but not least, the relevance of the SMPC via related rainfall variability for the society and environment in this region is exceptionally high.

Built on the probability-based method of Taylor et al. (2012) (henceforth T12), the analysis of the present study provides the first insight into the regional distribution of the SMPC strength and its variability in North Africa at a 1° horizontal resolution. This knowledge should be of particular relevance for socio-agricultural sector, as well as for climate change analysis, as various regions are expected to respond differently to the warming. Additionally, it can be used as a guiding information for planning the future measurement and monitoring campaigns.

Provision of statistical methods like that of T12, against which models might be validated, is per se in demand, as well as a thorough evaluation of the existing techniques is required. In this view, another contribution of the present study should be considered as being an evaluation of the recently suggested method of T12. The analyses presented here provide an insight into the limitations, robustness as well as ability of the method to preserve characteristics of physical processes.

The detailed description of the goal, tools and objectives of the study are presented in Section 1.4. The following two sections provide more in depth insight into the prevailing theoretical (Sec. 1.2) and existing observational (Sec. 1.3) evidence of the mechanisms involved in the notion of soil moisture - precipitation coupling.

1.2 Soil moisture - precipitation coupling (SMPC): definition and relevant processes

The idea of soil moisture relevance for convection and precipitation development stems from a broader notion of land surface influence on atmosphere and climate variability. The earliest published speculations on the soil moisture control on precipitation refer to the first half of the 20th century (Holzman (1937) cited in Eltahir (1998)). Until the 1990s the main focus of the research was given to the "albedo-drought" feedback (e.g. Charney, 1975; Courel et al., 1984) operating on larger (100 km and synoptic) scales, and later to the impact of vegetation on climate variability (e.g. Zeng et al., 1999). With the increase in understanding of the involved processes and scales, a major role was given to the soil moisture parameter, and the relevance of interactions on smaller (daily and meso-) scales was recognized (Ek and Mahrt, 1994; Betts and Ball, 1996; Nicholson, 2015).

1.2.1 Local SMPC verses moisture recycling

The core idea underlying the notion of SMPC is to describe and understand the ways and mechanisms through which previously wetted surface can affect the development of new rain storms and influence precipitation variability (Taylor et al., 2011b). The final goal is to improve predictability of rainfall on the sub-seasonal scales (e.g. Koster et al., 2011; van den Hurk et al., 2012; Collow et al., 2014). However, due to complexity of interactions involved into the coupling across a range of spatial and temporal scales, as well as the limitations of currently available models and observations, quantification of the SMPC remains notoriously difficult.

When considered over larger spatial scales ($>$ 1000 km, van der Ent and Savenije (2011)) the SMPC is usually referred to the concept of water recycling (Entekhabi et al., 1992; van der Ent et al., 2010; van der Ent and Savenije, 2011; Goessling and Reick, 2011, 2013). Following this concept, influence of soil moisture on precipitation is estimated via changes in the lower atmosphere's moisture budget. The strength of the SMPC in this case is quantified by a ratio of precipitated water to the amount of regional evapotranspiration directly available for the precipitation. Yet, various other measures exist, and their limitations are known (e.g. Goessling and Reick, 2011). Following the moisture recycling concept, increased evaporation can only lead to increased precipitation. Accordingly, the sign of the SMPC on these scales is identified as being positive.

With respect to rainfall predictability, however, local conditions have shown to be more decisive in comparison to moisture recycling (Schär et al., 1999). To put it in more simple words, it is the local state of the land surface and the atmosphere on scales of 10-100 km, which defines whether and where it will rain, while moisture required for precipitation might be advected from elsewhere. Evaluation of the strength and sign of the local SMPC is substantially complicated by a non-linearity of the manifold processes (like boundary layer response to surface turbulent flux partitioning and convection triggering) involved in the coupling (Pielke, 2001; Ek and Holtslag, 2004), as well as influence of other more dominant variability factors (like e.g. SST, Biasutti et al. (2008)) on precipitation and soil moisture evolution. For these reasons evidence of both, positive (e.g. Taylor et al., 1997; Clark et al., 2003; Wolters, 2010) - rain over wetter soils - and negative (e.g. Taylor and Ellis, 2006; Garcia-Carreras et al., 2011) - rain over drier soils - local SMPC exists.

1.2.2 Interaction steps involved into the SMPC

The complete soil moisture - precipitation coupling loop can be split into terrestrial and atmospheric legs, composed of the four intermediate coupling steps (Fig. 1.1):

The *terrestrial leg* of the SMPC includes the effect of rainfall on soil moisture (Fig. 1.1, step A) and the further control of soil moisture on partitioning of available energy into the heat and moisture fluxes (Fig. 1.1, step B). These coupling steps are relatively well understood, and multiple modelling and observational studies agree on the sign of interactions as well as their limitations (Seneviratne et al., 2010).

One of the most relevant findings here refers to the strength of the coupling between fluxes and soil moisture. The strong sensitivity of fluxes to soil moisture have shown to hold only in the medium range of soil moisture content Seneviratne et al. (2010). Below a certain soil moisture value, no or very little evaporation occurs, while above a certain value the fluxes become insensitive to variations in soil moisture. In the latter case, the atmospheric conditions (i.e. wind, radiation and atmospheric humidity) rather control the variability of heat and moisture fluxes. In this situation, the strong SMPC is unlikely. Accordingly, high sensitivity of surface energy fluxes to soil moisture is usually considered as one of the necessary but not sufficient conditions to observe a strong coupling between soil moisture and precipitation on both, monthly and daily scales (Koster et al., 2003). The North African region considered in this study shows particularly strong coupling between soil moisture and fluxes during the wet monsoon period, suggesting therefore higher potential to observe a strong soil moisture control on BL state and precipitation in this area (Dirmeyer, 2009, 2011; Guillod et al., 2014; Seneviratne et al., 2006; Teuling et al., 2009).

The *atmospheric leg* of the SMPC investigates the influence of modified surface turbulent fluxes on BL state and stability (Fig. 1.1, step C) and the probability of the BL conditions to further favour moist convection development or affect precipitation variability (Fig. 1.1, step D). As for the terrestrial leg, strong coupling between the surface energy fluxes and the BL state is equally considered to be a necessary condition to obtain a strong control of land surface on precipitation. The identified regions of strong land surface - BL coupling are found to coincide with the areas of strong soil moisture control on surface energy fluxes (e.g Dirmeyer et al., 2012; Dirmeyer and Wang, 2014; Gallego-Elvira and Taylor, 2016). The best agreement is found over the monsoon regions, with the Sahel being a "hot-spot" (Dirmeyer and Wang, 2014).

Although, a presence of a strong coupling in the terrestrial and atmospheric parts of the loop provides a possibility for SMPC, yet it does not allow to judge whether the resulting state of the BL overlaying wet or dry soils will favour convection. The link to precipitation amount and intensity is even more subtle. Accordingly, the last step (D), which considers the link between the BL and convection triggering or precipitation variability remains being highly uncertain.

A common one-dimensional perspective on the link between surface fluxes, BL variability and convection implies that wetter soil conditions through increased moisture and decreased sensible heat flux lead to a higher total surface heat flux and a moister and shallower BL. This in turn results in a weaker entrainment of dry air from above, a higher amount of moist static energy (MSE) per unit mass of BL, and a larger convective available potential energy (CAPE)(e.g. Eltahir, 1998; Alonge et al., 2007). These conditions are generally identified as being benign for convection triggering (e.g. Eltahir and Pal, 1996). Dry soils, on the contrary, are associated with a deeper and drier BL, and hence increased entrainment and reduced MSE and CAPE - potentially unfavourable conditions for convection development.

However, which of the two BL states will get close to triggering moist convection depends on many factors. Among others, the relevance of the spatial variability in soil moisture and moisture fluxes on the BL state and therefore on convection triggering was recently demonstrated (Taylor and Ellis, 2006; Taylor et al., 2007, 2011a). The latter suggested that the link between BL state and surface conditions is not one- but rather two-dimensional in essence. The other factors which can modulate the sign of the SMPC and have been considered until now include but not limited to:

- morning state of the BL (Findell and Eltahir, 2003b,a; Ferguson and Wood, 2011; Tawfik and Dirmeyer, 2014; Tawfik et al., 2015),
- stratification above the BL (Ek and Mahrt, 1994; van Heerwaarden and Guerau de Arellano, 2008),
- interaction of the BL state with characteristics of travelling disturbances (e.g. atmospheric and gravity waves, Mohr and Thorncroft (2006); Gaertner et al. (2010); Adler et al. (2011)),
- synoptic scale circulations and convergence zones (e.g. Birch et al., 2013),
- low-level wind advection (Findell and Eltahir, 2003a; Dixon et al., 2013; Baldi et al., 2008; Froidevaux et al., 2013), as well as
- maturity and size of convective systems (Taylor, 2010; Gantner and Kalthoff, 2010).

Most of the above evidence, however, is based on the analyses of one storm or one day simulation. Hence, providing estimation of the SMPC relationship over many rain events is crucial, and is a core of the present study.

Another aspect that is worth mentioning here is related to the methods used to estimate the probability of moist convection triggering over wet or dry soils. Estimation of co-variability of the precipitation with any land surface or BL parameter as in the previous coupling loops (A-C) have shown to be rather unreliable (Salvucci et al., 2002; Wei et al., 2008; Orlowsky and Seneviratne, 2010). The difficulty arises form causality issues, as well as the influence of synoptic controls on precipitation (i.e. persistence) and more dominant variability factors (like SST). Accordingly, estimates of the complete soil moisture - precipitation feedback have shown to be problematic. Therefore, recent focus was given to the local SMPC on daily scales, and methodological preference has shifted from co-variance measures to probability and event statistics analyses. These methods do not necessary avoid the problem of rainfall persistence but they are able to isolate soil moisture or ET forcing on rainfall, and are able to at least partly exclude effects of stronger variability factors when appropriate assumptions are introduced (Findell et al., 2011). The probability based method of T12 utilized in this study accordingly falls into this category, and is therefore worth exploring.

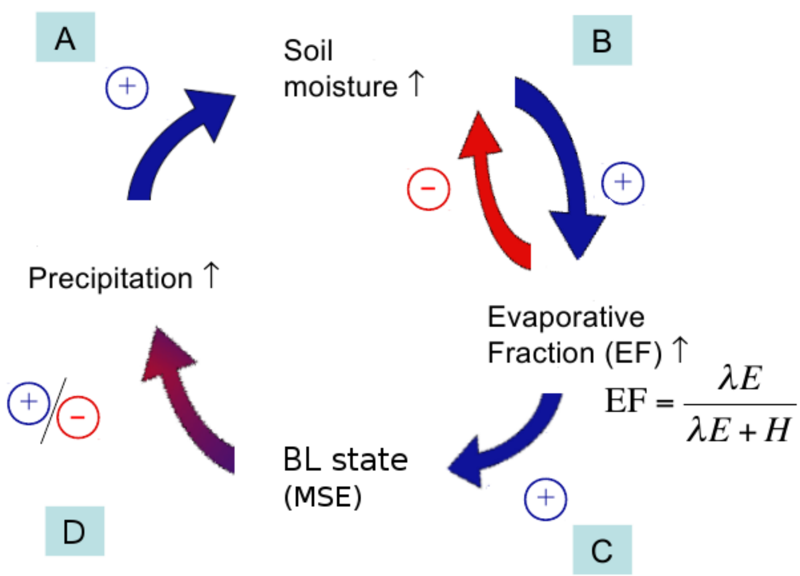


Figure 1.1: Simplified feedback loop between soil moisture and precipitation (adopted from Seneviratne et al. (2010). MSE and BL stands for moist static energy and boundary layer accordingly. λE and H represent latent and sensible heat flux terms accordingly. Blue (red) arrows indicate positive (negative) coupling respectively.

1.3 Existing observational evidence of the SMPC in Western Africa

This section presents an overview of existing observational evidence for a negative or positive sign of the local SMPC in Western Africa. Inter alia, the studies presented below provide a manifestation of some of the above listed factors, which can modulate the sign of the SMPC.

Existing evidence of the soil moisture - precipitation coupling over North Africa is almost entirely concentrated in its western part. First observational estimates in West Africa refer to the papers of Taylor et al. (1997) and Taylor and Lebel (1998), which used precipitation and soil moisture data from the first HAPEX-Sahel measurement campaign (Goutorbe et al., 1994). These studies indicated the presence of a positive soil moisture - precipitation feedback observed on 10-15 km scales in the south-west Niger area. The positive coupling implied that a previously wetted surface had higher probability to obtain new rainfall within the next days than the adjacent drier area. This observation indicated the relevance of rainfall persistence over the region linked to the persistence in soil moisture anomalies. Based on a case-study analysis from the Sahelian JET2000 campaign (Thorncroft et al., 2003) Taylor and Ellis (2003) assessed the variability of soil moisture and thermodynamic properties of the BL induced by recent rainfall on 10-100 km scales. Their results supported the persistence mechanism suggested in the previous study. They could also further demonstrate that wetter soils lead to a thermodynamic state more favourable for new convective initiation. The complementary analyses of satellite imagery proved the suppression of a successive cold cloud field over dry area in comparison to wet soils, thus indicating the potential of a positive coupling.

Later, Taylor and Ellis (2006), using satellite data over one summer, observed for the first time evidence of a negative coupling over the same Sahelian region. They justified the opposite outcome to the previous studies by the size of the meso-scale convective systems (MCS). The observed pattern of suppressed cold cloud occurrence over wet soil patch was largely associated to the initiation and passage of smaller rainfall systems. Larger systems, in turn showed less sensitivity to the underlying soil moisture conditions.

The relationship observed by Taylor and Ellis (2006) inter alia indicated a strong dependence on the size of the underlying soil moisture anomaly. This finding for the first time emphasized relevance of the soil moisture heterogeneity for convection triggering through generation of breeze-type circulations in the area. Previously, the role of thermally-induced circulations on moist convection initiation was only investigated in simulations of BL models (Chen and Avissar, 1994; Avissar and Schmidt, 1998), or was suggested to play a role at the vegetation-crop boundary (e.g. Doran et al., 1995). First direct observation of breeze-like circulations caused by strong spatial gradients in soil moisture was provided by Taylor et al. (2007).

Using satellite and AMMA-campaign observational data (Redelsperger et al., 2006), Taylor (2010) documented a case of a MCS triggered on a soil-moisture gradient around the region of Mali. This study could demonstrate, that the triggering over strong soil moisture heterogeneity occurred in combination with the arrived gravity wave, hence indicating the relevance of the synoptic environment for the SMPC relationship. The fact that convection was initiated over unfavourable thermodynamic conditions, i.e. over dry soils suggested that the mechanism of locally-induced circulations might be of particular relevance for moist convection triggering under unfavourable atmospheric state.

A unique observation of the full life-cycle of a selected rain storm based on radar and AMMA data was provided by Lothon and Campistron (2011). This study confirmed the effect of soil moisture gradients on the formation of a breeze-like circulation and their further role on triggering. Additionally, effect of thermally-induced circulations on moist convection development was also found to be relevant over other land cover heterogeneities, such as vegetation gradients (Garcia-Carreras et al., 2011), or wetland (Taylor, 2010; Lauwaet et al., 2012) and irrigated land (Alter et al., 2015) surroundings, all supporting a negative SMPC relationship. Results of the "best" observational case-studies identified during the campaigns were tested and supported by multiple cloud-resolving model simulations (e.g. Clark et al., 2003, 2004; Birch et al., 2013; Klüpfel et al., 2012; Couvreux et al., 2012).

For the first time statistical significance of the observed relationships was provided by Taylor et al. (2011a). They exploited 4-years of high-resolution satellite land surface temperature (LST) records as a proxy for soil moisture to investigate the effect of land surface on MCS initiation. Analyzing the initiation of more than 3000 storms they were able to show that spatial gradients in soil moisture exert strong control on moist convection initiation on scales of 10-40 km. The identified strong dependence of the observed relationship to the size of the surface moisture heterogeneity and wind direction supported the relevance of local breeze-like circulations for convection triggering on these scales.

First quantitative and variability estimates of the SMPC over the globe were provided by Ferguson and Wood (2011) and T12. Both studies also demonstrated significant differences between the observed and modelled relationships.

Ferguson and Wood (2011) extended the method of Findell and Eltahir (2003b) globally to expose areas of a potentially higher or lower sensitivity of moist convection to soil moisture based on the morning state of the BL. T12 examined the direct relationship between afternoon convective precipitation and the preceding spatial gradient in soil moisture. Applying the developed probability-based statistical framework to the 10-years of satellite microwave data, T12 found that a substantial part of the world, and especially the Sahel, experiences negative soil moisture - precipitation coupling, i.e. a preference of convective rainfall to occur over soils drier than their surroundings. Later, (Guillod et al., 2015) (hereafter, G15), using the same approach as T12, demonstrated the robustness of the identified relationships among multiple data set combinations. Moreover, they showed that the spatially negative relationship identified in T12 co-exists with and does not exclude a positive (over wet climates) or negative (over the Sahel) temporal coupling, i.e. a preference of convective rainfall to occur over soils wetter or drier than usual. The latter finding allowed for the first time a direct comparison of temporal and spatial effects of soil moisture on precipitation, therefore demonstrating how the one- and two-dimensional perspectives on the processes governing SMPC may co-exist.

Despite the advantages, both studies shared some common limitations. The horizontal resolution of the estimated SMPC relationships was rather course, i.e 5°, which did not allow an insight into the regional variability of the coupling relationships, and for the same reason an assessment of potential physical processes underlying the identified SMPC effects was impeded. These limitations represent the main gaps the present study aims to close.

1.4 Outline of the thesis

The overall goal of this thesis is to provide quantitative estimates and to improve process-oriented understanding of the soil moisture - precipitation coupling relationship at a higher than before (i.e. 1°) horizontal resolution in the North African region using state-of-the-art multi-year satellite data. Specifically, the spatial and temporal effects of soil moisture on subsequent rainfall are distinguished and analyzed here. The three scientific questions addressed in this thesis can be formulated as follows:

(I) - How do spatial and temporal SMPC vary across the North African region, and do "hot-spots" exist?

(II) - Are the spatial and temporal SMPC relationships independent of one another, and if not - how do they inter-relate?

(III)- Which physical processes underlie the estimated statistical SMPC relationships?

To answer these questions the probability-based method of T12 is reproduced and applied to available 10-years of summer-time (JJAS) satellite microwave soil moisture and precipitation data records. Because the core of the isolating effect of soil moisture on subsequent rainfall in the method relies largely on the introduced assumptions and constraints, an evaluation of the method is performed first (Chapter 4). Specifically, a series of sensitivity tests are carried out with respect to the changes in the magnitude and significance of the spatial SMPC measure at the original 5° horizontal resolution. The tests are meant to answer two major questions:

(i) - Is the original T12 set up optimal for its purposes?

(ii)- And how robust is the spatial SMPC signal?

The main focus here is given to the identification of a critical rainfall threshold value introduced in the method to define a rainfall event, and the role of rain field geometry (i.e. areal distribution) in determining a SMPC relationship. The results of this analysis additionally provide a link to physical mechanisms that underlay the method assumptions and, therefore, may serve to maximize a negative SMPC signal over the North African domain.

Once the set up of the method is proved to be optimal, the research questions (I-III) are approached. The regional variability of the spatial SMPC, as well as evidence of physical processes that underlay this coupling relationship is investigated in the first part of Chapter 5. Here, the sensitivity of the SMPC relationship to a higher horizontal resolution is studied first, and identified advantages of the higher resolution are outlined. Based on these results, the two "hot-spot" regions of the negative spatial SMPC are identified and studied in more detail. Particularly, the effect of wetlands and MCS life cycle on robustness and regional variability of the spatial SMPC are investigated.

In the second part of Chapter 5 the temporal SMPC is analyzed, and the link between the temporal and spatial coupling relationships is evaluated. As a result, a physical mechanism is proposed, which likely underlies the identified co-existence of the spatial and temporal SMPC. The chapter concludes with a discussion of why a temporally negative SMPC is not unexpected in the semi-arid environment of North Africa.

The final Chapter 6 summarizes most important findings of the thesis, and highlights implications of this work for future research.

Chapter 2

Domain and Data

2.1 Main climatic characteristics of the North African domain

We focus our analyses on the Sahelian region (5° - 20°N, 20°W - 40°E) (Fig. 2.1, inset rectangular). The latter has repeatedly shown to be a "hot spot" of the land-atmosphere interactions (Dirmeyer, 2011; Miralles et al., 2012; Gallego-Elvira and Taylor, 2016), and one of the key regions in the changing climate (Dirmeyer et al., 2012; Dirmeyer and Wang, 2014). The main feature of the Sahelian climate is the West African Monsoon (Janicot and Thorncroft, 2008), and associated with it precipitation variability (Nicholson, 2013). All surface parameters including soil moisture closely follow the precipitation signature at a large range of spatial and temporal scales. Following migration of the Inter Tropical Convergence Zone (ITCZ), atmospheric and surface parameters experience strong meridional gradient between 10° and 20°N (Figure 2.1, zonal plot), where 10°N corresponds to the mean location of the summer time rain belt, also referred as ITCZ. 18° - 20°N is featured by a surface wind convergence or Inter Tropical Front (ITF), where cool and moist Atlantic flow meets hot and dry Saharan air. Associated to this differential heating, the monsoon circulation and related large-scale disturbances like the African Easterly Jet (AEJ), African Easterly Waves (AEWs) and wind shear largely modulate convection activity over the region (Duvel, 1990; Mohr and Thorncroft, 2006). However, evidence supporting a significant role of the surface state in the triggering of the moist convection is steadily growing (Nicholson, 2015).

Along with the magnitude of the soil moisture, its temporal and spatial variability are typically higher in the southern part of the domain, where precipitation events are more frequent. This strong variability in soil moisture over relatively dry surrounding and sparse vegetation exerts substantial control on the surface heat and moisture fluxes (Schwendike et al., 2010; Lohou et al., 2014). The energy fluxes in turn can influence new convection and rainfall development through their effect on stratification and boundary layer depth (Kohler et al., 2010). All above mentioned makes the Sahel being more favourable for observing soil moisture - precipitation feedback, as reveals much stronger signal, compared to the regions of weaker coupling (Taylor, 2015).

Middle July to August conditions are known to be less favourable for the strong surface influence on convection, having typically a lower level of free convection (LFC, Taylor et al., 2011a; Guichard et al., 2009) and less pronounced spatial contrast between fluxes due to more dense vegetation (Kohler et al., 2010). In our study the role of the monsoon dynamics is not directly addressed to preserve maximum sample size for the sake of statistical significance. Potential effect of seasonality on the observed SMPC is briefly discussed in section 4.2.

We intentionally extend our analysis to the eastern orographical boundaries. Despite the remarkable zonal symmetry of surface and atmospheric parameters (as in precipitation in Fig. 2.1), considerable differences exist in rainfall and large-scale circulation regimes between East and West. Distinct local orography, intensity of surface and upper level jets and wave disturbances affect regional convection and hence, its sensitivity to the surface state. Eastern African domain can also impact convection in the rest of the region through formation of the westward propagating AEWs (Laing and Carbone, 2008) and long-lived MCSs (Laing et al., 2012). Yet, notably few studies investigating eastern Sahelian climate and especially land-atmosphere interactions exist.

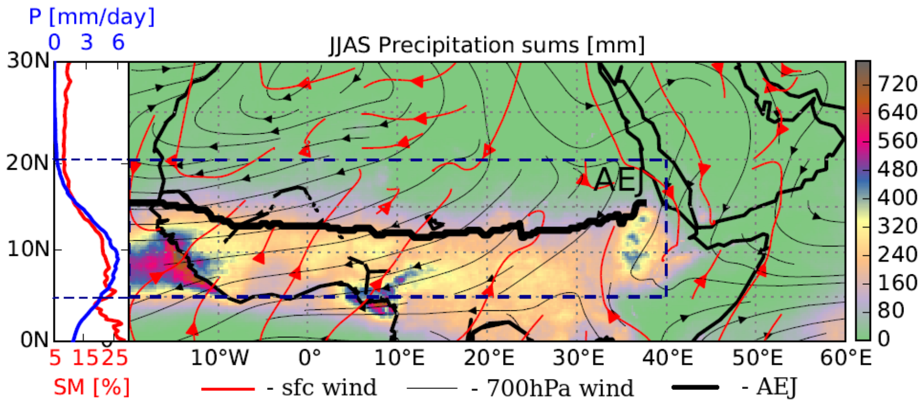


Figure 2.1: JJAS TMPA precipitation (color), mean surface (red streamline) and 700 hPa (black streamline) ERA-Interim wind climatology averaged over 2002-2011 period. Black thick line shows mean location of the African Easterly Jet (AEJ). Inset plot indicates zonal means of daily AMSR-E soil moisture and TMPA precipitation climatology. The dashed rectangular shows boundaries of the study domain.

2.2 Satellite data sets

2.2.1 AMSR-E soil moisture

Soil moisture (SM) data from the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E, Jun 2002 - Oct 2011) is analyzed in this study. The AMSR-E unit is carried on board of the polar orbiting AQUA satellite, measuring brightness temperatures in 12 channels, at 6 different frequencies (6.9-89 GHz) (Njoku and Jackson, 2003). Soil moisture derived from the lowest C-band frequency of 6.9 GHz is used here, as lower frequencies experience less signal contamination from vegetation and surface roughness and are able to receive emission information from deeper soil layers (still few centimetres, Owe et al., 2008). The AQUA orbit is sun-synchronous with typically one overpass per pixel per day at either 13:30 or 1:30 local solar time (LST). In order to capture the surface moisture state shortly before afternoon convection activity, only data of ascending day orbit, i.e. 13:30 is used here. It is important to note though, that the day orbit is prone to higher biases compared to the night overpass, because of the greater temperature difference between surface and canopy involved in the physics algorithm (Njoku and Jackson, 2003).

We utilize the Level 3 estimates of AMSR-E soil moisture derived with the Land Surface Parameter Model (LPRM, Owe et al., 2008) for JJAS 2002-2011 period. The product is available at 0.25° spatial resolution. The LPRM is not valid for dense vegetation and water bodies. Therefore pixels with an optical depth > 0.8 are excluded from further calculations. Water body and soil moisture quality masks were adopted from the materials of T12. Accordingly, pixels containing more than 5% water are excluded, using water body classification of the 1 km GLC2000 dataset. Application of the soil moisture quality mask, based on the correlation analysis between precipitation and soil moisture data sets, is intended to reduce the number of pixels covered with wetlands (for details see suppl. in T12). An additional filter for high soil moisture gradients exceeding 10% / 0.25° is applied especially to exclude unrealistic gradients around water bodies.

From the resulting total 1220 data days only 50-60% contain SM information due to satellite revision times. Over a given longitude per day the number of overpasses below 40°N do not exceed one with occasionally daily or every third day sampling (Fig.1 in Njoku and Jackson, 2003). The latter significantly reduces the size of the collected precipitation event sample, and affects the statistical significance of our results.

The AMSR-E instrument is chosen because of the relatively long measurement period and better performance over sparsely vegetated and deserted areas, in comparison to ASCAT (Dorigo et al., 2010). The AMSR-E product also proved to be accurate on the precipitation event scale, indicating a good agreement with the in-situ data over Sahelian Mali site in capturing rain-related soil moisture variability and timing (Gruhier and Rosnay, 2008).

2.2.2 TMPA-v7 precipitation

3-hourly precipitation time-series of the TMPA product (1998-2015, Huffman et al., 2007) at 0.25° horizontal resolution are used to estimate locations of afternoon convective precipitation events in the study.

The Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) represents a partial-global coverage (50°S - 50°N) product of combined precipitation estimates.The TMPA algorithm includes the following steps: (1) - merging multiple independent passive microwave sensors, (2) - their intercalibration to the TRMM Combined Instrument (TCI) precipitation estimates, (3) - further blending with preliminary calibrated infra-red products from geostationary satellites, and finally (3) scaling of the estimates to match monthly accumulated Global Precipitation Climatology Center (GPCC) rain gauge data. The detailed algorithm is provided by Huffman et al. (2007).

In this study we utilize the product version 7 (TRMM-3B42), which includes several modifications to the algorithm and additional satellite data (Huffman and Bolvin, 2014). Consistently with the soil moisture record, only 10 years (2002-2011) of JJAS precipitation data is used. To imply similar solar forcing on the surface and boundary layer, the 3-hr precipitation time-series for the present application are adjusted to LST (based on longitude) by taking the closest 3-hr UTC time step. It is important to note that any 3-hr TMPA value is not referred directly to its nominal hour, but represents the average of the "best" overpass data within 3 hourly window, centred around the nominal hour, i.e. +/- 90 min range. Variable time of the TMPA "best" data average and difference associated to the adjusted LST range are not expected to significantly affect our SMPC results.

Chapter 3

Description of probability-based statistical framework

3.1 Introduction

In this chapter the statistical framework of T12, which is used to link the probability of afternoon rainfall occurrence to the preceding soil moisture conditions, is introduced. The following sections present the three main steps of the method, i.e. the definition of a convective rainfall event (Sec. 3.2.1), the choice of the soil moisture parameter, and construction of the event and control samples (Sec. 3.2.2), and a definition of a coupling measure (Sec.3.2.3).

3.2 Modified method of Taylor et al. 2012

The soil moisture - precipitation coupling (SMPC) in this study is referred to as the relationship between the afternoon convective rainfall and preceding soil moisture conditions. Using the method of T12, it is examined whether afternoon rainfall is more likely on days when soils are (i) - untypically drier or wetter than their surrounding, and (ii) - untypically drier or wetter than their temporal mean. Accordingly, the higher probability of convective rainfall events to occur over spatially drier or wetter soils is referred to as *spatial SMPC*, while the higher likelihood of convective rainfall events to occur over temporally wetter or drier soils quantifies *temporal SMPC* relationship. The following paragraph describes criteria which are used to define a convective precipitation event, and aggregate antecedent to every event soil moisture statistics. The framework algorithm implemented in this study is summarized in Fig. 3.1.

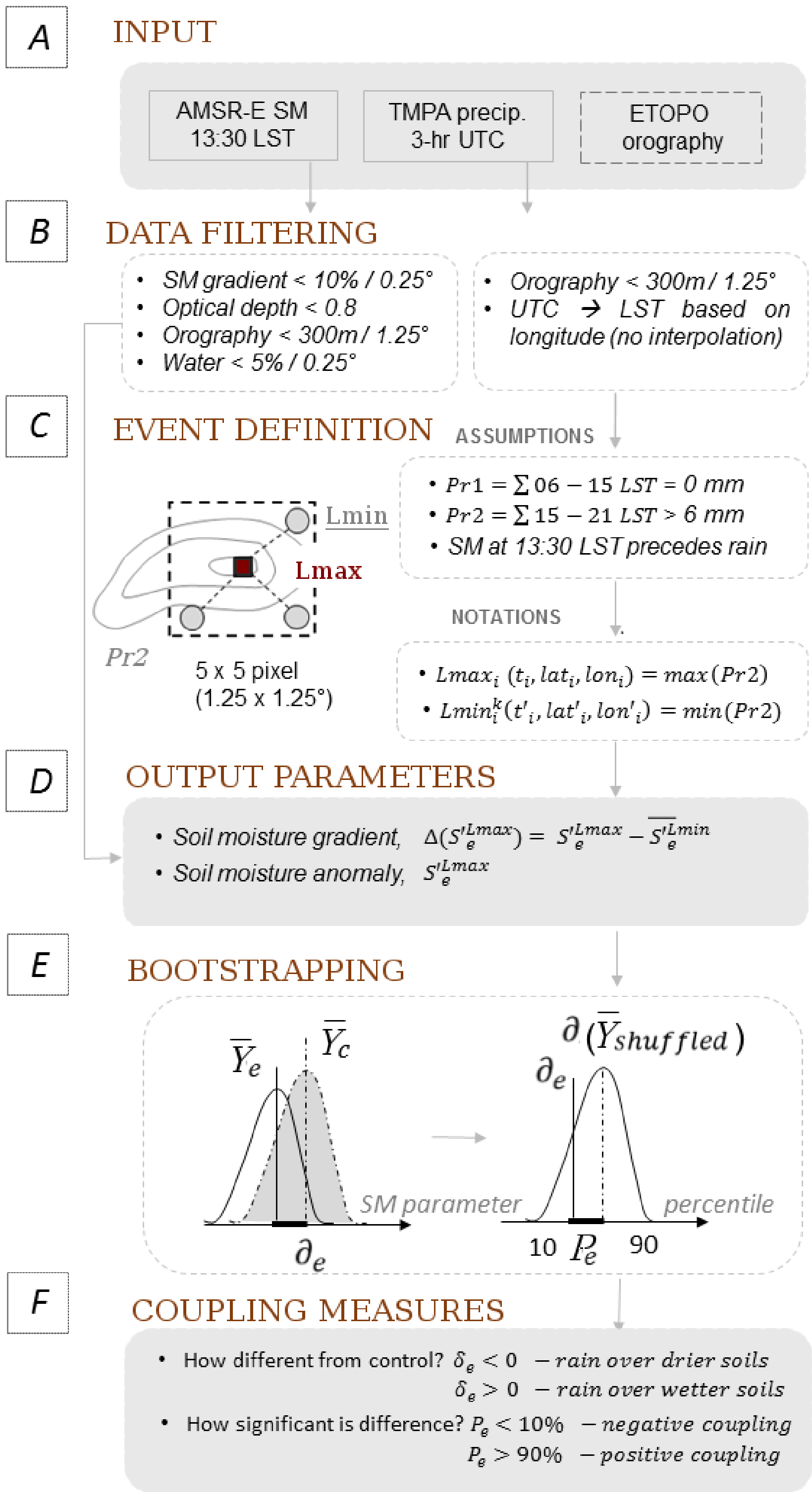


Figure 3.1: Data post-processing and statistical framework protocol implemented in the study.

3.2.1 Definition of convective rainfall event (Fig.3.1C)

A convective event location (*Lmax*) is defined as the location, where maximum accumulated afternoon precipitation between 15-21:00 LST exceeds a threshold of 6 mm. Then, locations of afternoon accumulated precipitation minima or zero (*Lmin*) are identified within a 5 × 5 pixel box (1.25° × 1.25°)[1] centred at *Lmax* (Fig.3.1C). The choice of the later than in T12 accumulation time (i.e. 15-21:00 LST instead of 12-21:00 LST) allows ensuring that the soil moisture measurement at 13:30 LST precedes precipitation without introducing additional filters. According to the complementary sensitivity tests, the twice larger than in T12 afternoon accumulated rainfall threshold does not qualitatively affect the SMPC results (not shown).

The following set of assumptions is used to improve the accuracy of the convective event sample:

(1) - accumulated precipitation in the preceding hours (6-15:00 LST) in the entire 1.25° box must be zero;

(2) - elevation height difference within the event box must not exceed 300 m. The latter is done to minimize the effect of orographic uplifting on the rainfall variability. The resulting distribution of the orography mask is shown in Fig. 3.2a.

(3) - number of *Lmin* locations within one box must be 3 or more (for averaging reasons), and an expressed rainfall gradient in all directions from *Lmax* must be present. The latter conditions were not considered in T12 and G15 methods, and allowed us to reduce erroneous event cases identified within or at the edge of propagating squall lines or large organized convective systems.

(4) - if boxes overlap, the event with larger afternoon accumulated maximum is retained.

3.2.2 Soil moisture statistics in event locations (Fig.3.1D-E)

Once events are identified, soil moisture anomaly S' measured prior to the precipitation event (i.e. at 13:30 LST) at *Lmax*, $\overline{Lmin}$ or any combination of the two can be stored and analyzed. $\overline{Lmin}$ is referred to the parameter average over *Lmin* locations of the single 1.25° event box. S' has its climatological mean subtracted, calculated as a departure from the ± 10 day mean over 10 years. To exclude contribution of a rain event onto the anomaly values, the year of the event is excluded from the climatological mean calculation. In order to investigate, whether it rains over spatially wetter or drier soils the pre-event soil moisture gradient is calculated between *Lmax* and $\overline{Lmin}$ scaled per 100 m, i.e. $Y_e = \Delta(S_e'^{Lmax})$, where Δ - stands for gradient (Fig.3.1D).

[1]Following T12, box size of 1.25° is selected as minimum possible size to resolve soil moisture variability around the center of the box, taking into account 50 km footprint of the AMSR-E soil moisture.

To estimate, whether it rains over temporally wetter or drier soils the pre-event soil moisture anomaly at $Lmax$ location is stored, i.e. $Y_e = S_e'^{Lmax}$.

For every of the two Y_e parameters the control sample Y_c is defined and is represented by an array of corresponding Y values measured in the same $Lmax$ and $Lmin$ event locations in the same calender month, but on the non-event years. The measure of coupling then is quantified by the magnitude of a difference between mean statistics of the event and control samples, $\delta_e = mean(Y_e) - mean(Y_c)$, and the measure of δ_e significance (Fig.3.1E). Significance is represented by a percentile, P_e, of the observed δ_e in a bootstrapped sample of δ values that is observed by chance. For that Y_e and Y_c are pooled together and re-sampled without replacement 5000 times.

3.2.3 Definition of temporal and spatial SMPC (Fig.3.1F)

Parameters of δ_e and P_e calculated for the soil moisture gradients $\Delta(S_e'^{Lmax})$ prior to the event indicate likelihood of rain to occur over soils drier ($\delta_e < 0$, $P_e \leq 10\%$) or wetter ($\delta_e > 0$, $P_e \geq 90\%$) than its 1.25° environment, and are referred to as a negative or positive *spatial SMPC* respectively. Same parameters estimated for the temporal soil moisture anomaly $S_e'^{Lmax}$ instead specify the probability of rain to occur over soils drier or wetter than its temporal mean, i.e. negative or positive *temporal SMPC* accordingly.

In this study, estimation of δ_e and its significance P_e for the spatial and temporal coupling is realized over 5° × 5°, 2.5° × 2.5° and 1° × 1° boxes. Aggregation of event statistics over smaller boxes, than used in the global studies of T12 and G15, allows to reduce the influence of meridional gradient in the parameter statistics, i.e. to make the spread in underlying surface and atmospheric moisture conditions across the box latitudes smaller (Section 5.2.2). The latter is crucial for interpretation of obtained statistics in terms of land cover and atmospheric state. Hence, most of the study focuses on the smallest 1° spatial grid.

3.3 Statistics of convective events

Application of the algorithm to the 10 years of JJAS AMSR-E soil moisture and TMPA precipitation time-series yields 10131 afternoon rainfall events.

The distribution of identified events over the domain at 1° and 5° grid is presented in Figure 3.2b and 3.2c respectively. Signature of orography and large-scale dynamic effects on event occurrence becomes evident only at the higher event-aggregation scale, thus giving an advantage to the highest horizontal resolution. From the Figure 3.2b it is seen that the highest event occurrence is enclosed between 10°N and 18°N, and is almost zonally distributed. Two maxima are found over the central Sahel, covering the area between 10°W - 15°E - aligned with the mean position of the AEJ core (Figure 2.1b). Another two maxima are evident at about 22°E and 30°E, and are likely formed as a combination of orography-induced propagating convective systems and the orography mask applied in this study. The obtained distribution at 1° grid is consistent with the observed one of intense meso-convective systems (MCS, Mathon and Laurent, 2001) over the region.

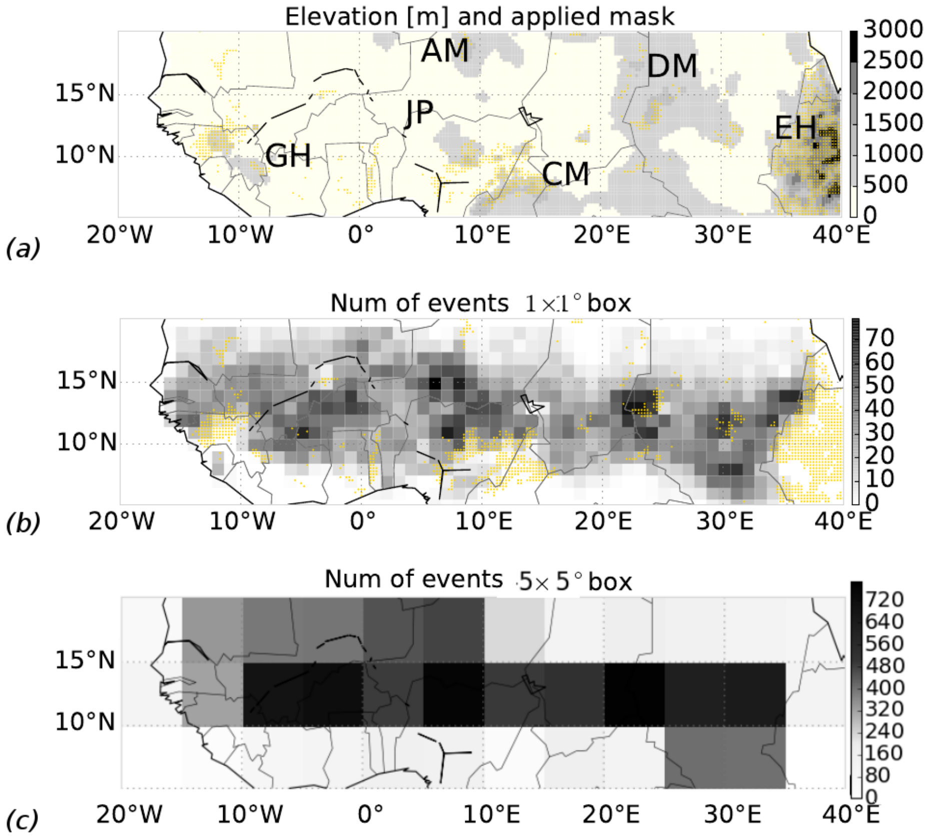


Figure 3.2: (a) - Elevation map based on 1 Arc-Minute Global Relief Model data ETOPO1 (Amante and Eakins, 2009) (grey shading) and orography mask used in the study (golden shading). The mask is applied when height difference exceeds 300 m in a 1.25 × 1.25° box. Main orographic features of the region are: AM - Air Mountains, DM - Darfur Mountains, EH - Ethiopian Highlands, CM - Cameroon Mountains, JF - Jos Plateau, GH - Guinea Highlands. (b) - Number of events in every 1° box (gray shading) bounded by orography mask (golden shading). (c) - Number of events in every 5° box (gray shading).

Chapter 4

Evaluation of the method of Taylor et al., 2012.

4.1 Introduction

Identification of the relationship between the land surface state and precipitation is notoriously difficult to obtain, because of the complex balance of many coupled processes involved across a range of spatial and temporal scales. The contribution of dominant variability factors like SST[1] for Western and Central Africa (Biasutti et al., 2008), soil moisture memory, rainfall variability and persistence (Wei et al., 2008), and the effect of precipitation on soil moisture itself (Guo et al., 2006) additionally complicates an evaluation of the coupling relationship and its strength. In this respect, studies based on regression-, correlation- and covariance- techniques, and also those accounting for a lag between soil moisture anomaly and precipitation, have been largely criticized (Salvucci et al., 2002; Orlowsky and Seneviratne, 2010) because they may report a false strong coupling relation due to the influence of any of the external factors cited above.

Alternative methods use probability statistics. These approaches also introduce a time shift between the precipitation event, and a land surface parameter, e.g. soil moisture, evapotranspiration or temperature (Findell et al., 2011; Taylor et al., 2012; Guillod et al., 2014). In the case of the event probability analyses, the temporal shift allows to isolate parameter forcing on subsequent rainfall. The latter, however, does not necesserely eliminate the causality problem, inherent to all the co-variance - based methods. In this respect, persistence of precipitation might still be an issue for all of the above techniques, and should be taken into account in future analyses.

In this study we reproduce and test the probability-based method suggested by Taylor et al. (2012). Recently introduced, this statistical approach allows for a direct evalua-

[1] sea surface temperature

tion of the soil moisture effects on precipitation, is simple in use, and is a straightforward framework for the rapidly advancing long-term satellite data records, and model evaluation. However, interpretation of the statistical relationships presented in the study of T12 and the follow on study of G15 at 5° scale in scope of underlying physical processes remains subtle. Prior to analysing contribution of the physical processes onto the method statistics (Chapter 5), an evaluation of the method is required.

In accordance to that, analysis of the limitations and advantages of the T12 methodology is carried out. Results of this analyses are discussed in the following sections 4.2-4.3. Specifically, a series of sensitivity tests are performed to answer two major questions:

(i) - Is the original set up of the method suggested by T12 optimal for its purposes, and

(ii) - how robust is the SMPC relationship identified over the North African domain?

4.2 Spatial SMPC over North Africa at 5° horizontal resolution

The soil moisture - precipitation coupling relationship and its robustness are estimated at the original 5° spatial resolution for the sake of consistency to the previous studies of T12 and G15. The distribution of convective precipitation events in every 5° box available for the analysis is presented in Fig. 3.2c.

Accumulated statistics of spatial soil moisture gradients $\Delta S_e'^{Lmax}$ preceding convective rainfall events, and averaged over the whole domain is presented by the red-colored histogram in Fig. 4.1. The gray binned histogram represents the control (i.e. typical) sample of soil moisture gradients accumulated in the same event locations in the same months but on non-event years. From the main Figure 4.1 and the two inset plots it is seen that events show systematically higher than typical occurrence frequency over the negative soil moisture gradients. On the contrary, the number of events is lower than typical over the positive $\Delta S_e'^{Lmax}$ tale. As seen from the Table 4.1 (JJAS case), this shift of the event distribution to the left relative to the control is reflected in the negative difference between the event and control sample means, i.e. the coupling parameter δ_e, and a stronger negative skewness of -2.6 of the event distribution compared to the -0.4 of the control. The corresponding shifts in the mean, skewness and kurtosis values between the event and control distributions, as estimated over the whole domain, are statistically significant at the 99.9% level (Table 4.1 (JJAS case)). All the above suggests, that the afternoon rainfall events indicate significantly higher than usual probability over negative soil moisture gradients, and therefore occur more often than expected over spatially drier soils.

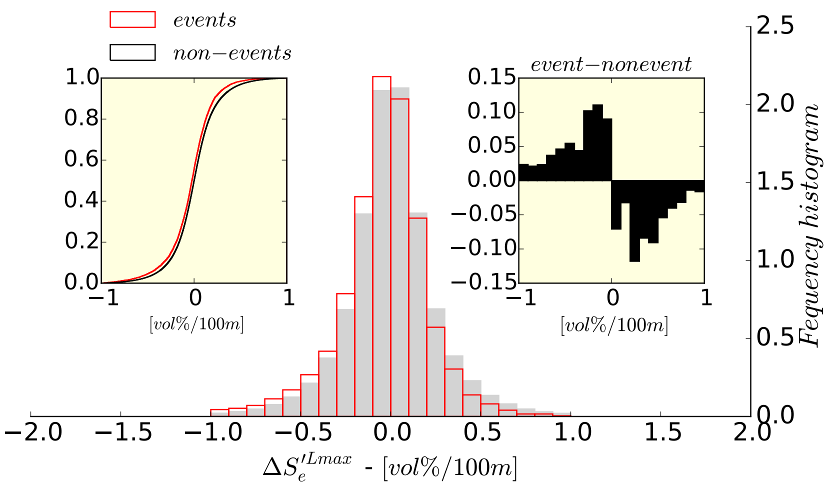


Figure 4.1: Frequency histogram of soil moisture gradients $\Delta S^{\prime Lmax}$ in event (red) and control (gray) samples. Inset plots illustrate cumulative distribution of the $\Delta S^{\prime Lmax}$ event and control samples (left) and the bin-wise difference between the two histograms of the event and control samples (right).

Table 4.1: Estimated total number of events, percentage of events lying within the lower quartile of the soil moisture gradients in the control sample, and the differences in the first four moments, i.e. mean, variance, skewness and kurtosis between event and control samples averaged over the whole domain. Significance of the difference is given in (%) in brakets, and is estimated from 1000 bootstraps with no replacement.

	$\#events$	$\#events, [\%] \leq P_{25}^{NonEv}$	$\Delta mean, \delta_e$	Δvar	$\Delta skew$	$\Delta kurtosis$
JJAS	10130	30.7	-0.07 (99.9)	0.04 (99.9)	-2.2 (99.9)	5.4 (95)
June	2147	29.5	-0.06 (99.9)	0.02 (99.3)	-1.7 (98.5)	3.5 (87)
July	**3045**	30.0	-0.07 (99.9)	0.03 (99.9)	**-2.5 (99.9)**	**10 (99)**
August	2741	31.5	-0.07 (99.9)	0.02 (99.9)	-1.8 (99.8)	1.1 (79)
September	2197	**31.6**	**-0.09 (99.9)**	**0.08 (99.9)**	-2.2 (99.6)	2.3 (80)

The signal of the negative SMPC is evident throughout the whole monsoon season. The strongest δ_e shift and the largest percentage of events within the lower quartile of soil moisture gradients in the control sample is observed in September, while the weakest differences to the typical state are identified in June (Table 4.1). The former is consistent with the evidence of the relatively strong soil moisture - convection initiation coupling in September identified by Taylor et al. (2011a). However, the weakest SMPC signal in June is opposite to what Taylor et al. (2011a) found for Western Africa. In their study August was identified as the month of the weakest coupling signal. The latter finding would be consistent with the typically less favourable conditions for strong surface influence on convection during the wettest monsoon period, i.e. July-August. The differences to the findings of Taylor et al. (2011a) arise from the inclusion of the higher latitudes in the present study. For the dry latitudes moist convection onset occurs during the wettest months of July and August, increasing the potential of coupling to the land surface. Despite the observed discrepancies, all four months indicate a significant (at the 99.9% level) shift from the typical state towards negative $\Delta S_e^{\prime Lmax}$ values, and hence support the relevance of negative SMPC throughout the whole monsoon period. The identified contradictions to the previous study call for a more detailed and accurate analysis on the effect of the monsoon dynamics on the SMPC, which should involve longer time-series of data, as well as additional information on the time of the monsoon onset and geo-location.

Taking into account this generally strong difference in soil moisture and precipitation dynamics between the wetter southern latitudes and the dry north, the regional variability of the SMPC relationship is also expected to vary. The regions of the domain where afternoon precipitation is observed more frequently than expected over spatially drier soils, based on the analysis of δ_e are shown in Figure 4.2a. The darkest colors indicate that estimated difference δ_e to the typical conditions (Fig. 4.2b) is significant at the 99% level, and a negative SMPC is observed. Larger percentage of the percentile values P_e less than 10% are found in the South, where variability of soil moisture in time and space is generally higher. In total, 72% of the 5° boxes have $P_e < 10\%$. At this horizontal scale no significant positive δ_e, and therefore positive SMPC is identified.

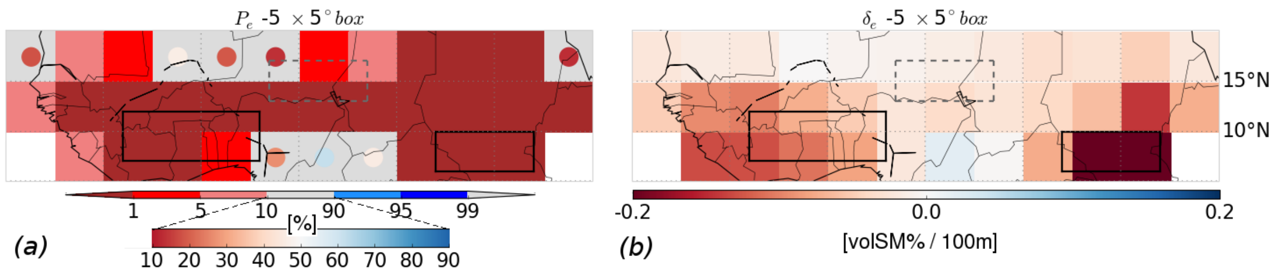


Figure 4.2: Distribution of percentiles, P_e (a) of the observed δ_e difference (b), estimated over the 5 × 5° boxes. Percentiles <10% indicate significant negative SMPC, i.e rain over spatially drier soils, and percentiles >90% - significant positive SMPC, i.e. rain over spatially wetter soils. The percentile values lying outside the significance range (10-90 %) are illustrated by circles. Black and grey rectangles on the maps indicate featured domains selected for an in-depth analysis in the following sections.

4.3 Robustness of the spatial SMPC relationship. Sensitivity tests.

Robustness of the identified SMPC relationship inter alia depends on the assumptions introduced by the method, and used to isolate effects of soil moisture on precipitation. The following sections discuss the sensitivity of the SMPC measure δ_e and its significance to the choice of selected parameters and assumptions. Specifically, selection strategy of *Lmin* locations surrounding an event (Section 4.3.1), averaging of the soil moisture gradients in event locations (Section 4.3.2) and the choice of precipitation threshold value (Section 4.3.3) are analyzed. Based on this analysis, a summary of inherent limitations and advantages of the applied method is provided in Section 4.4.

4.3.1 Selection of *Lmin* locations surrounding an event

In the current methodology, the spatial gradient in soil moisture prior to the rainfall event $\Delta S_e'^{Lmax}$ is calculated as the mean difference between the locations of a succeeding accumulated precipitation maximum - *Lmax* and surrounding minima - *Lmin*. This assumption, inter alia, takes into account the spatial distribution of the accumulated rainfall. However, it remains unclear whether the magnitude of the gradient and the resulting SMPC is sensitive to the choice of *Lmin* locations. Recent observational studies provided an evidence that moist convection tends to form or develop towards drier soil patch, altering common propagation direction around wetter area, or simply "avoiding" wetter soils (Taylor and Ellis, 2006; Taylor, 2010). Following this evidence, our starting hypotheses would be:

H1: that the locations of the succeeding rainfall minima are the wettest pixels in the event surrounding, consideration of which leads to a higher probability to observe a negative spatial soil moisture gradient relative to *Lmax* within the considered event box, and

H2: that this sensitivity of the gradient to the choice of *Lmin* locations significantly affects the magnitude of the SMPC.

To test the hypotheses we set up three experiments:

• two opposing ones, i.e.

(i) - where *Lmin* locations are defined as the locations of the accumulated afternoon precipitation minima: *min*, and

(ii) - where *Lmin* pixels are represented by all the locations excluding those of precipitation minima: *nonmin*,

• and a complimentary one,

(iii) - where all surrounding the event locations are considered as *Lmin*: *allmin*.

The resulting differences in the SMPC statistics between the experiments are discussed based on the frequency histograms and spatial maps presented in Fig. 4.3 and 4.4 accordingly.

Comparison of the frequency histograms built on the accumulated soil moisture gradient statistics over the whole domain indicates a consistent increase in the frequency of rainfall events over the negative soil moisture gradients $\Delta S_e'^{Lmax}$ and a decrease - over the positive ones in the *min*-experiment compared to the *nonmin*-case (Fig. 4.3a, solid line). The strongest increase is observed over the relatively modest gradients of -0.1 vol%/100m. A weaker secondary maximum can be seen over the less frequent and strong negative $\Delta S'^{Lmax}$ of about -0.6 vol%/100m. The differences in the event sample means and variances between the two experiments is significant at the 99.9% level. These findings suggest that negative soil moisture gradients between *Lmax* and *Lmin* locations are more likely to be observed prior to the rainfall event when the *Lmin* locations are represented by accumulated rainfall minima, than by any other (e.g. nonmin) location surrounding the event. This observation is consistent with the first hypothesis H1, and furthermore supports the idea of rainfall "avoiding" wetter soils.

The higher probability of negative soil moisture gradients in the *min* experiment, as a consequence, leads to a stronger difference between the pre-event $\Delta S_e'^{Lmax}$ statistics and its typical (control) state (Fig. 4.3c). The *min*-experiment results in an almost twice larger δ_e difference of -0.07 compared to the -0.04 of the *nonmin* case (Table 4.2). Both differences are significant at the 99.9% level. The difference in amount of the strong negative $\Delta S_e'^{Lmax}$ between the event and control samples is also larger in the *min* experiment. This is evident in the higher number of events lying within the lower quartile of $\Delta S_e'^{Lmax}$ in the control sample and a higher difference in the negative skewness between the event and control samples in the *min*-experiment compared to the *nonmin* case (Table 4.2). All the above suggests that the soil moisture gradients estimated for the *nonmin* locations lead to a smaller δ_e difference to the typical state (Fig 4.3c), and therefore a weaker signal of the negative SMPC. The latter statement is consistent with the second initial hypothesis H2.

The complementary *allmin* experiment represents an average case between the *min* and *nonmin* realizations, as it includes all the locations of both experiments. It is therefore not discussed in detail (Fig. 4.3, Table 4.2). The differences in the control samples between the experiments are largely concentrated around the small gradients, and do not reflect clear preference for a negative or a positive shift (Fig. 4.3b). Hence, the differences between the event sample statistics should be considered as decisive for the resulting magnitude of the SMPC in all the experiments.

The effect of *Lmin* location selection on the regional differences in the SMPC parameter δ_e and its significance are illustrated in Fig. 4.4. The *nonmin* experiment leads to a reduction in percentage of the boxes with significant negative δ_e by 28%, i.e. from 72% in the *min* experiment to 44% in the *nonmin* case (Fig. 4.4a-b). The decrease in δ_e magnitude from the *min* to the *nonmin* experiment is observed in 78% of the grid boxes, among which 39% are found to be statistically significant (Fig. 4.4c). The largest differences between the two experiments occur in the South-West and the East of the domain.

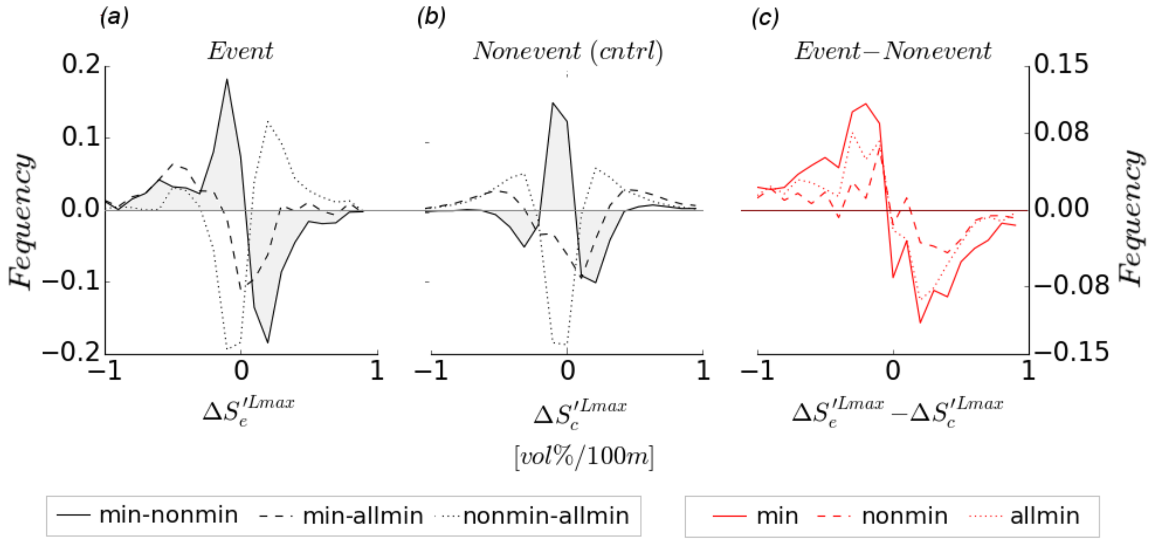


Figure 4.3: The difference between the histograms of soil moisture gradient (a) - event and (b) - control samples of every experiment, and (c) - the bin-wise difference histogram between event and control samples for each of the three experiments. The soil moisture gradients of the complete domain are considered in this analysis. The histograms are binned with the resolution of 0.1 vol%/100m.

Table 4.2: Estimated for three experiments: the total number of events, percentage of events lying within the lower quartile of the soil moisture gradients in the control sample, and the differences in the first two moments, i.e. mean and variance between the event and corresponding to it control samples averaged over the whole domain. Significance of the difference is given in (%) in brakets, and is estimated from 1000 bootstraps with no replacement.

Experiment	*#events*	*#events*, [%] $\leq P_{25}^{NonEv}$	$\Delta mean, \delta_e$	$\Delta skew$
min	10130	**30.7**	**-0.07 (99.9)**	**-2.2** (99.9)
nonmin	13646	26.8	-0.04 (99.9)	-1.6 (99.9)
allmin	14643	28.7	-0.05 (99.9)	-1.8 (99.9)

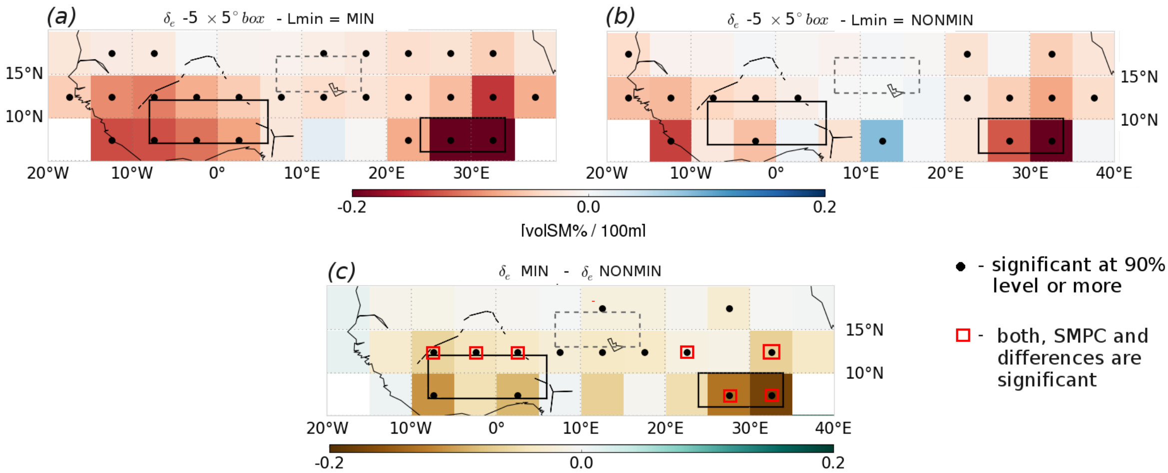


Figure 4.4: Distribution of the observed δ_e difference and its significance (black dot) for (a) - the *min* and (b) - *nonmin* experiments, and (c) - the difference between the two δ_e, estimated over 5 × 5° boxes. Significant δ_e value or the difference between the two δ_e are indicated by a black dot. Here, a significant threshold of at least 90% is chosen.

Consistency to physical mechanisms

The identified sensitivity of the soil moisture gradients and the SMPC relationship to the choice of the *Lmin* locations suggests the relevance of the underlying spatial variability in soil moisture for the moist convection development, and thereby reconciles a number of physical processes that might play a role.

One of the mechanisms that would support deepening of moist convection over a drier soil and on the contrary its suppression over a wetter patch could be related to the effect of local breeze-like circulations on convection initiation (Taylor et al., 2007, 2011a; Lothon and Campistron, 2011; Birch et al., 2013). These circulations occur as a result of the strong spatial differences in sensible heat flux formed by the spatial gradient in soil moisture. The updraughts of such circulations are the strongest over the driest area with high sensible heat flux, and hence may effectively bring the moist air up from the wetter surrounding, and serve as a focus for convection intensification. The downdraughts, on the contrary, would occur over the wetter regions, mixing drier air down and hence creating potentially unfavourable conditions for convection development, or its suppression. An observational evidence of such circulations formed over the strong soil moisture gradients was provided e.g. by Taylor et al. (2007). Effect of the circulations on the convection initiation and rainfall was studied e.g. by Taylor et al. (2011a); Garcia-Carreras et al. (2011); Froidevaux et al. (2013).

Another potential mechanism might be related to the intensification of propagating moist convection over drier soils through the interaction of the system growing cold pool with the underlying surface conditions. The boundary layer (BL) overlying the dry patch is expected to be drier than the surrounding, and therefore create a region of higher atmospheric water demand. Under these BL conditions, deepening of the growing cold pool by evaporative cooling might be facilitated, and further lead to a rainfall intensification and/ or moist convection propagation towards drier soils (McCaul and Cohen, 2002; Gentine et al., 2016). Till now only few studies addressed this question, and no ultimate agreement yet exists. A modelling evidence of the cold pool intensification under less vegetated land surface conditions was presented by Lauwaet and van Lipzig (2010). However, Clark et al. (2003) argued that the response time of the cold pool deepening is too long with respect to the propagation speed of the system and spatial scale of injected moisture anomaly. Studies on that topic are therefore highly required.

In summary, the results of the sensitivity test performed here indicate that consideration of the accumulated rainfall shape (i.e. its distribution in space) has a well-defined effect on the magnitude and sign of the underlying soil moisture gradient as estimated over 10000 storms, and hence hints on the relevance of the spatial variability of soil moisture on moist convection development. From the methodological perspective, selection of *Lmin* locations as locations of rainfall minima maximizes the likelihood of negative soil moisture gradient and hence increases significance of the negative SMPC signal regionally and over the whole domain.

4.3.2 Effect of averaging on the spatial SMPC statistics

The global application of the T12 and G15 analyses required averaging of the soil moisture gradients in order to reduce the computational costs. Storage of all the gradients, however, can be considered as being more "fair" compared to averaging. The soil moisture gradients in the event surrounding are often composed of both, positive and negative gradient values. Hence, the averaging may lead to a reduction in the number of strong negative and especially positive gradients in the $\Delta S_e'^{Lmax}$ statistics, and increase the frequency of the small gradient values around zero. Presence of extreme negative gradients in the pre-event soil moisture statistics could also result in a larger than expected negative shift relative to the typical state, when averaging is introduced. As the result an overestimation of the negative SMPC signal might be expected. In order to test whether the averaging effect has a significant impact on the resulting SMPC statistics, the coupling parameter δ_e and its significance are estimated as in the previous sections but this time retaining all soil moisture gradients around the event and non-event (control) locations. The experiment is referred to as $min-noaver$. The resulting coupling statistics is compared against the initial SMPC estimates of the original $min - aver$ set up.

Comparison of the accumulated over the whole domain $\Delta S_e'^{Lmax}$ statistics between the $min - aver$ and $min - noaver$ realizations is illustrated in Figure 4.5. Figure 4.5a illustrates that the averaging of the gradients, as expected, leads to a reduced contribution of the strong negative and to a larger extend positive $\Delta S_e'^{Lmax}$, and on the contrary, an overestimation of small $\Delta S_e'^{Lmax}$ in both, event and control samples. Despite the dissimilarities, the differences between the distributions are found to be statistically not significant. The identified significance levels of the difference in the mean parameter between the experiments is found to be less than 90% for both, the event and control samples. The effect of no-averaging on the extreme gradients is also found to be small. The deviation in the lowest decile value of the $\Delta S_e'^{Lmax}$ values between the event samples in the two experiments was identified being less than 0.1 vol%/100m. The latter indicates roughly similar probability of the extreme negative soil moisture gradients in the two realizations.

As the consequence of the above relationships, the difference in the deviations to the typical (control) conditions, i.e. δ_e, between the two experiments is also found to be not significant (56%, 4.5b). The mean regional differences of the δ_e parameter between the $min - noaver$ and the $min - aver$ experiment do not exceed 2% (not shown). All the above suggests, that the averaging of soil moisture gradients around the events does not significantly affect the difference in the pre-event soil moisture conditions to the typical state, and therefore the estimated SMPC. The accumulation of all the gradients, however, results in 10 times larger size of the soil moisture gradient event sample, and hence allows to obtain more accurate estimates of the distribution parameters and its significance.

To summarize the effects of all the considered experiment combinations on the SMPC relationship, a δ_e - δ_e plot between the original $min - aver$ set up and all the other experiments is illustrated in Fig 4.5c. The fitted linear regression lines indicate that each of the suggested experiments reduces the difference of the underlying pre-event soil moisture conditions to the typical state. The largest deviations occur in the $nonmin - noaver$ experiment. Especially, the differences are large over the strongest δ_e values, and therefore the wetter southern latitudes. The smallest deviations occur in the $min - noaver$ combination and over the weaker δ_e found in the drier northern regions. The original $min - aver$ combination leads to the largest δ_e, and therefore, can be considered as optimal and the most efficient assumption to maximize the negative SMPC signal regionally and over the whole domain.

Accordingly, further analysis of the physical processes underlying the observed statistical SMPC relationships (Chapter 5) will be carried out using the original T12 set up combination, where the pre-event spatial gradient in soil moisture is estimated between the locations of precipitation maxima and minima, followed by an averaging of the event gradients.

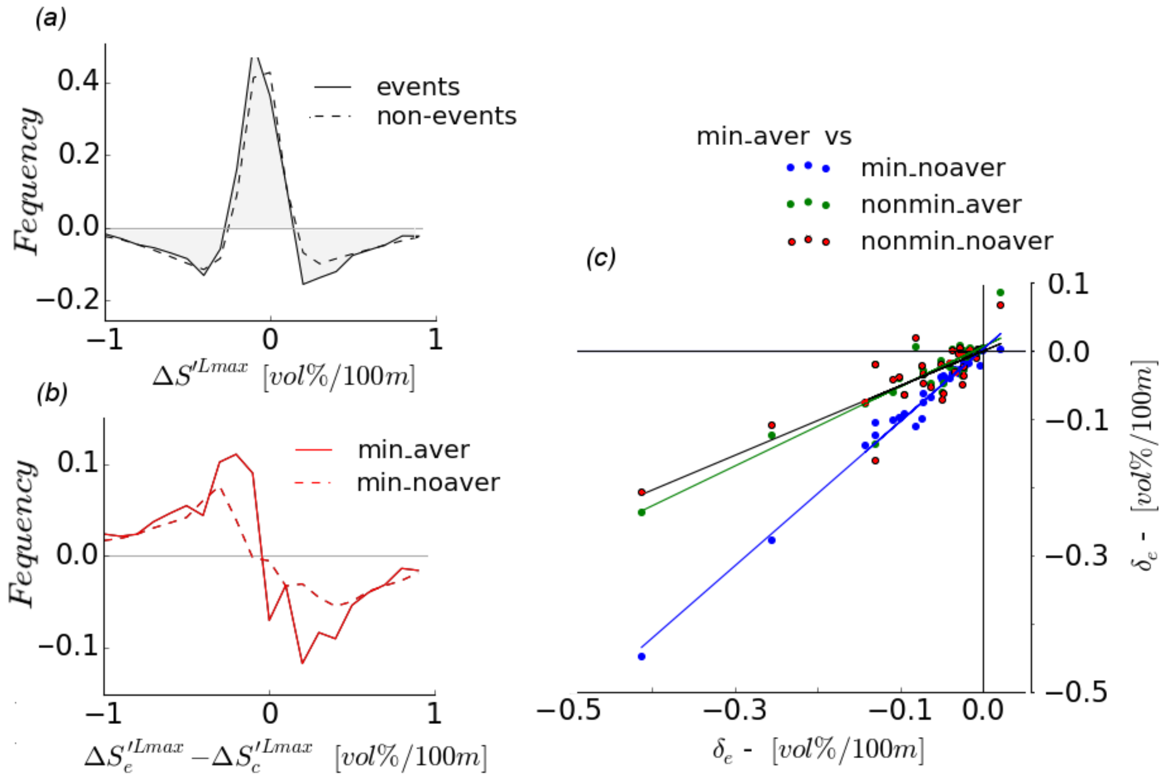


Figure 4.5: (a) - The bin-wise difference histograms of soil moisture gradient event (solid line) and control (dashed line) samples between the $min-aver$ and $min-noaver$ experiments, (b) - the bin-wise difference histogram between event and control samples for each experiment, and (c) - δ_e - δ_e scatter plot with fitted linear regression functions between the original $min-aver$ set up (coincides with the blue line) and all experiment combinations. The δ_e parameter is estimated at the 5° horizontal grid. The histograms are binned with the resolution of 0.1 vol%/100m.

4.3.3 Selection of accumulated afternoon precipitation (AAP) threshold

One of the central constraints on the definition of the convective rainfall events within the current framework is related to the choice of the accumulated afternoon precipitation (AAP) threshold. Following the original T12 method, the selection of the AAP threshold is aimed at maximizing the size of the event sample, and does not carry any physical meaning. Doubling the AAP threshold from 3 mm to 6 mm in T12 did not produce any qualitative differences in the SMPC signal over the globe. The AAP data limited by any of the two thresholds comprise not more than 30% of all possible values. Therefore, a large range of the potential AAP thresholds have not been yet tested, and the effect of the selected value of AAP on the SMPC statistics remains unclear.

The aim of the analysis presented in this section is, therefore, to justify the present selection of the AAP threshold, by investigating:

(i) - the presence of a critical AAP value with respect to the changes in the SMPC signal, and

(ii) - the effect of a positive correlation between the AAP value and the size of the convective system on the SMPC statistics, as an evidence of a link to the physical processes.

For this analysis the original and therefore optimal T12 set up is used, i.e *Lmin* locations are represented by the AAP minima, and the averaging between the soil moisture gradients of an event is applied.

4.3.3-a Critical value of the AAP threshold

To identify the critical AAP value, statistics of the spatial SMPC at the 5° horizontal resolution is re-estimated over the N. African domain using 8 different AAP thresholds: 3, 6, 9, 15, 20, 30, 35 and 50 mm/9hrs. The percentage of data available for calculation at every threshold is presented in Fig.4.6 (inset numbers) and summarized in Table 4.3. From the Figure it is seen that the distribution of all possible[2] AAP values > 1 mm/9hrs follows an exponential function, i.e. the frequency of occurrence and therefore amount of data decreases rapidly with the increase in the magnitude of the AAP. This relationship is not unexpected, and is consistent with the mean characteristics of rainfall produced by MCSs in the West African region (Goyens and Lauwaet, 2011; Mathon and Laurent, 2001; Mathon et al., 2002). Smaller convective systems are known to be less rain-efficient, but more numerous, while more scarce but large organized MCSs are found to yield almost 90% of the annual rainfall (Mathon and Laurent, 2001). Though AAP value does not fully reflect the rainfall efficiency of a convective system, the 50^{th} percentile value of 13 mm/9hrs of the AAP distribution is in range with the identified 14.7 mm average rainfall yield of a MCSs in the West African region (Mathon and Laurent, 2001).

From the methodological perspective, the higher AAP thresholds lead to a decrease in the number of identified convective rainfall events, and as a consequence, smaller number of events in every 5×5° box available for calculation of the SMPC statistics (Table 4.3). At the threshold of 15 mm/9hrs the total number of events and the average event amount in every box reduces to less than one half. At the same AAP threshold the significance of the negative SMPC signal drops. This is expressed by the increase of the mean percentile, P_e, magnitude towards the insignificant range, i.e. from 10 to 90%, and a decrease in amount of significant P_e values (P_e <10%) across the domain (Table 4.3). Accordingly, the most robust and significant negative SMPC signal is observed for the lowest 3, 6 and 9 mm/9hrs thresholds. Interestingly, the mean difference to the typical conditions δ_e, underlying the P_e values, does not vary strongly between the realizations with different thresholds. Hence, it is largely the size

[2] i.e. not constrained by the soil moisture data availability.

of event samples that affects the significance of the δ_e, and therefore magnitude of P_e.

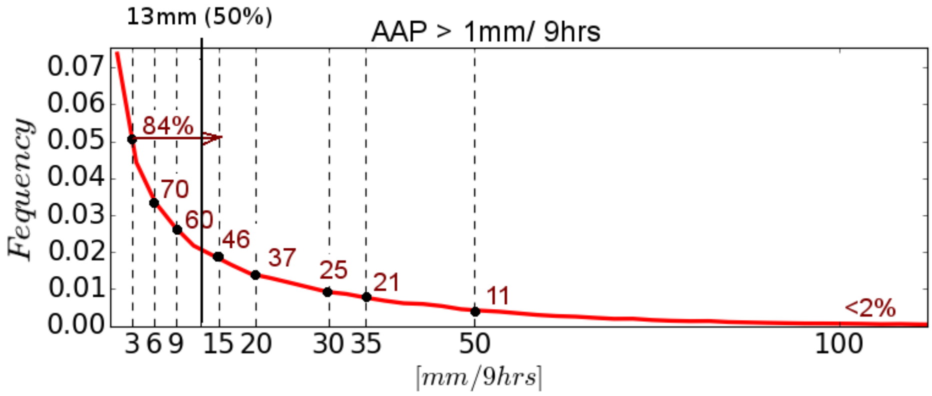


Figure 4.6: Distribution of the accumulated afternoon rainfall values >1mm/9hrs in event locations. To better represent statistics of the accumulated rainfall thresholds, all possible event locations are considered here, i.e. the availability of the soil moisture data is not taken into account. Horizontal axis mark positions of seven thresholds selected for the sensitivity analysis, and corresponding percentage of data lying above the threshold is indicated by the corresponding percentile number on the plot.

Table 4.3: Statistics of identified rainfall events and corresponding SMPC as estimated at (I.) - seven various cumulative afternoon precipitation (AAP) thresholds and (II.) - alternative thresholds considering additionally percentage of box area covered with the AAP > 1mm/9hrs. The *% of total data* here is referred to the percentage of data lying above the selected threshold of the total number of events with afternoon rainfall >1mm, not constrained by the availability of soil moisture data. Value of $\overline{P_e}$ is calculated as an average over the percentiles identified for every 5° box across the domain.

I. AAP Threshold $[mm/9hrs]$	% of total data	# events	# events with common $Lmax$	mean # events in every $5 \times 5°$ box	$\overline{\delta_e}$ over $5 \times 5°$ boxes	$\overline{P_e}$ over $5 \times 5°$ boxes (% of signif. boxes)
3 (T12, G15)	84	12925	10130	393	-0.06	7 (72)
6 (this study)	**70**	**10130**	——	**309**	**-0.07**	**8 (72)**
9	60	8236	8236	250	-0.06	10 (72)
15	46	5851	5851	177	-0.06	15 (53)
20	37	4484	4484	136	-0.05	17 (53)
30	25	2746	2746	84	-0.06	21 (44)
35	21	2191	2191	67	-0.05	24 (36)
50	11	1130	1130	34	-0.05	28 (27)
II. Alternative threshold tests						
AAP area < 50% of 5° box	48	4664		170	-0.07	11 (70)
AAP area > 50% of 5° box	52	5748		138	-0.06	17 (55)
area < 50% & AAP < 25mm	47	4598		136	-0.07	13 (58)
area > 50% & AAP > 25mm	26	2415		72	-0.05	23 (45)

The differences in the spatial variability of P_e across the domain identified for every AAP threshold are summarized in Figure 4.7. Consistently to the changes in the mean domain statistics, the spatial variability of the percentiles notably increases starting from the same 15 mm/9hrs threshold. In all the realizations, however, the same regions of significant negative δ_e values with corresponding P_e <10% remain prominent, i.e. the South-West (7-15°N, 10°W-7°E) and the East (5-13°N, 24-34°E) of the domain (not shown). Further analysis shows that the reason for this robust negative SMPC signal is attributed to the presence of the extreme soil moisture gradients in the event statistics over these areas, resulting in a strong, and therefore, significant difference to the typical state. The detailed analysis on the role of extreme soil moisture gradients in the SMPC statistics is discussed in Sec 5.2.3 of the thesis.

In summary, the effect of the AAP threshold on the SMPC statistics is largely modulated by the size of the resulting rainfall event sample. Within the current set up, a critical AAP value exists, which corresponds approximately to 50% of the total size of the AAP data. The AAP thresholds lying above the critical value lead mainly to the reduction in the amount of 5° grid boxes with significant negative SMPC relationship, but do not change the identified preference of the afternoon rain to occur over spatially drier soils. The SMPC statistics almost does not vary for the thresholds lying below the critical value. The choice of the lowest AAP thresholds, therefore, is an advantage. Equally, the longer time span and more extensive observational data is a benefit. It is important to note, however, that too low threshold values (e.g. ≤1mm/9hrs) may lead to an increase of the false rain detection ratio, and therefore result in a higher uncertainty of rainfall estimates.

Accordingly, the different threshold of 6 mm used in the present study against 3 mm and 4 mm applied in the studies of T12 and G15, respectively, is not expected to cause any qualitative differences in the SMPC results. The choice of the 6 mm threshold in this study was done in favour of the largest identified magnitude of δ_e difference to the typical state (Table 4.3).

4.3.3-b Relationship between AAP and size of a convective rainfall system. Effect on the spatial SMPC statistics

Theoretically, the magnitude of the AAP values might be associated with the areal extent of the convective systems, as the most intense precipitation and stronger rainfall yield is likely to be produced by larger and organized MCSs (Goyens and Lauwaet, 2011). The organization and the size of the MCSs in turn has shown to influence the sensitivity of the convective systems to the underlying surface conditions, revealing the possibility of both, negative and positive signs of the SMPC (Taylor and Lebel, 1998; Clark et al., 2003; Taylor and Ellis, 2006; Taylor, 2010). In this respect, the choice of the AAP threshold in the current framework may allow isolating the effect of surface moisture variability on the intensification of the smaller or larger MCSs. Depending on

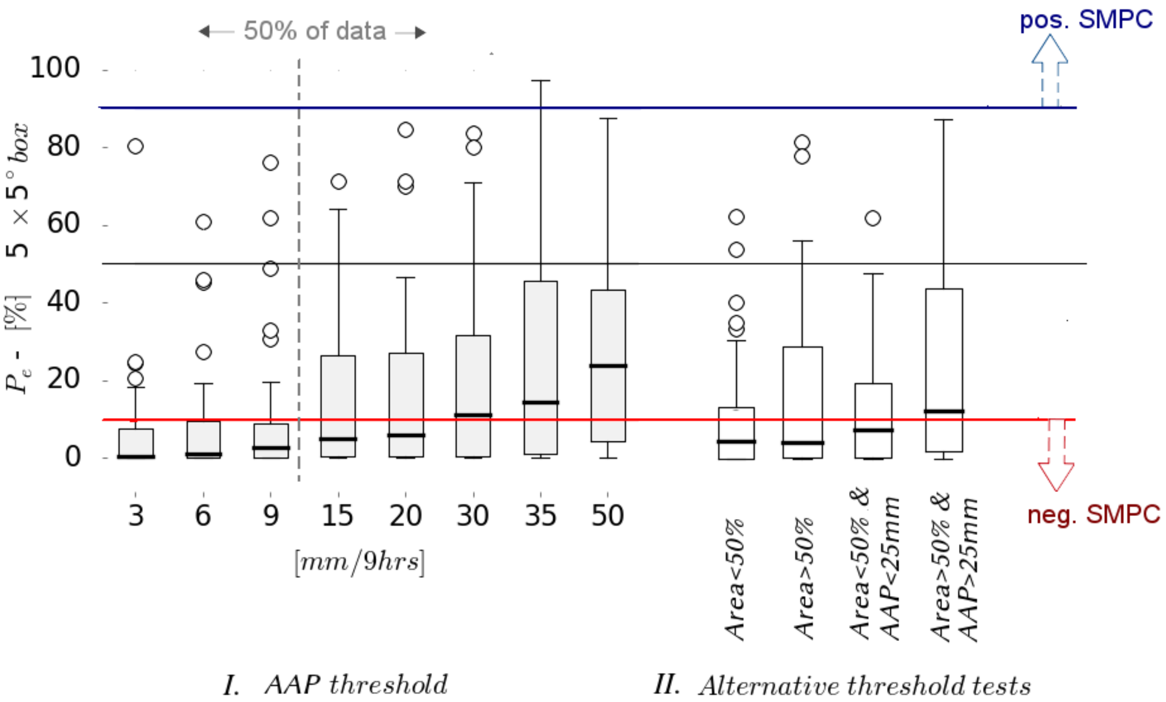


Figure 4.7: Statistics of the domain percentile values P_e at the 5° horizontal grid, obtained using (I.) - different accumulated afternoon precipitation (AAP) thresholds and (II.) - alternative thresholds considering additionally percentage of box area covered with the AAP > 1mm/9hrs. Note, the black thick line indicates median of P_e, and therefore may not coincide with the $\overline{P_e}$ mean value presented in Table 4.3.

the outcome of this analysis, the relevance of a physical relationship for the selection of the AAP threshold may be confirmed or rejected.

To investigate the effect of a positive correlation between the AAP value and the size of the convective system on the SMPC statistics, the relationship between the AAP magnitude and the percentage of the grid box with non-zero AAP is studied first. The percentage of the grid box with AAP>1 mm (henceforth, *area*) is used as an approximation to the size of the MCS involved in the analysis. Examples of rainfall events identified in conjunction with smaller or larger convective systems are given in Figure 4.8.

Assessment of the relationship between the AAP value and its *area* in the complete event sample, i.e. not limited by availability of the soil moisture data, confirms existence of a significant (p<-0.001) and positive correlation between the two parameters (Fig. 4.9a). The correlation is shown to be independent of the box size, and is found to be 0.75, 0.73, 0.69 and 0.65 for 3°, 5°, 7° and 9° box size accordingly. The 9° box is commensurate with the 90^{th} percentile of all possible MCS size values, i.e. 200 000 km^2 (Goyens and Lauwaet, 2011), and therefore should be well suited for capturing the range of possible AAP areas at various AAP thresholds. The identified relationship is in agreement with the positive correlation identified between the MCS cloud coverage and its total precipitation yield by Goyens and Lauwaet (2011), and observed inter alia by Mathon et al. (2002).

Following the identified strong and positive correlation between the AAP magnitude and its area, a new threshold criteria for rainfall event definition might be introduced to isolate small and less intense MCSs from large and more intense convective systems. In accordance with Fig. 4.9b, the following four experiments are set up at the 5×5° horizontal grid resolution:

(i) - the AAP area in the 5° box is less than 50% - *smaller systems*,

(ii) - the AAP area in the 5° box is more than 50% - *larger systems*,

(iii) - the AAP area $<$ 50% and AAP threshold is less than 25 mm/9hrs - *smaller and less intense systems*, and

(iv) - the AAP area $>$ 50% and AAP threshold is more than 25 mm/9hrs - *larger and more intense systems*.

The 25 mm/9hrs threshold is identified as the AAP value corresponding to the *area* of 50% at the 75^{th} percentile line of the event data (Fig. 4.9b, where upper red shading crosses 50% vertical line). The first two experiments are introduced to account for the large scatter of the data lying beyond 25^{th} and 75^{th} percentiles (Fig. 4.9b). The large spread in the relationship between MCS size and rain yield was also noted by Goyens and Lauwaet (2011), and is related to the complexity of MCS evolution processes, including merging, splits and regeneration, and therefore complicates the positive relationship between rainfall and MCS cloud properties. Similarly to the preceding tests, averaged domain statistics of the event sample size, and SMPC relationship for all four experiments is summarized in Table 4.3. The changes in the spatial variability of the SMPC relationship is shown in Figure 4.7.

Selection of the events with the AAP area>50% at any intensity yields the differences in the SMPC statistics that are comparable with the differences induced by the reduction of event sample size only (Table 4.3). The latter, therefore, makes it difficult to judge on the observed changes from the perspective of physical mechanisms. The differences in the realizations involving smaller rainfall systems, however, are more explicit and are independent of the data sample size. Selection of the events with the AAP area<50% at any intensity leads to a slightly stronger δ_e and a notably larger amount of the grid boxes with significant δ_e, i.e. $P_e < 10\%$ (Fig. 4.7). The negative and most significant SMPC relationship is identified in the experiment (i), with the AAP area<50%. Despite halving of the data sample size in this experiment the significant P_e values <10% dominate the domain (Fig. 4.7) resulting in a low mean domain P_e value of 11% - comparable to the average P_e of the experiments with the lowest AAP thresholds. This identified stronger evidence of a negative SMPC for the events with a smaller rainfall areal extent is consistent with the higher sensitivity of the smaller and less organized MCSs to the thermally-induced surface convergence zones and a higher likelihood of these systems to develop over spatially drier soils, adjacent to the strong gradients (e.g, Gantner and Kalthoff, 2010). The choice of events with the smaller AAP area presented in this study, however, does not exclude the possibility of an event being a part of the large and organized MCS, as it still may evolve as a separate (isolated) convective cell (see example in Fig. 4.8, case-V.). The latter, inter alia, hints on the relevance of the horizontal scale of the involved processes on the SMPC rather that organisation of the MCS. In summary, all the above suggests that the stratification of the rainfall events by size might have a larger impact and more physical meaning for the spatial SMPC relationship than thresholding rainfall by its accumulation rate.

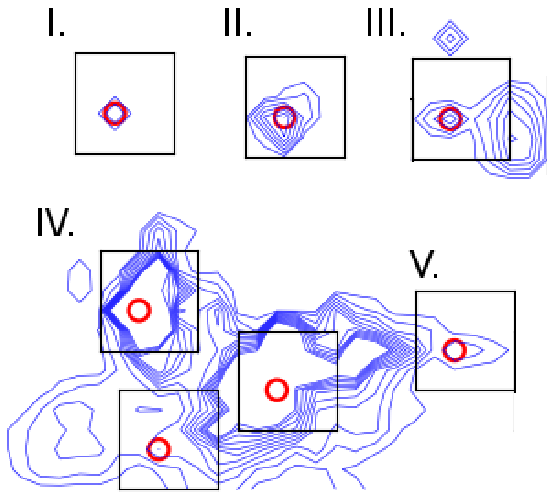


Figure 4.8: Examples of accumulated afternoon precipitation (contours) associated with different rainfall events and size of the convective systems. Black boxes are 5×5° large. Red circles represent locations of AAP maxima, i.e. *Lmax*.

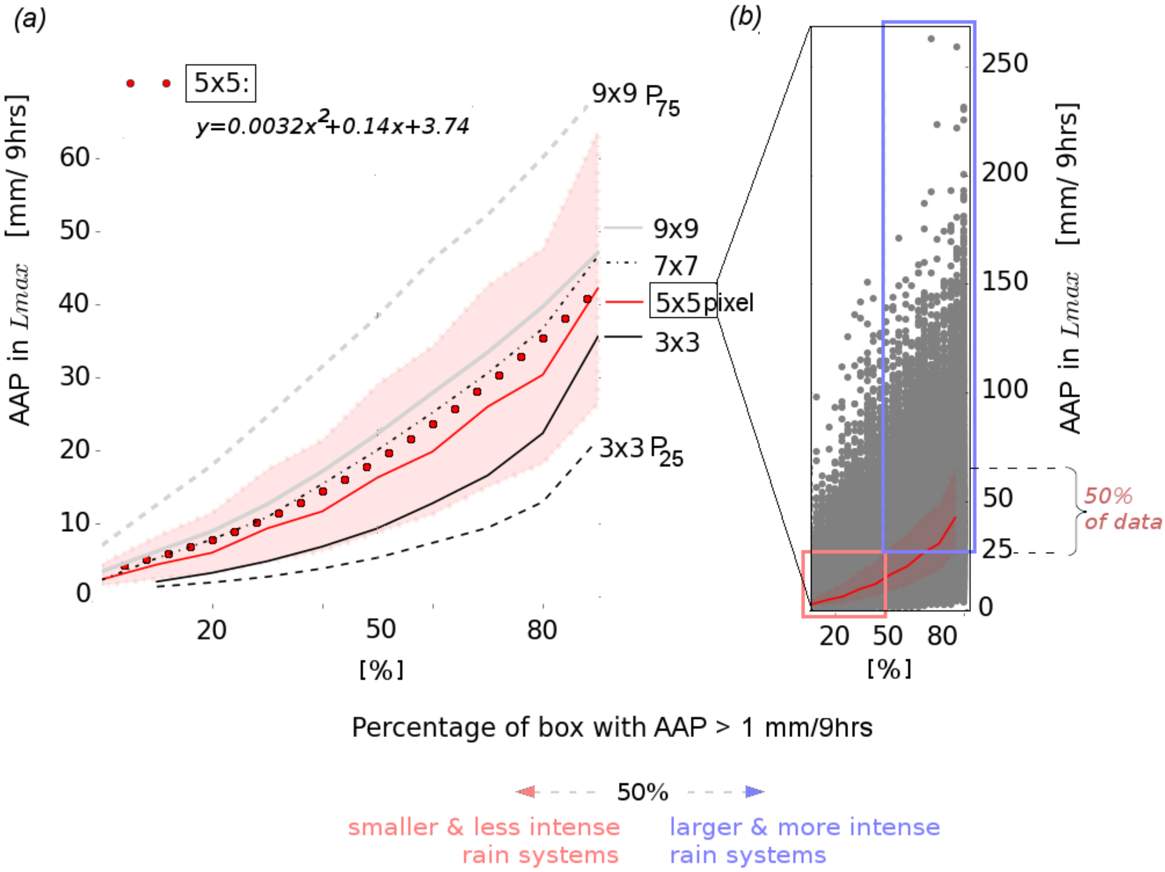


Figure 4.9: Estimated relationship between the AAP threshold and the percentage of a corresponding grid box area occupied by AAP > 1mm/9hrs. (a) - Median of the observed AAP values as a function of binned AAP area in (%) obtained for different grid box sizes, i.e. from 3 to 9°. The binning is done with the resolution of 10%. Red shading indicates the data range between 25^{th} and 75^{th} percentile lines of the estimated relationship at the 5° grid size. Fitted 2^{nd} order polynomial function for the AAP threshold - AAP area relationship estimated at the 5° grid is provided on the top of the plot. (b) - Same as (a) but for the 5° box only. Additionally all the underlying data points are shown as a scatter.

4.4 Summary and conclusions

4.4.1 Conclusions of the sensitivity tests

Regional application of the T12 method with the original set up over the North African domain reveals a featured preference of the afternoon rainfall events to occur more often over spatially drier soils, providing an evidence of a negative spatial SMPC anywhere in the domain. The magnitude of the deviation from the typical (control) soil moisture conditions underlying the SMPC relationship varies in accordance with the change in the magnitude of the soil moisture variability with latitude. Hence, one has to be aware that strongest differences in the SMPC parameter δ_e between the sensitivity experiments are likely to be found over the wetter southern latitudes of the domain, respectively.

Following the results of the sensitivity tests presented here, the main limiting factor of the proposed statistical method remains the size of the rainfall event sample. Accordingly, the major constraint on the event sample size can be identified as being the length of the input satellite data record, and especially of the soil moisture time-series.

Selection of the afternoon accumulated precipitation (AAP) threshold represents the second largest constraint on the size of the rainfall event sample. The amount of data decreases exponentially with an increase of the AAP threshold. The critical AAP value with respect to the SMPC significance loss is identified as being 15 mm/9hrs - the value at which the total amount of data is reduced to less than one half. The sensitivity assessment of the SMPC to the various AAP threshold shows, however, that a reduced number of events though leads to a decrease in the amount of significant grid boxes, yet does not qualitatively affect the dominant preference of the afternoon rainfall to occur over spatially drier soils. The difference to the typical conditions δ_e does not vary much between the realizations with different AAP thresholds. All the above confirms the robustness of the negative SMPC relationship in the North African region as defined by the current method. As a consequence, it might be further assumed, that it is rather a combination of the resolved variability of input data and the assumptions considered by the method, than the amount of data, that maximizes the preference of rain over the drier soils.

One of such relevant assumptions is identified as being the areal distribution of the afternoon accumulated precipitation. The soil moisture gradients estimated between the maxima and minima of the AAP result in the strongest deviation δ_e from the typical conditions, as compared to any other combination of locations, and hence lead to the most robust and significant negative SMPC signal. The latter inter alia suggests that the rainfall not only tends to propagate towards drier soils but also "avoids" wetter surrounding. This, on the one hand, emphasises the relevance of the underlying soil moisture spatial variability for moist convection development, while on the other hand, indicates potential for further homogenization of the surface moisture in space. From the methodological perspective, accounting for the areal distribution of the AAP should be considered as being the necessary assumption to maximize the significance of the negative spatial SMPC. Besides, the shape (i.e. areal distribution) of the rainfall is considered to be a well captured property of rain field compared to the less certain rain rate.

The relevance of the involved horizontal scales becomes more evident once the sensitivity of the SMPC statistics to the areal extent of the AAP is investigated. Following this analysis, selection of events associated with the smaller AAP area, i.e covering less than 50% of the 5×5° box, increases the probability of negative SMPC, independent of the reduced event sample size. This result is found to be consistent with relevant literature, indicating higher sensitivity of the smaller and less organized MCSs to thermally-induced surface convergence zones. However, the results presented here suggest, that the rainfall of an isolated cell even being a part of the large and organized MCS may still be sensitive to the underlying soil moisture conditions. The latter would hint rather to the relevance of the interaction between the spatial scales of the involved processes than to the organization of the MCS.In this view it is important to emphasise that the scale and the resolution dependence of the SMPC estimates remains an open question of this study in particular and the research field in general.

Taking into account the results of the above presented sensitivity tests, it appears to be essential to additionally consider properties of the MCSs associated with the precipitation event. Knowledge about the size, maturity, propagation speed and type of a convective system would be a valuable improvement to the method, also allowing for a better and more accurate interpretation of the method results in terms of the physical processes involved. This, inter alia, would allow linking the initiation of convection to the precipitation properties, for a better comparison of the SMPC results to the existing observational knowledge of the measurement campaigns, like e.g. AMMA (Redelsperger et al., 2006).

As an overall conclusion, the need for a longer time-series of soil moisture and precipitation data appears to be the key ingredient for a better and more accurate estimate of the SMPC and the interpretation of this and other recently suggested statistical frameworks. The spatial gaps in soil moisture fields together with the error associated with the dense vegetation result in substantial loss of the rainfall events, directly affecting the event sample size and significance of the SMPC parameter. In this respect, the length of the time-series might be increased in the future by extending AMSR-E data with the follow on higher quality Advanced Microwave Scanning Radiometer (AMSR-2, 2012-present) and recently launched Soil Moisture Active Passive (SMAP) estimates. Finally, the results of the sensitivity tests suggest that the choice of the original set up as in T12 should be considered as optimal, and therefore will be further applied to study the role of physical processes in the observed SMPC relationship.

4.4.2 Other relevant data and method limitations

From the methodological perspective it is important also to note that the T12 algorithm does not account for the fast-moving long-lived propagating systems that formed in the morning hours or previous day some hundreds kilometres away from the identified later event location. The condition of zero morning precipitation within $\sim$ 200 km box does not guarantee formation of the precipitating system on that day, and hence, does not allow distinguishing between the long-lived and locally-formed convective systems. The growth and propagation of these large and organized MCSs is expected to be governed by distinct mechanisms, and therefore should be excluded from the total event sample. The filtering of the organized long-lived MCSs might be archived with the above suggested tracking of the MCSs properties.

The reconsideration of the water mask applied in the T12 framework is also recommended. Following the sensitivity tests, few regions have shown to produce a robust SMPC, independent of the event sample size. This robust signal is found to be associated with the presence of extreme soil moisture gradients formed in the vicinity of wetlands. In the present set up, only pixels with >5% of water are excluded based on the monthly estimates of land cover product GLC2000 (see methodology). Taking into account strong influence of wetlands on the convection initiation, suppression and development, it appears to be essential to account for the dynamics of flooded areas, and therefore introduce an improved water body mask at a higher temporal resolution.

Effect of boundary conditions on the selection of convective rainfall events should also be taken into account. Mentioned earlier extensive spatial gaps in the soil moisture product emerge as a boundary for the rainfall accumulations, and therefore affect the shape of the resulting AAP fields, and identification of event locations.

Another soil moisture data limitation that could potentially affect T12 method results is the water content of the deeper soil layers, excluded from consideration. Existing satellite data products, including AMSR-E LPRM, allow obtaining soil moisture signal from only few centimetres below the surface. During the monsoon onset in the Western Sahel rainfall efficiently was found to change only the first 5 - 10 cm of soil with the largest amplitude at the surface (Schwendike et al., 2010; Taylor and Ellis, 2003). However, over the southern domain latitudes with higher vegetation cover and deeper system of roots, hydrology of deeper layers is expected to become relevant (Guillod et al., 2015), especially during the wettest monsoon period. Hence, a follow on sensitivity and modelling experiments studying the role of deeper soil layers in the resulting SMPC signal over the North African region can be beneficial.

Finally, it is important to emphasize that comparison of the existing evidence of SMPC both from models and observations is additionally restrained by the diversity of the applied definitions, spatio-temporal scales, and introduced assumptions. It therefore appears to be important to consider not only a response of every involved process to the length scale but also consistency in definition and methodology of the follow on studies.

Chapter 5

Regional co-variability of spatial and temporal soil moisture - precipitation coupling in the African Sahel: an observational perspective [1]

5.1 Introduction

Soil moisture can affect the state of the lower atmosphere through its impact on evapotranspiration and surface energy flux partitioning (e.g., Eltahir, 1998; Klüpfel et al., 2011). Especially in the "hot spots" of soil moisture - precipitation coupling (SMPC), like the semi-arid Sahel (Koster et al., 2004; Miralles et al., 2012), soil moisture exerts strong control on evapotranspiration (e.g., Dirmeyer, 2011), influencing development of the daytime planetary boundary layer (BL), and hence convective initiation and precipitation variability. Most of the physical understanding on how soil moisture could alter BL properties and affect development of convection comes from 1 to 3-D model analyses (Seneviratne et al., 2010; Nicholson, 2015). Observational evidence of the SMPC largely relies on the measurements of recent field campaigns (like African HAPEX and AMMA: Goutorbe et al., 1994; Redelsperger et al., 2006) and hence is often limited to a short spatio-temporal scale. Such observational analyses present a unique evidence of environmental conditions preceding convection development (e.g., Lothon and Campistron, 2011) and are predominantly used as a test-ground to evaluate and improve parameterization of the physical processes proposed by theory and

[1] **Petrova I.**, C.C. van Heerwaarden, C. Hohenegger, S.Bakan (2016): Regional co-variability of spatial and temporal soil moisture - precipitation coupling in the African Sahel: an observational perspective. (prepared for submission in J. of Hydrometeorology)

model results (e.g., Couvreux et al., 2013). Both, observational and modelling studies agree reasonably well on the effect of soil moisture availability and heterogeneity on the lower atmospheric stability (e.g., Kohler et al., 2010) and convective initiation at meso-scales (e.g., Taylor, 2010; Birch et al., 2013). However, impact of soil moisture on convective precipitation remains highly uncertain. The disagreement in the sign of the SMPC exists between models and observations (Taylor et al., 2012, 2013), as well as across models (e.g., Hohenegger et al., 2009). Recent satellite-based analysis has demonstrated that the choice of soil moisture parameter itself (temporal anomaly or spatial gradient) and related differences in physical mechanisms have a direct effect on the resulting sign of the observed soil moisture - precipitation coupling on 100 km scales (Guillod et al., 2015). Our study addresses the question of co-existence of spatial (i.e. using spatial soil moisture gradient) and temporal (i.e. using soil moisture anomaly) SMPC in the region of the African Sahel at 1° horizontal resolution. To overcome spatio-temporal limitations of the observational data (Findell and Gentine, 2015), we use 10-year satellite records of daily soil moisture from the AMSR-E and 3-hourly TMPA precipitation product.

Both, modelling and observational studies reported the possibility of negative as well as positive soil moisture - precipitation coupling (Nicholson, 2015). Spatial gradients in soil moisture can affect BL state and convection initiation through the mechanism of thermally-induced meso-scale circulations, recognized on 10 to 100 km scales (Taylor and Ellis, 2006; Taylor et al., 2007). In association with this mechanism and under favourable thermodynamic conditions, convection is likely to be initiated over spatially drier soils, indicating a negative SMPC relationship (Taylor et al., 2011a; Garcia-Carreras et al., 2011). However, whether the further development and propagation of moist convection will occur over drier or wetter soils remains subtle. The modelling study of Froidevaux et al. (2013) suggested that negative SMPC is possible under very weak surface wind conditions, and is associated to stationarity of convective systems once initiated. The opposite sign is therefore expected under a stronger horizontal advection, which will support propagation of the developing moist convection downwind, i.e. from dry to wet soils, and its further amplification over wetter areas. Another factor is attributed to a life-cycle of meso-convective systems (MCS) and hence their organization and size (Mathon et al., 2002). Small-scale convective systems are expected to be more sensitive to surface moisture variability and will propagate preferentially towards spatially drier soil, bounded by a wetter surrounding (Taylor and Ellis, 2006). Larger organized systems, on the contrary, rather evolve towards wetter soils - areas of increased latent heat flux, convective available potential and moist static energy (Taylor and Lebel, 1998; Clark et al., 2003) - and hence, are rather more sensitive to soil moisture availability.

The impact of soil moisture and its temporal anomaly on the atmospheric boundary layer and moist convection is largely governed by thermodynamical processes, and may likewise result in a coupling of both signs. Wet soils are expected to lead to an increase of moist static energy (MSE) per unit area, through a decreased BL height, higher equivalent potential temperature, less vigorous entrainment and increased total surface heat flux (e.g. Eltahir, 1998; Alonge et al., 2007). The enhanced MSE over wet soils favours higher probability of rainfall formation. Dry soils, on the contrary, are associated with a reduced MSE and thus provide lower potential for convection development or may even suppress already existing MCS (Gantner and Kalthoff, 2010) or deviate its propagation direction (Wolters, 2010). However, modelling and observational evidence indicated that both, dry and wet soils, can favour moist convection, depending on the morning stratification of the BL (Findell and Eltahir, 2003b,a) and stability of the layer into which BL is growing to (Ek and Mahrt, 1994; van Heerwaarden and Guerau de Arellano, 2008).

The spatial and temporal effects of soil moisture on convection triggering are typically considered in conjunction. The relevance of spatial heterogeneity and its horizontal scale in favouring convection over wet and dry soil moisture anomaly was indicated by e.g. Clark et al. (2003) and Taylor and Ellis (2006) respectively. Until recent, however, no attempts were made to directly compare temporal and spatial aspects. The study of Guillod et al. (2015) (hereafter, G15) using 10-years of global satellite-based soil moisture and precipitation data compared for the first time the spatial and temporal effects of soil moisture on precipitation at 5° horizontal resolution. Using the probability-based approach of Taylor et al. (2012) (hereafter, T12), they demonstrated that a negative spatial (rain over spatially drier soils) and a positive temporal (rain on days wetter than usual) SMPC dominate over most of the globe and do not exclude one another. G15 suggested that the two effects might be interconnected through the spatial coupling mechanisms, in which adjacent precipitation would provide required moisture to enhance convection development over spatially but not temporally drier soil. Using multiple data sets, G15 proved that the signal is robust and independent on the input data discrepancies. However, in a few regions over the globe, including the African Sahel, an opposite temporal relationship was revealed: spatially and temporally negative coupling was found to co-exist in opposition to the global relationship. The reason for this correlation remained unexplained.

In this study, we analyze the spatial and temporal SMPC in the African Sahel region using the method of T12. First we focus on identification of the factors and physical processes that can affect the magnitude and variability of the spatial SMPC measure. Then, we analyze the link between the spatial and temporal effects of soil moisture on precipitation by answering two questions: are spatial and temporal negative coupling relationships independent, and if not, how do they inter-relate? We reproduce and apply the probability-based approach of T12 to 10-years of daily AMSR-E soil moisture and 3-hourly TMPA precipitation records. In contrast to the previous studies we estimate the temporal and spatial coupling effects at a higher 1° horizontal resolution, which allows to reveal previously-averaged effects of land cover features on the SMPC relationship.

The first part of the study includes analysis of the regional variability and robustness of the observed spatial SMPC distribution at the highest 1° grid. Specifically, the sensitivity of the spatial SMPC relationship to the higher horizontal scale is tested, i.e. from original 5° to 2.5° and 1° (Sections 4.1-4.2). Identification of the factors relevant for the observed spatial SMPC distribution includes the sensitivity analysis of the spatial coupling measure to the presence of soil moisture parameter extremes (Section 4.3) and MCS life cycle (Section 4.4). The link between the temporal and spatial SMPC is assessed using correlation analysis and discussed in Section 5.1. Section 5.2 argues on the reasons behind the opposite sign of the temporal coupling identified in the North African region as compared to the positive relationship identified in G15.

5.2 Results of spatial SMPC analysis

5.2.1 SMPC at 5° horizontal resolution. Consistency to previous studies

We start our assessment by investigating the spatial soil moisture - precipitation coupling relationship. In agreement with the global-scale studies of T12 and G15, we find an indication of a dominant negative spatial SMPC in the Sahelian domain at the 5° scale, i.e. a strong preference for convective rainfall events to occur over spatially drier soils (Fig. 5.1a). The majority of the 5° boxes (72%) have percentile values P_e lower than 10%, implying a significant negative difference in the mean magnitude of soil moisture gradients $\Delta(S_e'^{Lmax})$ prior to the events relative to their typical (non-event) state. No significant positive difference between event and non-event conditions is found at the 5° scale (Table 5.1).

In comparison with the previous analyses based on the T12 approach, our set up indicates the largest percentage of the domain area with significant negative coupling (Fig. 5.2). The differences arise due to the quality of the input data sets (G15, T12) and methodological discrepancies between the studies. As well as for the global scale (G15), the weakest negative coupling signal in the Sahelian domain is attributed to the PERSIANN precipitation data set, and, as was shown by T12, is linked to the lower consistency between the PERSIANN precipitation and soil moisture variability in time. On average, all the experiments summarized in Fig. 5.2 agree that afternoon precipitation occurs more often than expected over spatially drier soils in 42% of the studied boxes, against only 4% with a preference over spatially wetter soils.

The variability of spatial SMPC patterns among different data set combinations has shown to be quite strong over the globe and was not analyzed further in G15. We note, however, that in the Sahelian region, areas of significant negative spatial coupling are fairly consistent. One of the most robust negative spatial SMPC signal is found in the south-western part of the domain (Fig. 5.1ab). 14 out of 18 data set combinations summarized in Fig. 5.2, including this study, locate the cluster of the lowest percentiles

Table 5.1: General statistics of the average event number, percentile P_e and δ_e difference estimated at various scales for three soil moisture parameters: soil moisture gradient $\Delta(S_e'^{Lmax})$, temporal soil moisture anomaly $S_e'^{Lmax}$, and (not presented in the methodolgy) soil moisture variance over the 1.25° box, $\sigma S_e^{1.25}$. Percentiles $P_e < 10\%$ ($> 90\%$) indicate significant negative (positive) δ_e difference, and hence negative (positive) SMPC relationship.

Parameter	*Scale*	$\overline{Num_e}$	$P < 10$, [%]	$P > 90$, [%]	$\delta_{ev} < 0$, [%]	$\delta_{ev} > 0$, [%]
$\Delta(S_e'^{Lmax})$:	$5 \times 5°$	309	72	0	92	<0.1
	$2.5 \times 2.5°$	84	42	<0.1	73	0.1
	$1 \times 1°$	17	21	<0.1	43	14
$S_e'^{Lmax}$:	$1 \times 1°$	-	67	0.8	92	8
$\sigma S_e^{1.25}$:	$1 \times 1°$	-	33	3	78	22

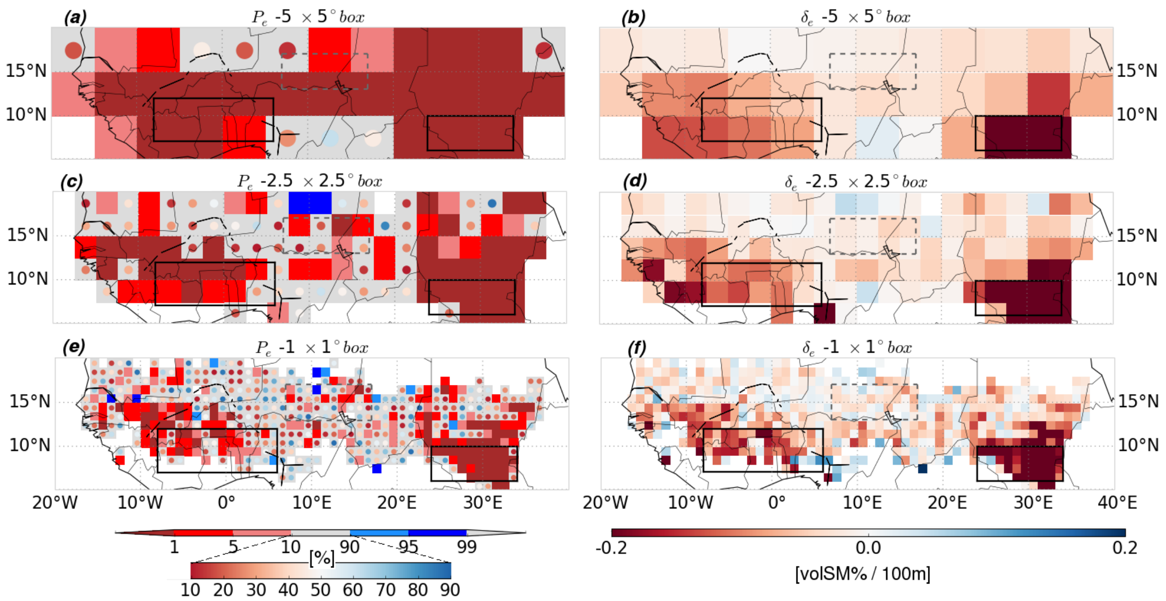


Figure 5.1: Distribution of percentiles P_e (*left*) of the observed δ_e difference (*right*), estimated over $5 \times 5°$, $2.5 \times 2.5°$ and $1 \times 1°$ boxes. Percentiles <10% indicate significant negative coupling, i.e rain over spatially drier soils, and percentiles >90% - significant positive coupling, i.e. rain over spatially wetter soils. The percentile values lying outside the significance range (10-90 %) are illustrated by circles. Black and grey rectangulars on the maps indicate featured domains selected for an in-depth analysis.

roughly between 5 - 15°N and 10°W - 10°E (Fig. 5.2, crosses). This region occupies a relatively vast and flat area, and is associated to a reduced orographic forcing on convection development as compared to the East, and related to it regional minimum in the cold cloud occurrence (Laing and Carbone, 2008). The effect of large-scale disturbances like AEWs and AEJ on convection on the contrary is expected to be stronger in the western Sahel than further East. This, however, does not exclude or may even favour higher sensitivity of convection triggering to soil moisture heterogeneities (Gantner and Kalthoff, 2010; Adler et al., 2011). The identified negative spatial SMPC relationship in the region is consistent with the recent observational- (Taylor and Ellis, 2006; Taylor, 2010; Lothon and Campistron, 2011) and model-based (e.g. Gantner and Kalthoff, 2010; Garcia-Carreras et al., 2011; Birch et al., 2013) evidence from the Western Sahel.

Following our results, another cluster of the lowest percentiles and the largest differences in soil moisture state between event and non-event days δ_e is identified in the south-east of the domain (Fig. 5.1ab). Proximity to the Ethiopian Highlands and presence of extensive seasonally flooded regions in this area makes it difficult to isolate effect of surface state on convection, resulting also less coherence in the spatial SMPC estimates identified in the G15 and T12 analyses. Unlike the western Sahel no accurate estimates of the SMPC relationship exist further than 15°E.

5.2.2 Robustness of the negative SMPC at higher 2.5° and 1° horizontal resolution

A large part of this study is devoted to the identification of the factors and potential physical processes that affect the magnitude and variability of the SMPC as defined by the current method. The influence of these factors, however, becomes evident only when we reduce the event-aggregation scale to the finer 2.5° and 1° horizontal grid[2]. In particular, aggregation of the convective rainfall events and corresponding soil moisture statistics over the smallest 1° grid boxes reveals previously-averaged effects of land surface features on the SMPC.

The percentile maps obtained for the finer scales of event-aggregation are presented in Figures 5.1c and 5.1e. Despite the reduction in the amount of significant δ_e values, largely due to the decreased number of events in every box, negative spatial SMPC relationship remains dominant at the finer scales, and exhibits a similar spatial pattern as at the 5° resolution. The featured regions of significant negative coupling now scale down to the territories of Burkina Faso, Benin, parts of Ivory Coast, Ghana and Mali (7 - 15°N, 10°W - 7°E) in the West, as well as South Sudan (5 - 13°N, 24 - 34°E) in the East. In total, 42 and 21% of the boxes reveal significant negative difference δ_e for

[2]The SMPC statistics is calculated if at least 8 events in a box are present, following the 8-points average rule.

the 2.5° and 1° grid resolutions respectively, versus initial 72% at the 5° scale (Table 5.1).

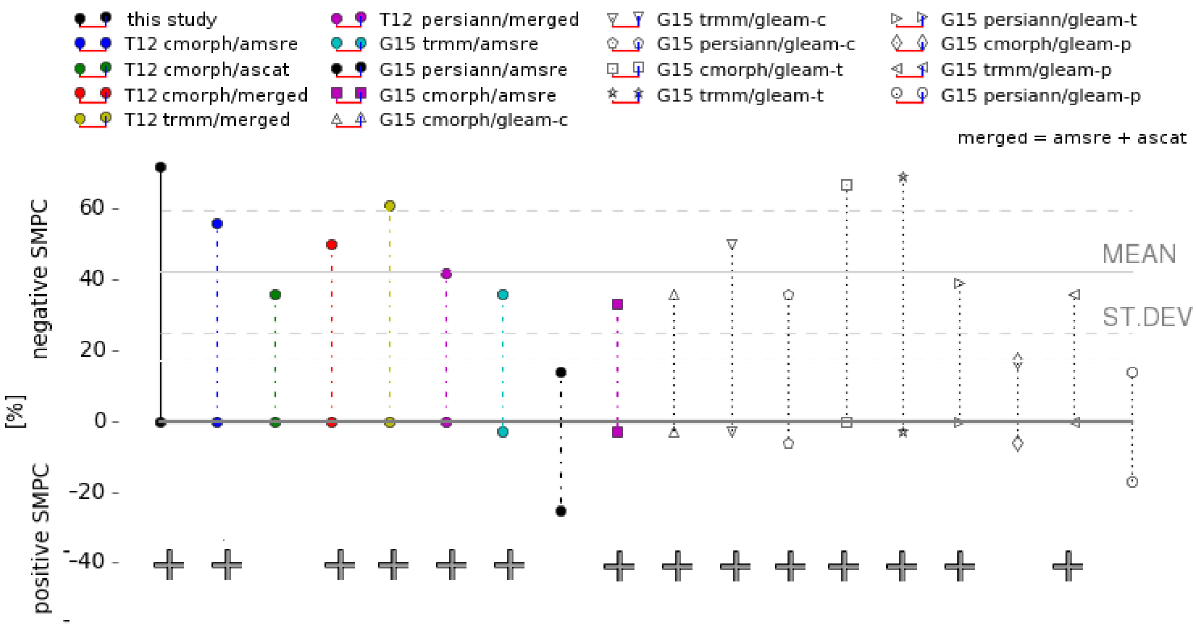


Figure 5.2: Percentage of 5° grid boxes with significantly negative ($P_e < 10\%$) or positive ($P_e > 90\%$) spatial SMPC over Sahelian domain in this study and previous studies of T12 and G15. Various markers and colors represent different data set combinations used in T12 and G15. Colourless markers indicate soil moisture derived from GLEAM model with precipitation input from TRMM, CMORPH or PERSIANN datasets, referred as GLEAM-T, GLEAM-C and GLEAM-P respectively. Mean and st.dev. are calculated for the negative SMPC only. Following visual inspection, the experiments, in which significant negative SMPC relationship exists in the western region of the Sahelian domain are indicated by *plus* markers.

The overall distribution of the δ_e does not change at the finer scales (Fig. 5.1d,f). However, local areas of the opposite difference sign do emerge. For example, a small region enclosed between the Cameroon mountains and Jos Plateau (7°N; 8°E, Fig. 5.1f) now indicates a positive δ_e difference and, hence, a higher likelihood of rainfall to occur over spatially wetter soils. This relationship, though non-significant, yet is reasonable. The area includes a Niger river valley and represents a prominent location of intense convection and a local maxima of the cold cloud occurrence, linked to the initiation of convection at the lee side of the high terrain (Laing and Carbone, 2008). In total, 14% of the 1° boxes reveal a positive δ_e shift, against less than 0.1% for a coarser 2.5° and 5° grids.

5.2.3 Evidence for "wetland-breeze" mechanism in the SMPC statistics

In the regions, like the Cameroon Mountains, where orography or floodplains has an affect on moist convection development, persistent wet and dry surface moisture patterns may pre-exist or develop, and therefore, lead to the occurrence of stronger than usual spatial soil moisture gradients. In the SMPC statistics such gradients occur as extremes in a given distribution of soil moisture gradients $\Delta(S_e'^{Lmax})$ attributed to a 1° grid box. Here, $\Delta(S_e'^{Lmax})$ is considered to be an extreme if it lies outside the (Q_{25}-1.5*IQR, Q_{75}+1.5*IQR) range, where Q_{75} and Q_{25} are the third and first quartiles respectively, and the interquartile range (IQR) is the difference between them. Distribution and magnitude of the extreme soil moisture gradients identified in the domain are shown in Figure 5.4.

We find that 28% of all valid 1° boxes and thus δ_e values are affected by extremes. A large part of the extreme soil moisture gradients are located in the regions of significant negative coupling, in the West and East (Fig. 5.4). In these areas, extreme $\Delta(S_e'^{Lmax})$ lead to the overestimation of the SMPC magnitude, and in some cases predefine its significance. Removal of extremes leads to a decrease of the number of boxes with significant negative spatial coupling by 30%. In most of the cases, however, the sign of the coupling remains unchanged. In the grid boxes, where extreme $\Delta(S_e'^{Lmax})$ affect the sign of the SMPC, the mean and median of $\Delta(S_e'^{Lmax})$ distribution have opposite sign (Fig. 5.4, black dots).

Further analysis shows that extremes tend to cluster around major rivers and wetland areas in the East and West (Fig.5.3 and 5.4), confirming our hypothesis. Strong positive soil moisture gradients are found around the Senegal river close to the coast, and on the lee side of the Cameroon Mountains. Strong negative soil moisture gradients are more numerous and seen all along the western flow of the Niger river, downwind of the permanent wetlands of Ez Zeraf Game Reserve and irrigated lands of the Gezira Scheme in Sudan. The scatter of the extremes in the East is likely attributed to the recurrently flooded flows of the White Nile river.

The identified sensitivity of the afternoon rainfall to the strong negative soil moisture gradients around water bodies is in agreement with the results of the observational-based study of Taylor (2010). Analyzing 24 years of Meteosat brightness temperatures over the Niger Inland Delta, they found that convection was initiated more often over and to the east of the wetland in the morning hours. However, later in the day mesoscale convective systems tended to develop and propagate away from the wet areas towards drier soils, suggesting formation of deep convection and afternoon precipitation over negative soil moisture gradients. Similarly, observed by Alter et al. (2015) enhancement of rain to the East of irrigated land at 14°N, 33°E and its suppression over the Gezira Scheme itself is consistent with the identified in Fig. 5.4 location of negative (positive) extreme soil moisture gradients to the West (East) of the irrigated region. All the above suggests the relevance of thermally-driven "wetland-breeze" circulations on convection triggering as well as moist convection intensification over the drier soils adjacent to the flooded areas.

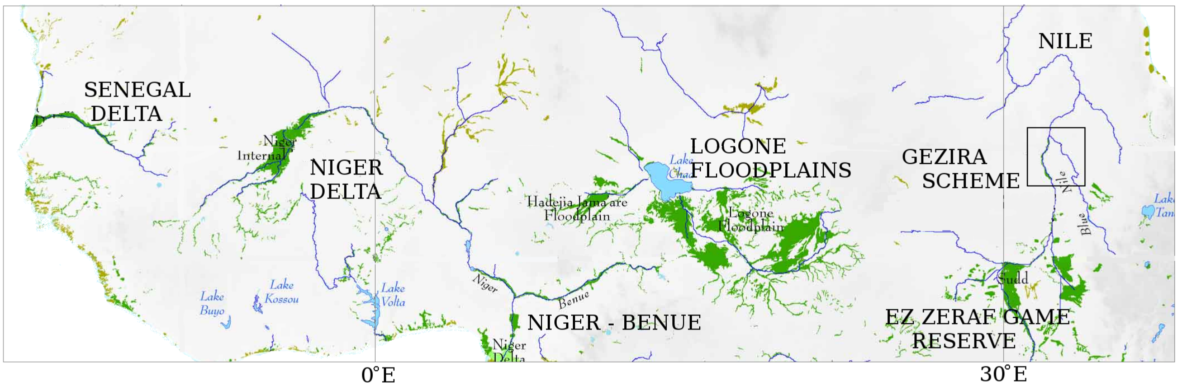


Figure 5.3: Major river flows (blue) and river flood planes (green) of the northern African domain [Adopted from the World Maps and Satellite Photos: http://www.zonu.com/fullsize-en/2009-11-07-10918/African-Wetlands.html].

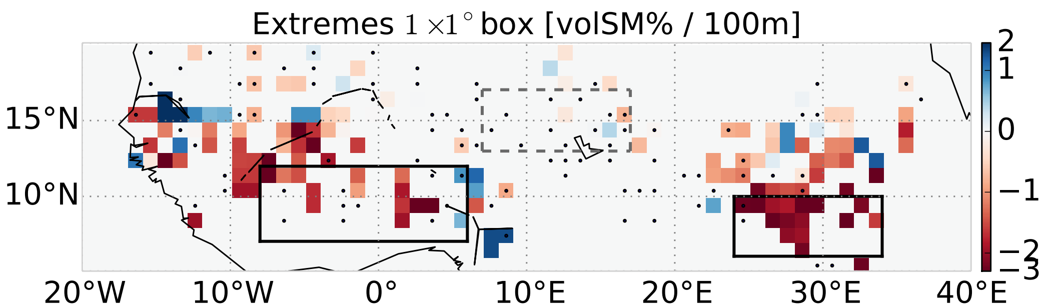


Figure 5.4: Distribution of soil moisture gradient $\Delta(S_e'^{Lmax})$ extremes in the corresponding event sample of a 1° box. $\Delta(S_e'^{Lmax})$ is considered to be an extreme if it lies outside the (Q_{25}-1.5*IQR, Q_{75}+1.5*IQR) range, where Q_{75} and Q_{25} are the third and first quartiles respectively, and the interquartile range (IQR) is the difference between them. Black dots indicate boxes, in which $\Delta(S_e'^{Lmax})$ sample mean and median have opposite signs.

5.2.4 Effect of moist convection propagation on the SMPC statistics in eastern and western sites.

Another physical effect that may influence the SMPC relationship and is not accounted by the current algorithm is related to the propagation and evolution of mesoscale convective systems. Previous studies indicated that an opposite SMPC relationship might be expected at early versus late stages of MCS development (Taylor and Lebel, 1998; Taylor and Ellis, 2006; Taylor, 2010; Alonge et al., 2007; Clark et al., 2003; Gantner and Kalthoff, 2010). In this respect, a distinct strength or even sign of the spatial SMPC measure may result from stratification of the rainfall events into those formed by a weaker and smaller MCSs - mostly found in the early afternoon - or by a long-lived and organized MCSs - dominant during late afternoon hours (Mathon and Laurent, 2001). Differences in SMPC response to MCS life cycle are also expected to exist between the two regions of significant negative coupling, in the East and West. To characterize these differences, we analyze precipitation diurnal cycles averaged over event days in the East and West first (Fig. 5.5), and then estimate sensitivity of the spatial SMPC to varying rainfall accumulation times (Fig. 5.6).

The Hovmöller diagram of rainfall averaged over 1000 event days in the Western domain (black rectangular in Fig. 5.4) shows that intensification of the moist convection in the region is generally concentrated around main orographical features (Fig. 5.5a,c). The peak in precipitation occurs at similar times across the domain, and thereby does not reveal expressed signature of the system propagation. Most of the MCS are therefore expected to be short-lived and small, suggesting that their dissipation locations would be found close to their initiation (Mathon and Laurent, 2001).

In the East, on the contrary, the strong south-western propagation component of moist convection dominates the zonal progression of the most intense rainfall during diurnal cycle averaged over 754 event days (Fig. 5.5d). A large number of MCS initiate at the lee side of the Ethiopian Highlands and propagate westward undergoing cycles of regeneration and growing into a mature and organized MCS (Laing and Carbone, 2008; Laing et al., 2012). The emergence of an absolute rain rate maximum downwind of the permanent wetlands of the Ez Zeraf Game Reserve during afternoon hours indicates a strong influence of the flooded areas on moist convection intensification in the region (Fig. 5.5d,f). Consistently to the results of Taylor (2010) obtained for the Niger Inland Delta, presence of wetlands in the Eastern domain is expected to increase the number of organized and long-lived propagating MCS in the late afternoon, originating from either locally triggered MCS, i.e. formed at the dry land-wetland boundary, or from the re-intensified pre-existing westward propagating systems. The identified location of the maximum rain rate westward from the permanent wetlands at 30°E is consistent with the increase in cold cloud occurrence observed by Taylor (2010) downwind of the wetlands of the Niger Inland Delta. The latter supports the presence of similar mechanisms operating in the Ez Zeraf Game Reserve. We may therefore expect a greater sample of long-lived and organized propagating MCS to be found in the late afternoon hours in the Eastern domain than in the Western site. Accordingly, the response of the SMPC statistics to propagating MCS is expected to be stronger in the East compared to the West. Figure 5.6, which shows the change of the SMPC parameter between different rainfall accumulation time periods, confirms this hypothesis. For this assessment additional domain in the North is considered (gray rectangular in Fig. 5.4), as representative for the area with different to the East and West large-scale atmospheric and surface conditions.

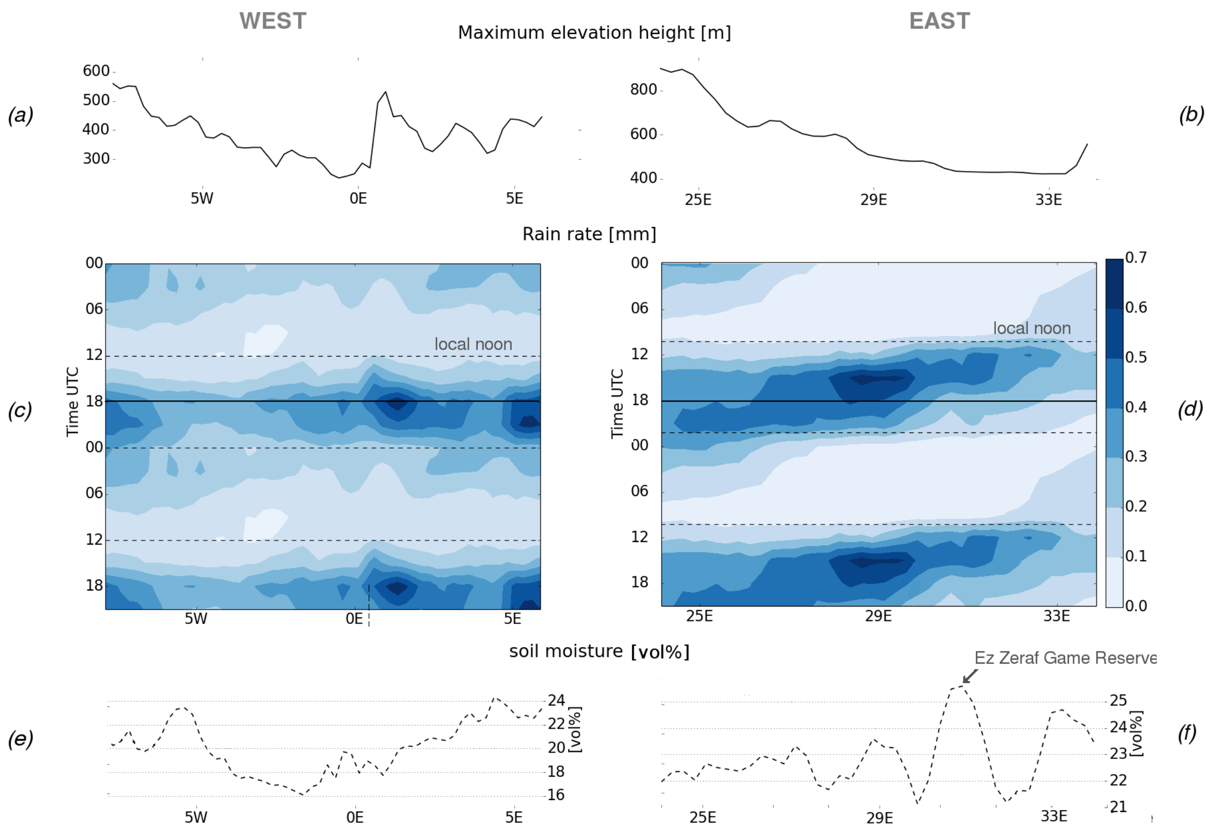


Figure 5.5: (a),(b) - Longitudinal cross-sections of maximum elevation height in the Western and Eastern domains respectively, (c),(d) - diurnal cycles of the rain rate averaged over event days and domain latitudes, and (e),(f) - Longitudinal cross section of soil moisture averaged over domain latitudes. Location of the Ez Zeraf Game Reserve permanent wetlands is marked by an arrow. All the times are given in UTC. Note, the UTC+2 hour difference to LST in the East.

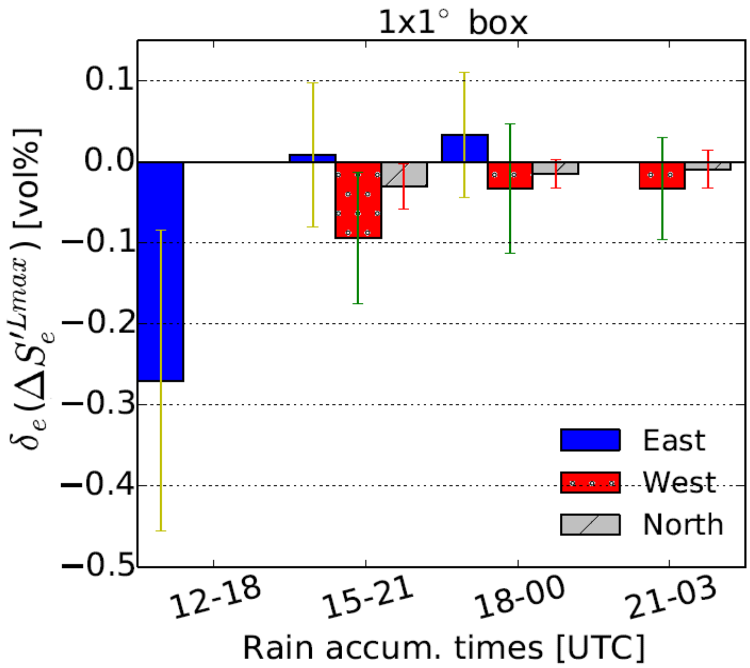


Figure 5.6: Value of the coupling measure δ_e calculated for various afternoon rainfall accumulation times, and averaged over selected domains, i.e East (6-10°N, 24-34°E), West (7-12°N, 8°W-6°E) and North (14-17°N, 7-14°E). Locations of the domains are shown in Fig.4. Error bars indicate one std.dev. of δ_e values in every domain. Note, that all times are indicated in UTC.

From Figure 5.6 it is seen that the earlier rainfall accumulation time periods, i.e. 12-18 UTC in the East and 15-21 UTC in the West and North, result in the strongest negative δ_e difference, and hence spatial SMPC relationship in all three domains. No positive δ_e values are found for these time periods, and the fraction of negative soil moisture gradients preceding rainfall events is the highest: 62%, 57% and 55% for East, West and North accordingly. Later accumulation times lead to a decrease in the magnitude and significance of the coupling parameter δ_e, and an increase in its spatial variability across the domains. These changes are associated with an increase in amount of the positive soil moisture gradients in the regions.

Despite the similarities, the differences in the SMPC response exist between the domains. In the East, spatial SMPC shows the strongest sensitivity to the rainfall accumulation time and switches the sign to a positive one for the 18-00 UTC period. In accordance with Fig. 5.5d, the 18-00 UTC period reflects the afternoon progression of the mature MCS formed during early afternoon hours at the Ethiopian Highlands and around wetlands. The large and organized MCS are known to be more efficient in developing over wetter soils, associated to a well expressed BL moisture anomaly and higher MSE and CAPE (Taylor and Lebel, 1998; Taylor, 2010) and, at the same time, might get suppressed over drier surfaces (Clark et al., 2003). These observations are consistent with the identified here increase in fraction of positive $\Delta(S_e^{\prime Lmax})$ in all the domains towards late afternoon hours, and the strongest SMPC response in the East.

The Eastern domain also exhibits the strongest negative δ_e of the three domains, when the earliest time period (12-18 UTC) is considered. This time period includes the rain rate maximum formed likely in conjunction with the triggering of convection by the "wetland-breeze" mechanism, and related to it extreme negative soil moisture gradients. The latter dominate the statistics of the identified strong negative SMPC. Additional analysis reveals that the majority of large and negative soil moisture gradients in all domains are linked to the rainfall events that set on during the first afternoon time step (i.e 12 UTC and 15 UTC for the East and West respectively), and hence are linked to weak MCS at the early stage of their development (not shown). The smaller and less organized MCSs have shown to be more sensitive to the thermally-induced surface convergence zones and are likely to develop over spatially drier soils, adjacent to the strong gradients (e.g, Gantner and Kalthoff, 2010). This knowledge is consistent with the identified here strongest negative δ_e difference and hence SMPC relationship during early afternoon times in all three domains.

5.3 Results of temporal SMPC analysis

5.3.1 Co-variability of the spatial and temporal SMPC

The identified above characteristic features of physical effects underlying the negative spatial SMPC relationship support the potential relevance of breeze-like circulations for moist convection intensification over spatially drier soils. To increase the probability of "breeze-like" circulations over the strong soil moisture gradients, the overall soil moisture content is expected to be relatively low (Avissar and Schmidt, 1998; Taylor, 2015). The latter condition is analyzed by estimating the soil moisture anomaly $S_e'^{Lmax}$ prior to the event and its difference δ_e to the typical state, i.e. temporal SMPC.

Analysis of $S_e'^{Lmax}$ and its δ_e indicates a strong preference for rainfall events to occur over soils that are drier than their temporal mean (Fig.5.7a) and drier than usual (Fig. 5.7b). The percentile values P_e lower than 10% are found in 67% of the studied 1° boxes (Table 1). The latter implies, that a temporally negative SMPC dominates the domain, and with that reaffirms the co-existence of the negative spatial and temporal coupling identified by G15, but at a higher 1° grid.

The question remains whether the two coupling relationships are independent of one another. To answer this question we calculate the Spearman rank correlation coefficient[3] event-wise between the soil moisture anomaly $S_e'^{Lmax}$ and soil moisture gradients $\Delta(S_e'^{Lmax})$ in every 1° box. The correlation map in Figure 5.7c shows that a high and significant correlation exists between $S_e'^{Lmax}$ and $\Delta(S_e'^{Lmax})$ anywhere in the domain.

[3] Spearman correlation is a measure of monotonic relationship. Therefore, zero or low correlation value does not imply zero relationship between two variables.

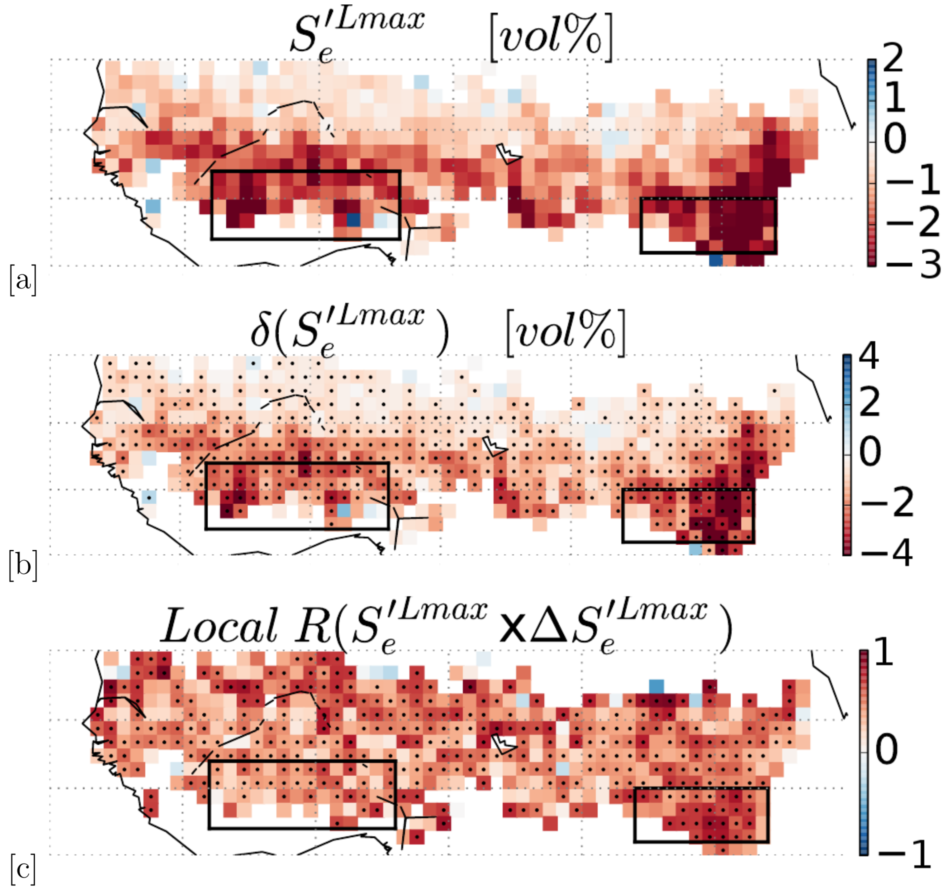


Figure 5.7: Distribution of the (a) temporal soil moisture anomaly $S_e'^{Lmax}$ in event locations and (b) its difference to the typical non-event conditions, δ_e, averaged over 1° boxes; and (c) *Local* Spearman rank correlation coefficient calculated event-wise between soil moisture anomaly $S_e'^{Lmax}$ and spatial soil moisture gradients $\Delta S_e'^{Lmax}$ in every 1° box. Significant δ_e values with percentiles P_e below 10% (above 90%) and correlation coefficients with p-values lower than 0.05 are indicated by black dots.

The mean correlation of 0.47 over the domain supports a presence of relatively strong and positive monotonic relationship between the magnitude of spatial soil moisture gradient and soil moisture anomaly measured in the *Lmax* location. For comparison, the mean correlation estimated between soil moisture gradients and mean soil moisture anomaly over the 1.25° event box is small, i.e. 0.13. All the above suggests that in the North African region the spatial and temporal SMPC relationships, as defined by the current framework, are not independent of each other.

The strong and positive correlation (*intime*) identified between the soil moisture anomalies and gradients also yields a regional co-variability of the SMPC patterns. The *spatial* correlation between the two coupling distributions is high, i.e. 0.64. The largest magnitudes of both $S_e'^{Lmax}$ and $\Delta(S_e'^{Lmax})$ parameters and their corresponding δ_e measures are found in the southern part of the domain. These regions are generally characterized as the areas of higher BL moisture and rainfall frequency, and therefore higher variability of soil moisture in time and space.

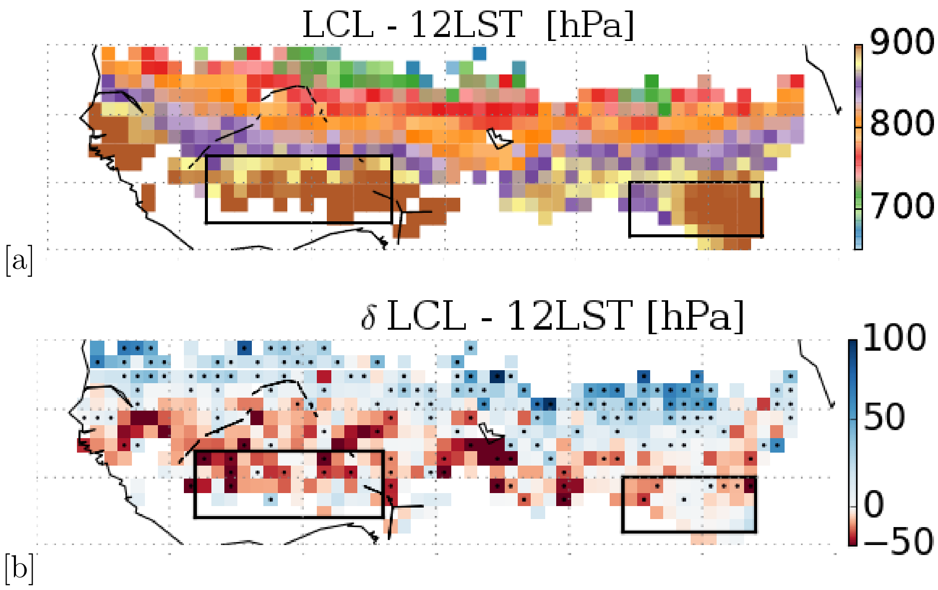


Figure 5.8: (a) Lifting condensation level (LCL) measured on event days at 12 LST and averaged over the 1° box, and (b) corresponding δ_e difference of the mean LCL prior to the events relative to their typical state. The dot indicates significant δ_e values with percentiles P_e below 10% (above 90%). The positive (negative) δ_e values indicate lower (higher) than usual LCL.

Mechanistically, presence of the temporally negative SMPC in the areas of the highest BL moisture in the domain (LCL is shown instead, Fig. 5.8a), is consistent with the higher relevance of mechanisms associated with the BL growth for convection initialization in regions of higher CAPE and lower CIN (Klüpfel et al., 2011; Gantner and Kalthoff, 2010; Adler et al., 2011). In this way, larger deviations of the soil moisture amount from its climatological mean and typical value, i.e. δ_e, would imply presence of a stronger than usual thermals, which can easier overcome CIN and release CAPE (Klüpfel et al., 2011). In combination with a strong negative spatial gradients, these strong thermals can initiate breeze-like circulations, creating more favourable conditions for bringing BL up to the LFC, especially over the southern regions, where BL moisture is in abundance. A slight increase of the LCL in the South, associated to a decrease of BL moisture on event days relative to the typical state is seen in Fig. 5.8b (red shading). This observation supports the relevance of drier surface conditions for convection intensification as opposed to variations in BL moisture prior to the events.

A different picture is observed over the drier latitudes in the North. At these latitudes the northward excursion of moist monsoon air is highly relevant for convective activity (Barthe et al., 2010; Cuesta et al., 2010). The estimated difference in LCL prior to the events relative to the typical state indicates, that a significantly lower than usual LCL, and hence a significantly higher BL moisture, is present on the event days over the dry regions (Fig. 5.8b, blue shading). This result is consistent with the reported earlier decisive role of low-level moisture on MCS evolution in the drier Sahelian regions (Klüpfel et al., 2012).

Considering additionally relatively large number of dry days (10 days on average) preceding rain events in the North, it is unlikely that underlying surface heterogeneity caused by a previous rainfall could have an influence on convection development on the event day. In the case study of Klüpfel et al. (2012) MCS was initiated due to the arrival of the cold pool and convergence zone emanated by a remote convective system hundreds kilometers away. Similar mechanisms may play a role in the moist convection development in the North.

5.3.2 Role of rainfall persistence

In the context of this study, the drying of the soil prior to the rainfall events might be considered as the primary process that underlies the magnitude of both SMPC relationships, and helps to explain the opposite sign of the temporal coupling identified in the Sahelian region as compared to the temperate latitudes and wet climates (G15).

Consistently to the observed 2 to 4 day periodicity of rainfall in the Western Africa (Laing et al., 2012; Taylor and Lebel, 1998), 2 to 3 dry days (rain $<$1mm) on average are found to precede each convective event day over southern latitudes, suggesting a strong drying of the upper soil layer in the event locations prior to the rain. The number of dry days reaches 10 over the dry and deserted regions in the North. Following the analysis of Schwendike et al. (2010) an almost complete recovery of the pre-rainfall surface moisture conditions may be expected in 2-3 days following the rainfall. Schematically, this typical variability of rainfall and soil moisture might be illustrated as a sequence of daily rain events separated by the periods of drying (Fig. 5.9a). From the Figure it is seen that prior to the rain events the soil dries out, and soil moisture reaches certain minimum value S_{min}. The climatology value S_{clim} of soil moisture in the same location, however, is expected to be higher than any S_{min} in most of the cases, as it includes all, dry and wet event days. Hence, when subtracted from the climatological value, a soil moisture measured prior to the event will very likely yield a negative anomaly - $S_e'^{Lmax}$, especially when averaged over many events. Therefore, a negative correlation between soil moisture anomaly and rainfall might be expected.

A different situation can be observed in the temperate latitudes, where variability of rainfall is to a large extent synoptically controlled, i.e. most of the rainfall occurs in episodes associated with fluctuations between passage of a cyclone and a blocking situation (Schär et al., 1999). Such a behavior might be illustrated as a sequence of rain event periods, associated to precipitation persistence as defined by the persistence in the weather regimes (Fig.5.9b, see also Fig.2 in Hohenegger et al. (2009)). During these periods soil moisture increases and remains relatively high. Hence, a higher fraction of events might be expected to occur over soils that are wetter than usual, resulting in a positive soil moisture anomaly $S_e^{\prime Lmax}$ prior to the event. The above relationship is consistent with the negative spatial but positive temporal SMPC, identified in G15.

The modulation of the SMPC sign depending on the large-scale circulation, i.e weather regime was studied e.g. by Boé (2012) over France. The analyses showed that the synoptic blocking situation associated with generally drier conditions lead to a negative SMPC, while positive correlation of rainfall to drier soil conditions was observed in a wet circulation regime. Similarly, most pronounced effect of negative soil moisture gradients on convection initiation over Europe and a higher correlation of the gradients to land surface temperatures was observed for the period with less antecedent rainfall (Taylor, 2015).

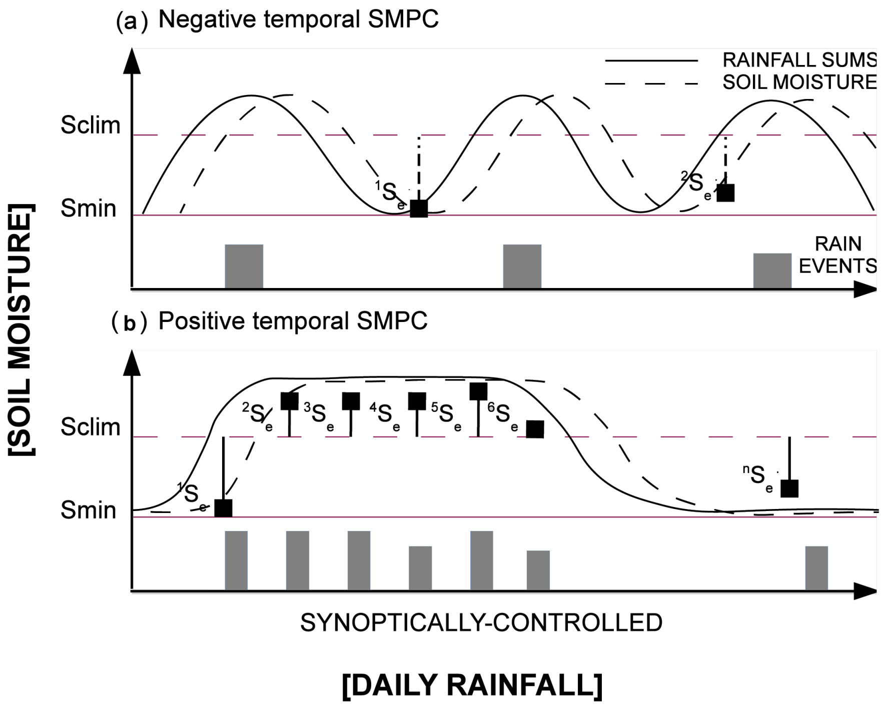


Figure 5.9: Conceptual diagram showing the relationship between daily rainfall occurrence and associated to it surface moisture variability in time as representative for (a) West Africa and (b) Central Europe or temperate latitudes.

5.4 Summary and conclusions

In this study, the soil moisture - precipitation coupling (SMPC) relationship in the northern African region is investigated at 1° horizontal resolution using the probability-based approach of T12 and the 10 years of satellite-based soil moisture and precipitation data. Specifically, we distinguish and analyze the temporal and spatial effects of the soil moisture on the afternoon convective rain.

We find that in the North African region spatial and temporal effects of soil moisture on afternoon precipitation are negative and are not independent of one another. The negative sign of the temporal coupling in the semi-arid conditions of the Sahelian environment is not unexpected. The drying of the soil for several days prior to the rainfall events explains the preference of rain to occur over temporally drier soils, and additionally may justify the opposite sign of the temporal coupling as compared to the positive relationship identified in wetter climates by G15.

The co-existence and co-variability of negative temporal and spatial SMPC across the Sahel supports the idea of soil moisture effects on convection triggering being a two-dimensional and not one-dimensional phenomenon as suggested by earlier studies. Furthermore, it also hints on the relevance of processes associated with the dominance of sensible heat flux and boundary layer growth on convection development. In particular, the identified preference of rainfall to occur over temporally drier soils and strong negative soil moisture gradients might be considered as the most effective combination to maximize both, the buoyancy and moisture flux in event location through formation of the thermally-induced circulations, and hence lead to a higher probability of convection development. Schematic representation of the moist convection intensification by the breeze-like circulations formed under the co-existence of the two SMPC effects is illustrated in Figure 5.10

Analysis of the BL moisture conditions (here, LCL) preceding the rainfall events suggests that the co-existence of two coupling effects, and hence potential role of "breeze-like" circulations on convection development is expected to be more relevant in the South of the domain, where BL moisture is in abundance. In the drier northern latitudes variability of BL moisture, associated to intrusions of moisture from the south, seems to be more decisive.

Analysis of the spatial SMPC measure as well as factors which can affect its magnitude and variability in particular reveals two "hotspots" of significant negative spatial coupling in the South, i.e. the Western Sahel (7 - 15°N, 10°W - 7°E), and South Sudan in the East (5 - 13°N, 24 - 34°E). In the Western domain the negative spatial SMPC signal is indicated to be most robust. In the East, the spatial coupling is found to be largely modulated by the presence of wetlands and is susceptible to the amount of longer-lived propagating MCS. The number of propagating and mature MCS in the East increases towards late afternoon. Accordingly, changing the rainfall accumulation time period from early to late afternoon leads to a decrease in significance of the negative SMPC and a switch of its sign to a positive one. Conversely, in the West majority of convective systems might be expected to be short-lived, and therefore smaller and less organized. In this region, negative spatial SMPC varies less with the selected afternoon time range.

Another factor which affects the magnitude and distribution of the spatial SMPC is related to the presence of extreme soil moisture gradients formed in the vicinity of wetlands and irrigated land. We find that removal of extremes leads to a decrease of the number of boxes with significant negative spatial coupling by 30%. Concurrently, the identified sensitivity of the afternoon rainfall to the strong gradients in soil moisture adjacent to wetland areas hints on the relevance of wetland-breeze mechanism on convection intensification over spatially drier soils.

Following our analysis, a number of framework limitations might be summarized. Apparent non-local effects of water bodies and strong elevation height differences, that are originally excluded by the method, hints on the potential gaps in the filtering procedure and emphasizes not-accounted by the method role of moist convection evolution and propagation. The presence of wetland regions itself as we have shown complicates interpretation of the SMPC relationships. The uncertainty estimates of the soil moisture parameter derived over the recursively flooded regions are still missing.

Notwithstanding these limitations, this study demonstrates that the observed SMPC statistics is consistent with a number of characteristic features of the physical effects and agrees on the sign of the soil moisture - precipitation coupling suggested by previous case- and modelling studies. The identified surface-related effects are evident only at the highest considered 1° event-aggregation scale, hence indicating the advantage of the finer scale over the coarser 5 ° grid. The knowledge on the regional variability of the SMPC presented here is valuable, and can be further used in drought and climate change research, in the observational campaigns and as a basis for GCMs validation. The identified here co-existence and co-variance of the temporal and spatial SMPC relationships is not expected to be bounded to the region of the Sahel, and is likely to be applicable to other transitional climates.

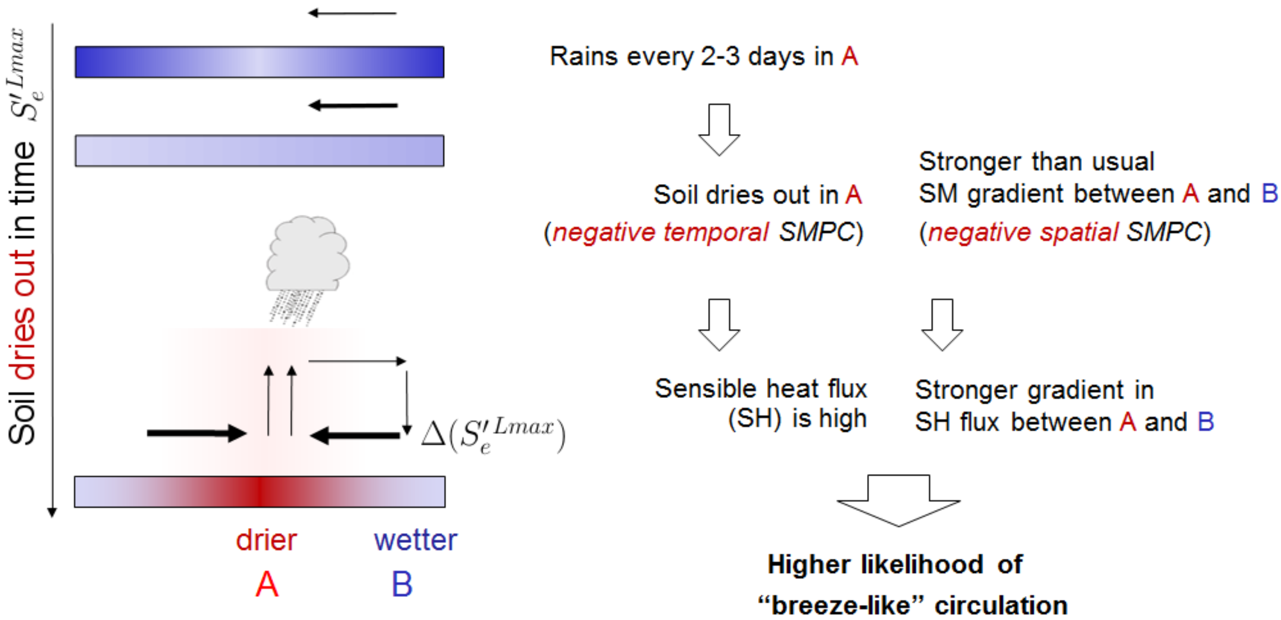


Figure 5.10: Conceptual diagram illustrating intensification of moist convection initiated by "breeze-like" circulation under favourable condition of co-existing negative spatial and negative temporal SMPC effects.

Chapter 6

Summary and Conclusions

6.1 Summary of most relevant findings

A prominent role of land surface in atmospheric dynamics and moist convection development in North Africa and remaining uncertainty of the mechanisms involved in this interaction explains the need for a better understanding of the coupling between soil moisture and precipitation. The results presented in this thesis contribute to this understanding by

(1) evaluating the link between the soil moisture conditions and subsequent rainfall over 1° horizontal resolution using multi-year satellite data;

(2) investigating regional variability of the SMPC, represented by two separate effects, i.e. spatial and temporal effects of soil moisture on rainfall, and

(3) establishing the link between the obtained SMPC relationships and known physical processes.

This is done using 10-years (2002-2011) of state-of-the-art daily satellite-based estimates of AMSR-E soil moisture and TMPA-v7 precipitation. A probability-based framework of Taylor et al. (2012) (hereafter, T12) is reproduced and applied to the data in order to define a sample of convective rainfall events, isolate effect of soil moisture on afternoon precipitation, and estimate the soil moisture-precipitation coupling (SMPC) relationship. The study focuses on the monsoon period only, i.e. JJAS months. First, the analysis of the method limitations and advantages is carried out (Chapter 4).

6.1.1 Evaluation of the probability-based method of T12

The main advantage and a novelty of the T12 method in comparison to other existing frameworks is its spatial approach, i.e. the established relationship between the spatial variability in soil moisture and moist convection development. This also allows to circumvent the problem of rainfall persistence inherent to all the other probability-type analysis as both spatial locations are likely to exhibit the same large-scale atmospheric conditions. The spatial approach of T12, therefore, provides a better isolation of the soil moisture forcing on precipitation.

One of the major limitations of the method remains being the size of the rainfall event sample. Accordingly, the length of the input satellite data, reduction of the events due to masks introduced by the method, as well as the threshold of the afternoon accumulated precipitation (AAP) value contribute to the size limitation. The latter condition is one of the central method constrains, which is used to define a convective rainfall event. The critical AAP threshold value with respect to the SMPC significance loss is identified as being 15 mm/9hrs - the value, which corresponds to the reduction of the initial amount of rainfall events by two times. Beyond that, reduction of the sample size does not seem to strongly affect preference of rainfall to occur over spatially drier soils, emphasizing (i) robustness of the negative spatial coupling signal in North African region as well as (ii) more deterministic role of the assumptions used in the method.

The results of the sensitivity tests show that especially the geometry of the rainfall field is found to be relevant. Particularly, the areal extent and distribution of the AAP strongly modulate the significance and magnitude of the SMPC measure. In this way, the probability of negative spatial coupling is found to be maximized when (i) the rain events with smaller AAP area are considered and (ii) the spatial distribution of the AAP is taken into account. While the former finding (i) hints on the relevance of the MCS size and organization for higher/lower sensitivity of moist convection to spatial soil moisture variability, the latter finding (ii) clearly demonstrates that the spatial variability does matter for system development. The results show that rainfall not only tends to propagate towards drier soils but also "avoids" wetter surrounding. This provides a potential for further homogenization of the surface moisture in space.

Answering the questions posed by the sensitivity analysis, it can be concluded that:

(i) - the original set up of the T12 method can be overall considered as being optimal for maximizing negative spatial SMPC relationship, and

(ii) - the preference of rainfall to occur over spatially drier soils as defined by the method is robust.

However, the results presented in this study further indicate that the physical interpretation of the AAP threshold used in the method, especially in its lower range, is not trivial. Therefore, its application might be reconsidered. In this way, additionally accounting for the size of MCSs could provide more physical meaning and hence can add to the interpretation of the SMPC results in the follow on studies. Furthermore, the identified sensitivity of the SMPC measure to the AAP geometry overall hints on the relevance of the horizontal scales of processes and parameters involved in the

SMPC. In this respect, the role of resolved variability of input data within every 1.25° event box might equally affect or even predefine coupling results. This aspect therefore should be explored in depth in the future.

6.1.2 SMPC in the North African domain at 1° horizontal resolution. Spatial and temporal effects.

The major findings on the soil moisture - precipitation coupling in the North African domain are organized along the main research questions posed in the beginning of this thesis:

(I) - How does the spatial and temporal SMPC vary across the North African region, and do "hot-spots" exist?

A clear dominance of the negative spatial and negative temporal SMPC relationships is identified over the North African region.This co-existence is shown to be robust with respect to the smaller, i.e. 1° event aggregation scale. However, the two regions in the south of the domain stand out, revealing the strongest and significant deviations from their local typical conditions. These are the Western Sahel (7 - 15°N, 10°W - 7°E), and South Sudan in the East (5 - 13°N, 24 - 34°E). Both regions indicate a strong preference of rainfall to occur over spatially and temporally drier soils. At the same time these regions occupy areas of the highest low-atmospheric moisture content in the domain. This combination supports higher relevance of drier soils and hence mechanisms related to boundary layer growth for moist convection triggering. In the drier northern latitudes, on the contrary, role of spatial variability in soil moisture for moist convection initiation is expected to be strongly reduced, while variability in boundary layer moisture seems to be more decisive. Hence, the two featured regions in the West and East of the North can be considered as the regional "hot spots" of the SMPC.

(II) - Are the spatial and temporal SMPC relationships independent of one another, and if not - how do they inter-relate?

The results of the correlation analysis indicate that the two coupling effects are not independent of one another. The latter implies that if the afternoon rainfall falls over temporally drier soils, it is likely to be surrounded by a wetter environment. This combination could be particularly favourable for initiation of local "breeze-like" circulations, which would imply a higher buoyancy and moisture flux in event location, and as a result higher probability of convection development. Following the argumentation of the previous paragraph, this mechanism is expected to be more efficient in the two featured regions in the East and West. Considering a relatively weak mean surface wind of 2-3 m/s observed prior to the rainfall events over these latitudes, the meso-scale circulations are likely to be initiated.

Further analysis indicates, that the negative sign of the temporal SMPC is not unexpected in the semi-arid environment of North Africa. Typical 2-3 day periodicity of rain events in the area and the associated strong drying of the soil prior to the next rain, explains resulting preference of rainfall to occur over temporally drier soils. For comparison, persistence of rain events during synoptically prime conditions in wet climates leads to prolonged wetter soil conditions and a positive temporal SMPC. The latter argumentation helps explaining opposite sign of the temporal SMPC in the Sahel as compared to wet climates identified by G15. To corroborate the work of G15, it can be noted that the temporal SMPC relationship in North Africa is not expected to reflect preference of rainfall to occur over soils with the higher or lower soil moisture content, and should be rather considered as being a consequence of the identified negative spatial SMPC relationship.

(III)- Which physical processes underlie the estimated SMPC relationships?

A number of factors linked to characteristic features of physical effects is identified to underlie the spatial SMPC relationship and to affect its magnitude and variability. The most relevant one is attributed to the presence of wetland and irrigated land regions in the East and West, and their effect on moist convection triggering and re-intensification. Extreme negative soil moisture gradients identified in the vicinity of floodlands contribute to significance of the negative SMPC in 30% of the grid boxes. Preference of rain events to occur over these gradients hints on the relevance of the "wetland-breeze" mechanism for moist convection intensification.

Another physical effect that influences the SMPC and that is not accounted for by the current algorithm is related to the propagation and growth of meso-scale convective systems (MCS). The number of large and organized MCS increases towards late afternoon in the region, resulting in an increasing preference of rainfall to occur over wetter soils. The latter is reflected in a decrease of the significance and magnitude of the negative spatial SMPC towards late afternoon. In the East, the spatial coupling even switches sign to a positive one when calculated for the late afternoon times. The negative spatial coupling in the West varies less, and is therefore most robust.

Overall, the identified link to the wetlands and the observed sensitivity of the spatial coupling to the MCS life cycle further supports the potential relevance of the "breeze-like" circulations in the preferential development of convection over spatially drier soils, suggested by the identified co-existence of the spatial and temporal SMPC.

6.2 Discussion

Application of the multi-year satellite-derived soil moisture product from AMSR-E and the precipitation product from TMPA is crucial for enhancing the understanding of the SMPC in the North African region. Especially in the east of North Africa, where no long-term ground measurements exist and the estimates of the SMPC are generally missing, satellite-based products might be the only choice. The identified regions of the strong SMPC would therefore require more modelling and observational activities especially in eastern North Africa in the near future. The ongoing satellite missions SMOS (Soil Moisture Ocean Salinity) and the more recently launched Soil Moisture Active Passive (SMAP) satellite provide state-of-the-art estimates of soil moisture for an improved SMPC quantification and validation of modelling results. The increase in availability, time span and quality of satellite estimates, in turn, raises demand in the statistical tools. In this view, the novel, spatial approach of the method of T12, applied and tested in the present study, together with its simplicity holds much potential for its further applicability and improvement.

One of the main advantages of the T12 framework in general, and of the results presented in this thesis in particular, refers to the demonstration of the sensitivity of moist convection development to the underlying soil moisture conditions. Previously, this dependence was hypothesized by simulations with the cloud-resolving models (e.g. Lynn et al., 1998). The case-studies of Taylor and Ellis (2006) and Taylor (2010) were the first to demonstrate that a MCS at the early stage of its development followed the distribution of the underlying soil moisture. Using the T12 approach, the results of the sensitivity tests presented in this thesis could explicitly demonstrate that accounting for the rainfall distribution as a response parameter is essential, as it maximizes the probability of the negative spatial SMPC. As the latter evidence is based on statistics of thousands of rain events, it further implies that the idea of rainfall "avoiding" wetter soils suggested by earlier case studies may well be a systematic feature in the North African region, and therefore may have further implications for the rainfall predictability.

The general drawback of the T12 approach and other probability-type methods can be identified as their inability to account for all potentially relevant factors, also because the latter comes at the expense of the sample size, and hence significance of obtained relationships. Among other factors, the maturity and size of the MCSs have shown to be relevant, as it influences the sensitivity of moist convection to surface conditions and may therefore affect the sign of the coupling (case studies, Taylor (2010); Gantner and Kalthoff (2010)). The current set up of the T12 method does not account for evolution and propagation of MCSs. This likely leads to a superposition of locally originated convection and pre-existed westward propagated MCSs, and therefore results in a combination of distinct SMPC mechanisms in a single sample. Using a simplified approach, the present study demonstrates that stratification of MCS by their properties affects the spatial SMPC. Consideration of the rain events with smaller rain field area (Chapter 4) and at the early stage of their development (Chapter 5) in the present framework significantly increases the probability of a negative spatial coupling signal. The relevance of the MCS stage and organisation for SMPC is not expected to be bounded to the Sahel area (Ford et al., 2015). Hence, consideration of the MCS properties should be understand as being necessary in the probability-type methods in general, especially when using rainfall as a response parameter.

In addition to MCS organization, the relevance of spatial scales should be also taken into account. Analysis of the individual rain cases in the present study indicates that a separately evolving (i.e. isolated) cell, even being a part of a large and mature MCS, may still be sensitive to the spatial gradients in soil moisture and evolve over drier soils. These results hint on the relevance of the horizontal scales of processes involved in the SMPC, and therefore resolved variability of input parameters, rather than system organization per se. Yet, the role of scales and parameter resolution in the SMPC remains being a challenging issue, and is an open question of the research field in general (Clark et al., 2003, 2004; Taylor and Ellis, 2006).

Another essential limitation of the method relates to the choice of the soil moisture anomaly as a forcing parameter. The spatial difference in the soil moisture anomaly does not allow to judge on the resulting contribution of surface fluxes on the boundary layer state. In this view, substantial differences in the interpretation of the obtained SMPC relationship might be expected in the wetter southern latitudes, where the deeper soil layers as well as emergent vegetation modulate the surface fluxes, especially during the wetter phase of the monsoon. Therefore, supporting the analysis with existing satellite-based evapotransiration products in the future could shed new light on the process-oriented understanding of the presented SMPC results.

Notwithstanding the above limitations, the method demonstrates its ability to preserve a number of characteristic features of physical processes. The results obtained with this method fit into the mechanistic framework developed by previous case-studies over West Africa (e.g. Taylor and Ellis, 2006; Garcia-Carreras et al., 2011) that links the spatial variability in soil moisture to moist convection development. The SMPC "hot-spot" in the East, identified in the present study, provides the first insight into the SMPC relationship in this region, as no accurate estimates of the coupling exist for the region beyond 15° E. This finding, therefore, reveals a number of further relevant implications.

First, the identified link between the negative spatial SMPC and flooded areas suggests that the role of wetlands in initiation and re-intensification of the moist convection is not expected to be bounded to the Niger Inland Delta only (Taylor, 2010), but it is likely to be equally or even more relevant (due to frequent MCS initiation at the Ethiopian Highlands) in the East. If this is the case, wetlands of the Ez Zeraf Game Reserve at 30°E might be expected to strongly affect convection and hydrology in the region, as well as in the rest of the Sahel through formation of the long-lived MCS, which can further develop into the African Easterly Waves (Laing and Carbone, 2008; Laing et al., 2012). The propagating nature of moist convection in this region, and the rainfall intensification downwind of the wetlands, demonstrated in the present study, supports this possibility.

Second, the identified strong sensitivity of the spatial SMPC to the maturity and size of MCSs in the East may have additional implications for climate change analyses. The negative SMPC sign identified for the MCSs at the early stage of their development hints on the homogenization of the moisture on land, while positive SMPC of the mature and large MCS would be consistent with the mechanisms of rainfall persistence. The two effects together may represent contrasting impacts of a warmer climate on rainfall variability in the region. This hypothesis is not new (Nicholson, 2015), although no studies yet were directly addressing this issue. Considering the higher relevance of mature MCSs on total seasonal rainfall in North Africa in general, the identified positive SMPC might be of more relevance.

Finally, the identified link of the temporal SMPC to the drying cycle of the soils suggests overall low predictability potential of the temporal effect on rainfall in the region. On the contrary, the spatial negative SMPC implies that the next rain will likely occur in the vicinity of the previous rainfall, just shifted towards the drier soil (Schwendike et al., 2010), and hence may have more relevance for the rainfall predictability. In this view, the SMPC "hot-spots" identified in the present study may represent the regions where predictability skill might be higher than anywhere else in the domain.

6.3 Research perspectives

6.3.1 Temporal variability of SMPC in North Africa

One of the main advantages and expectations from the application of the multi-year satellite data for the SMPC analysis is its ability to provide variability estimates to the SMPC relationship in space and time. The analysis presented in this thesis gave an insight into the spatial variability of the coupling. It appears therefore natural to ask next, how does SMPC vary in time?

The relevance of this question for the Sahel area is particularly high. The region experiences droughts of varying severity every 2-3 years, and is still in the recovery stage from the most dramatic drought of 1980s. The knowledge on the strength of the SMPC and its sign may indicate whether the drought conditions are likely to be intensified or dampened by SMPC. Considering presence of the regional coupling "hot spots" identified by the present study, one can further suggest that the response to the drought conditions will also vary between the regions. The follow up study using the same method of T12 might therefore provide further insight into this aspect.

Preliminary analysis of the inter-annual variability of the coupling in North Africa has indicated that spatial SMPC measure as defined by the method of T12 varies in phase with variability in rainfall (Fig.6.1). Moreover, the Eastern region shows much higher correlation to the rainfall index than the West, likely related to the annual variability in wetland extend. However, whether the latter hypothesis is true, and whether SMPC dependence on the rainfall provide some causality, is a matter of the follow up research.

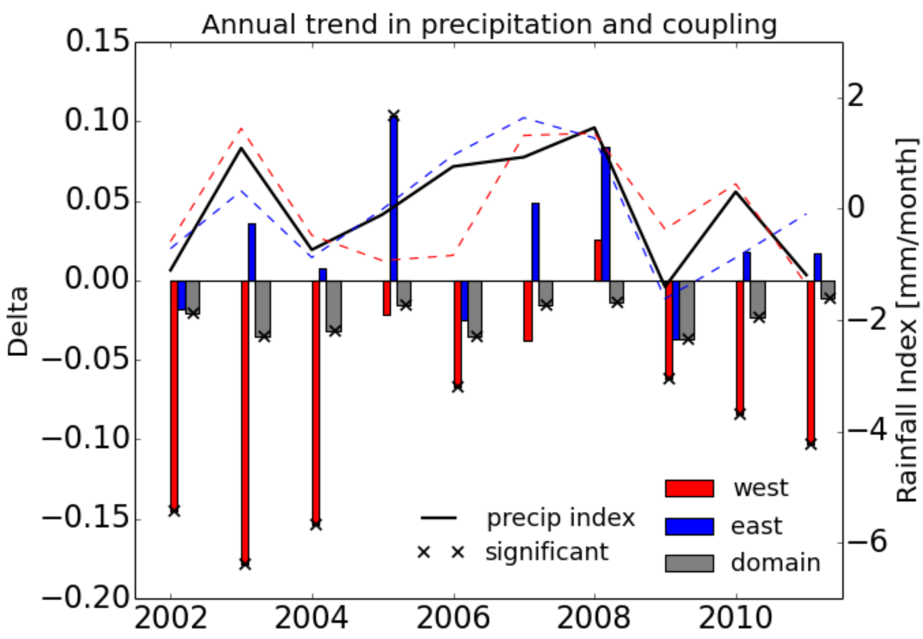


Figure 6.1: (lines): Annual variability of rainfall index estimated over the complete North African (black solid line), western (red dashed line) and eastern (blue dashed line) domains for the period of 2002-2010, and (bars): corresponding changes of δ_e values representing spatial SMPC measure. The rainfall averages are not detrended and are standardized such that the mean and standard deviation of the series are 0 and 1 accordingly. Black crosses indicate significant δ_e. Significance is estimated using 1000 bootstraps and percentile threshold of $<$10% and $>$ 90%

6.3.2 Other relevant aspects to consider

Various issues could not be addressed within the scope of the present work and are left for future studies. On of them is related to the effect of Logone floodplains in the vicinity of the lake Chad on moist convection development. Analysis of the extreme soil moisture gradients attributed to the spatial SMPC in the present study did not reveal the strong link to the Logone floodplains (Fig. 5.3-5.4). However, wetlands can be expected to influence MCS dynamics in a similar manner anywhere in the domain. The role of the lake Chad on the intensification and suppression of MCSs was, for example, demonstrated by the modelling study of (Lauwaet et al., 2012). Hence, a separate research devoted to a better understanding of the role of wetlands on MCS dynamics and SMPC could be initiated, and would have a direct implications for regional hydrology, rainfall predictability, as well as potential impacts of climate change.

The "hot-spots" of the SMPC identified in the present study also correspond to the regions with the highest boundary layer moisture, and hence cloudiness in the domain. Preliminary analysis of the ERA-Interim data indicate that the dominant contribution into the morning cloud cover in both locations comes from the low level clouds. On the one hand, the presence of low clouds may indicate a reduction of the incoming short-wave radiation on these days leading to a potentially more stable and shallower BL. On the other hand, shallow morning convection may develop into a deep convection during the course of the day. The implications of clouds on the spatial SMPC remains being unknown. The present set up of the method only accounts for the absence of precipitation during morning hours, but does not exclude the clouds. Accordingly, the separation of the days into the clear sky and overcasted days would be a logical next step to refine and improve interpretation of the obtained SMPC results.

The satellite-based soil moisture estimates provide information only from the first few centimetres of soil depth. In the south of the domain the effect of deeper soil layers as well as vegetation should become more relevant, especially during wetter monsoon phase. Both effects are expected to modulate spatial gradients in surface fluxes, reducing the magnitude of BL moisture anomaly above. The latter should therefore reduce the sensitivity of moist convention to the spatial soil moisture gradient, and therefore decrease the probability to observe a spatial SMPC. This aspect should be investigated in more detail.

The current set up of the method does not account for the underlying land cover conditions. Additional flagging of the land cover properties could allow better filtering of rain events, and therefore more accurate interpretation of the SMPC results. Additionally performed analysis suggests that soil drying rate calculated from the soil moisture parameter might be sufficient to provide a basic knowledge on the type of the surface without acquiring additional land cover information. In this way, locations where the drying rate varies less, and is always high can be representative e.g. for the flooded areas, while regions where drying rate is always small regardless the soil moisture range can indicate surfaces with strong draining like e.g. stone desert. It is further suggested that accurately defined parameter of the drying rate may be used as a proxy to estimate the differences in evapotranspiration flux between the neighbouring locations. This in turn may provide additional information on potential contribution of the soil moisture gradient on the boundary layer state. The potential of using drying rate parameter in the future should be therefore investigated.

Bibliography

Adler, B., Kalthoff, N., and Gantner, L. (2011). The impact of soil moisture inhomogeneities on the modification of a mesoscale convective system: An idealised model study. *Atmospheric Research*, 101(1-2):354–372.

Alonge, C. J., Mohr, K. I., and Tao, W.-K. (2007). Numerical Studies of Wet versus Dry Soil Regimes in the West African Sahel. *Journal of Hydrometeorology*, 8(1):102–116.

Alter, R., Im, E., and Eltahir, E. (2015). Rainfall consistently enhanced around the Gezira Scheme in East Africa due to irrigation. *Nature Geoscience*, (September).

Amante, C. and Eakins, B. (2009). ETOPO1 1 arc-minute global relief model: procedures, data sources and analysis.

Atlas, R., Wolfson, N., and Terry, J. (1993). The effect of SST and soil moisture anomalies on GLA model simulations of the 1988 US summer drought. *Journal of Climate*.

Avissar, R. and Schmidt, T. (1998). An evaluation of the scale at which ground-surface heat flux patchiness affects the convective boundary layer using large-eddy simulations. *Journal of the Atmospheric Sciences*, (1995):2666–2689.

Baldi, M., Dalu, G. A., and Pielke, R. A. (2008). Vertical Velocities and Available Potential Energy Generated by Landscape Variability—Theory. *Journal of Applied Meteorology and Climatology*, 47(2):397–410.

Barthe, C., Asencio, N., Lafore, J.-P., Chong, M., Campistron, B., and Cazenave, F. (2010). Multi-scale analysis of the 25-27 July 2006 convective period over Niamey: Comparison between Doppler radar observations and simulations. *Quarterly Journal of the Royal Meteorological Society*, 136(S1):190–208.

Betts, A. and Ball (1996). The land surface -atmosphere interaction: A review based on observational and global modeling perspectives. *Journal of Geophysical Research*, 101:7209–7225.

Biasutti, M., Held, I., Sobel, A., and Giannini, A. (2008). SST forcings and Sahel rainfall variability in simulations of the twentieth and twenty-first centuries. *Journal of Climate*, pages 3471–3486.

Birch, C. E., Parker, D. J., O'Leary, A., Marsham, J. H., Taylor, C. M., Harris, P. P., and Lister, G. M. S. (2013). Impact of soil moisture and convectively generated waves on the initiation of a West African mesoscale convective system. *Quarterly Journal of the Royal Meteorological Society*, 139(676):1712–1730.

Boé, J. (2012). Modulation of soil moisture–precipitation interactions over France by large scale circulation. *Climate Dynamics*, 40(3-4):875–892.

Charney, J. (1975). Dynamics of deserts and drought in the Sahel. *Quarterly Journal of the Royal Meteorological Society*, 101(March 1974).

Chen, F. and Avissar, R. (1994). Impact of land-surface moisture variability on local shallow convective cumulus and precipitation in large-scale models. *Journal of Applied Meteorology*.

Cheresnick, D. R. and Basara, J. B. (2005). The Impact of Land–Atmosphere Interactions on the Benson, Minnesota, Tornado of 11 June 2001. *Bulletin of the American Meteorological Society*, 86(5):637–642.

Clark, D., Taylor, C., and Thorpe, A. (2004). Feedback between the land surface and rainfall at convective length scales. *American Meteorological Society*, pages 625–639.

Clark, D. B., Taylor, C. M., Thorpe, a. J., Harding, R. J., and Nicholls, M. E. (2003). The influence of spatial variability of boundary-layer moisture on tropical continental squall lines. *Quarterly Journal of the Royal Meteorological Society*, 129(589):1101–1121.

Collow, T., Robock, A., and Wu, W. (2014). Influences of soil moisture and vegetation on convective precipitation forecasts over the United States Great Plains. *Journal of Geophysical Research: Atmospheres*, pages 9338–9358.

Courel, M., Kandel, R., and Rasool, S. (1984). Surface albedo and the Sahel drought.

Couvreux, F., Guichard, F., Gounou, a., Bouniol, D., Peyrillé, P., and Köhler, M. (2013). Modelling of the Thermodynamical Diurnal Cycle in the Lower Atmosphere: A Joint Evaluation of Four Contrasted Regimes in the Tropics Over Land. *Boundary-Layer Meteorology*, 150(2):185–214.

Couvreux, F., Rio, C., Guichard, F., Lothon, M., Canut, G., Bouniol, D., and Gounou, a. (2012). Initiation of daytime local convection in a semi-arid region analysed with high-resolution simulations and AMMA observations. *Quarterly Journal of the Royal Meteorological Society*, 138(662):56–71.

Cuesta, J., Lavaysse, C., Flamant, C., Mimouni, M., and Knippertz, P. (2010). Northward bursts of the West African monsoon leading to rainfall over the Hoggar Massif, Algeria. *Quarterly Journal of the Royal Meteorological Society*, 136(S1):174–189.

Dirmeyer, P. (2009). Precipitation, recycling, and land memory: An integrated analysis. *Journal of Hydrometeorology*, 10:278–288.

Dirmeyer, P., Koster, R., and Guo, Z. (2006). Do global models properly represent the feedback between land and atmosphere? *Journal of Hydrometeorology*, pages 1177–1198.

Dirmeyer, P. and Wang, Z. (2014). Intensified land surface control on boundary layer growth in a changing climate. *Geophysical Research Letters*, 45:1290–1294.

Dirmeyer, P. a. (2011). The terrestrial segment of soil moisture-climate coupling. *Geophysical Research Letters*, 38(16).

Dirmeyer, P. a., Cash, B. a., Kinter, J. L., Stan, C., Jung, T., Marx, L., Towers, P., Wedi, N., Adams, J. M., Altshuler, E. L., Huang, B., Jin, E. K., and Manganello, J. (2012). Evidence for Enhanced Land–Atmosphere Feedback in a Warming Climate. *Journal of Hydrometeorology*, 13(3):981–995.

Dirmeyer, P. a., Jin, Y., Singh, B., and Yan, X. (2013a). Evolving Land–Atmosphere Interactions over North America from CMIP5 Simulations. *Journal of Climate*, 26(19):7313–7327.

Dirmeyer, P. a., Jin, Y., Singh, B., and Yan, X. (2013b). Trends in Land–Atmosphere Interactions from CMIP5 Simulations. *Journal of Hydrometeorology*, 14(3):829–849.

Dixon, N. S., Parker, D. J., Taylor, C. M., Garcia-Carreras, L., Harris, P. P., Marsham, J. H., Polcher, J., and Woolley, a. (2013). The effect of background wind on mesoscale circulations above variable soil moisture in the Sahel. *Quarterly Journal of the Royal Meteorological Society*, 139(673):1009–1024.

Doran, J., Shaw, W., and Hubbe, J. (1995). Boundary layer characteristics over areas of inhomogeneous surface fluxes. *American Meteorological Society*.

Dorigo, W. a., Scipal, K., Parinussa, R. M., Liu, Y. Y., Wagner, W., de Jeu, R. a. M., and Naeimi, V. (2010). Error characterisation of global active and passive microwave soil moisture datasets. *Hydrology and Earth System Sciences*, 14(12):2605–2616.

Duvel, J. (1990). Convection over tropical Africa and the Atlantic Ocean during northern summer. Part II: Modulation by easterly waves. *Monthly Weather Review*, 118:1885–1868.

Ek, M. and Holtslag, A. (2004). Influence of soil moisture on boundary layer cloud development. *Journal of Hydrometeorology*, (section 2):86–99.

Ek, M. and Mahrt, L. (1994). Daytime evolution of relative humidity at the boundary layer top. *American Meteorological Society*, 122:2709–2721.

Eltahir, E. and Pal, J. (1996). Relationship between surface conditions and subsequent. *Journal of Geophysical Research*, 101.

Eltahir, E. a. B. (1998). A Soil Moisture-Rainfall Feedback Mechanism: 1. Theory and observations. *Water Resources Research*, 34(4):765–776.

Entekhabi, D., Rodriguez-Iturbe, I., and Bras, R. (1992). Variability in large-scale water balance with land surface-atmosphere interaction. *Journal of Climate*.

Evans, C., Schumacher, R. S., and Galarneau, T. J. (2011). Sensitivity in the Overland Reintensification of Tropical Cyclone Erin (2007) to Near-Surface Soil Moisture Characteristics. *Monthly Weather Review*, 139(12):3848–3870.

Ferguson, C. R. and Wood, E. F. (2011). Observed Land–Atmosphere Coupling from Satellite Remote Sensing and Reanalysis. *J. Hydrometeor*, 12(6):1221–1254.

Findell, K. and Eltahir, E. (2003a). Atmospheric controls on soil moisture-boundary layer interactions. Part I: Framework development. *Journal of Hydrometeorology*, pages 552–569.

Findell, K. and Eltahir, E. (2003b). Atmospheric controls on soil moisture-boundary layer interactions. Part II: Feedbacks within the continental United States. *Journal of Hydrometeorology*, pages 570–583.

Findell, K. and Gentine, P. (2015). Data length requirements for observational estimates of land–atmosphere coupling strength. *American Meteorological Society*.

Findell, K. L., Gentine, P., Lintner, B. R., and Kerr, C. (2011). Probability of afternoon precipitation in eastern United States and Mexico enhanced by high evaporation. *Nature Geoscience*, 4(7):434–439.

Fischer, E. M., Seneviratne, S. I., Lüthi, D., and Schär, C. (2007a). Contribution of land-atmosphere coupling to recent European summer heat waves. *Geophysical Research Letters*, 34(6):L06707.

Fischer, E. M., Seneviratne, S. I., Vidale, P. L., Lüthi, D., and Schär, C. (2007b). Soil Moisture–Atmosphere Interactions during the 2003 European Summer Heat Wave. *Journal of Climate*, 20(20):5081–5099.

Ford, T. W., Rapp, a. D., Quiring, S. M., and Blake, J. (2015). Soil moisture–precipitation coupling: observations from the Oklahoma Mesonet and underlying physical mechanisms. *Hydrology and Earth System Sciences*, 19(8):3617–3631.

Froidevaux, P., Schlemmer, L., Schmidli, J., Langhans, W., and Schär, C. (2013). Influence of the Background Wind on the Local Soil Moisture-Precipitation Feedback. *Journal of the Atmospheric Sciences*, page 131004144514007.

Gaertner, M. a., Domínguez, M., and Garvert, M. (2010). A modelling case-study of soil moisture-atmosphere coupling. *Quarterly Journal of the Royal Meteorological Society*, 136(S1):483–495.

Gallego-Elvira, B. and Taylor, C. (2016). Global observational diagnosis of soil moisture control on the land surface energy balance. *Geophysical Research Letters*, pages 2623–2631.

Gantner, L. and Kalthoff, N. (2010). Sensitivity of a modelled life cycle of a mesoscale convective system to soil conditions over West Africa. *Quarterly Journal of the Royal Meteorological Society*, 136(S1):471–482.

Garcia-Carreras, L., Parker, D. J., and Marsham, J. H. (2011). What is the Mechanism for the Modification of Convective Cloud Distributions by Land Surface–Induced Flows? *Journal of the Atmospheric Sciences*, 68(3):619–634.

García-Herrera, R., Díaz, J., Trigo, R. M., Luterbacher, J., and Fischer, E. M. (2010). A Review of the European Summer Heat Wave of 2003. *Critical Reviews in Environmental Science and Technology*, 40(4):267–306.

Gentine, P., Garelli, A., and Park, S. (2016). Role of surface heat fluxes underneath cold pools. *Geophysical Research Letters*.

Goessling, H. F. and Reick, C. H. (2011). What do moisture recycling estimates tell us? Exploring the extreme case of non-evaporating continents. *Hydrology and Earth System Sciences*, 15(10):3217–3235.

Goessling, H. F. and Reick, C. H. (2013). Continental moisture recycling as a Poisson process. *Hydrology and Earth System Sciences*, 17(10):4133–4142.

Goutorbe, J., Lebel, T., and Tinga, A. (1994). HAPEX-Sahel: a large-scale study of land-atmosphere interactions in the semi-arid tropics. *Annales Geophysicae*, 12(1):53–63.

Goyens, C. and Lauwaet, D. (2011). Tracking mesoscale convective systems in the Sahel: relation between cloud parameters and precipitation. *International Journal of Climatology*, 1934(August):1921–1934.

Gruhier, C. and Rosnay, P. D. (2008). Evaluation of AMSR[U+2010]E soil moisture product based on ground measurements over temperate and semi[U+2010]arid regions. *Geophysical Research Letters*, 35:2–7.

Guichard, F., Kergoat, L., Mougin, E., and Timouk, F. (2009). Surface thermodynamics and radiative budget in the Sahelian Gourma: Seasonal and diurnal cycles. *Journal of hydrology*, 375(1-2):161–177.

Guillod, B., Orlowsky, B., and Miralles, D. (2015). Reconciling spatial and temporal soil moisture effects on afternoon rainfall. *Nature communications*, 6:1–6.

Guillod, B. P., Orlowsky, B., Miralles, D., Teuling, a. J., Blanken, P. D., Buchmann, N., Ciais, P., Ek, M., Findell, K. L., Gentine, P., Lintner, B. R., Scott, R. L., Van den Hurk, B., and I. Seneviratne, S. (2014). Land-surface controls on afternoon precipitation diagnosed from observational data: uncertainties and confounding factors. *Atmospheric Chemistry and Physics*, 14(16):8343–8367.

Guo, Z., Dirmeyer, P. a., Hu, Z.-Z., Gao, X., and Zhao, M. (2006). Evaluation of the Second Global Soil Wetness Project soil moisture simulations: 2. Sensitivity to external meteorological forcing. *Journal of Geophysical Research*, 111(D22):D22S03.

Hirschi, M., Seneviratne, S. I., Alexandrov, V., Boberg, F., Boroneant, C., Christensen, O. B., Formayer, H., Orlowsky, B., and Stepanek, P. (2010). Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. *Nature Geoscience*, 4(1):17–21.

Hohenegger, C., Brockhaus, P., Bretherton, C. S., and Schär, C. (2009). The Soil Moisture–Precipitation Feedback in Simulations with Explicit and Parameterized Convection. *Journal of Climate*, 22(19):5003–5020.

Holzman, B. (1937). *Sources of moisture for precipitation in the United States*. Number 58.

Huffman, G. J. and Bolvin, D. T. (2014). TRMM and Other Data Precipitation Data Set Documentation. Technical Report May, Mesoscale Atmospheric Processes Laboratory, NASA Goddard Space Flight Center.

Huffman, G. J., Bolvin, D. T., Nelkin, E. J., Wolff, D. B., Adler, R. F., Gu, G., Hong, Y., Bowman, K. P., and Stocker, E. F. (2007). The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales. *Journal of Hydrometeorology*, 8(1):38–55.

IPCC (2007). *Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]*. Cambridge University Press.

Janicot, S. and Thorncroft, C. (2008). Large-scale overview of the summer monsoon over West Africa during the AMMA field experiment in 2006. *Annales Geophysicae*, pages 2569–2595.

Kandji, S., Verchot, L., and Mackensen, J. (2006). Climate change and variability in the Sahel region: impacts and adaptation strategies in the agricultural sector. (254 20).

Klüpfel, V., Kalthoff, N., Gantner, L., and Kottmeier, C. (2011). Evaluation of soil moisture ensemble runs to estimate precipitation variability in convection-permitting model simulations for West Africa. *Atmospheric Research*, 101(1-2):178–193.

Klüpfel, V., Kalthoff, N., Gantner, L., and Taylor, C. M. (2012). Convergence zones and their impact on the initiation of a mesoscale convective system in West Africa. *Quarterly Journal of the Royal Meteorological Society*, 138(665):950–963.

Kohler, M., Kalthoff, N., and Kottmeier, C. (2010). The impact of soil moisture modifications on CBL characteristics in West Africa: A case-study from the AMMA campaign. *Quarterly Journal of the Royal Meteorological Society*, 136(S1):442–455.

Koster, R. D., Dirmeyer, P. a., Guo, Z., Bonan, G., Chan, E., Cox, P., Gordon, C. T., Kanae, S., Kowalczyk, E., Lawrence, D., Liu, P., Lu, C.-H., Malyshev, S., McAvaney, B., Mitchell, K., Mocko, D., Oki, T., Oleson, K., Pitman, A., Sud, Y. C., Taylor, C. M., Verseghy, D., Vasic, R., Xue, Y., and Yamada, T. (2004). Regions of strong coupling between soil moisture and precipitation. *Science (New York, N.Y.)*, 305(5687):1138–40.

Koster, R. D., Mahanama, S. P. P., Yamada, T. J., Balsamo, G., Berg, a. a., Boisserie, M., Dirmeyer, P. a., Doblas-Reyes, F. J., Drewitt, G., Gordon, C. T., Guo, Z., Jeong, J.-H., Lee, W.-S., Li, Z., Luo, L., Malyshev, S., Merryfield, W. J., Seneviratne, S. I., Stanelle, T., van den Hurk, B. J. J. M., Vitart, F., and Wood, E. F. (2011). The Second Phase of the Global Land–Atmosphere Coupling Experiment: Soil Moisture Contributions to Subseasonal Forecast Skill. *Journal of Hydrometeorology*, 12(5):805–822.

Koster, R. D., Suarez, M. J., Higgins, R. W., and Van den Dool, H. M. (2003). Observational evidence that soil moisture variations affect precipitation. *Geophysical Research Letters*, 30(5).

Laing, A. and Carbone, R. (2008). The propagation and diurnal cycles of deep convection in northern tropical Africa. *Quarterly Journal of the Royal Meteorological Society*, 109:93–109.

Laing, A. G., Trier, S. B., and Davis, C. a. (2012). Numerical Simulation of Episodes of Organized Convection in Tropical Northern Africa. *Monthly Weather Review*, 140(9):2874–2886.

Lare, A. R. and Nicholson, S. E. (1994). Contrasting Conditions of Surface Water Balance in Wet Years and Dry Years as a Possible Land Surface-Atmosphere Feedback Mechanism in the West African Sahel. *Journal of Climate*, 7:653–668.

Laureano Bozeman, M., Niyogi, D., Gopalakrishnan, S., Marks, F. D., Zhang, X., and Tallapragada, V. (2012). An HWRF-based ensemble assessment of the land surface feedback on the post-landfall intensification of Tropical Storm Fay (2008). *Natural Hazards*, 63(3):1543–1571.

Lauwaet, D. and van Lipzig, N. (2010). Impact of vegetation changes on a mesoscale convective system in West Africa. *Meteorol and atmospheric physics*, pages 109–122.

Lauwaet, D., van Lipzig, N. P. M., Van Weverberg, K., De Ridder, K., and Goyens, C. (2012). The precipitation response to the desiccation of Lake Chad. *Quarterly Journal of the Royal Meteorological Society*, 138(664):707–719.

Lohou, F., Kergoat, L., Guichard, F., Boone, A., Cappelaere, B., Cohard, J.-M., Demarty, J., Galle, S., Grippa, M., Peugeot, C., Ramier, D., Taylor, C. M., and Timouk, F. (2014). Surface response to rain events throughout the West African monsoon. *Atmospheric Chemistry and Physics*, 14(8):3883–3898.

Lothon, M. and Campistron, B. (2011). Life cycle of a mesoscale circular gust front observed by a C-band Doppler radar in West Africa. *Monthly Weather Review*.

Lynn, B., Tao, W., and Wetzel, P. (1998). A study of landscape-generated deep moist convection. *Monthly weather review*, (1995):928–942.

Mathon, V. and Laurent, H. (2001). Life cycle of Sahelian mesoscale convective cloud systems. *Quarterly Journal of the Royal Meteorological Society*, 127:377–406.

Mathon, V., Laurent, H., and Lebel, T. (2002). Mesoscale convective system rainfall in the Sahel. *Journal of applied meteorology*, 41:1081–1092.

McCaul, E. W. J. and Cohen, C. (2002). The impact on simulated storm structure and intensity of variations in the mixed layer and moist layer depths. *Monthly weather review*, pages 1722–1748.

Miralles, D. G., van den Berg, M. J., Teuling, a. J., and de Jeu, R. a. M. (2012). Soil moisture-temperature coupling: A multiscale observational analysis. *Geophysical Research Letters*, 39(21).

Mohr, K. and Thorncroft, C. (2006). Intense convective systems in West Africa and their relationship to the African easterly jet. *Quarterly Journal of the Royal Meteorological Society*, 132:163–176.

Nicholson, S. E. (2013). The West African Sahel: A Review of Recent Studies on the Rainfall Regime and Its Interannual Variability. *ISRN Meteorology*, 2013:1–32.

Nicholson, S. E. (2015). Evolution and current state of our understanding of the role played in the climate system by land surface processes in semi-arid regions. *Global and Planetary Change*, 133:201–222.

Njoku, E. and Jackson, T. (2003). Soil moisture retrieval from AMSR-E. *IEEE Transactions on Geoscience and Remote Sensing*, 41(2):215–229.

Orlowsky, B. and Seneviratne, S. I. (2010). Statistical Analyses of Land–Atmosphere Feedbacks and Their Possible Pitfalls. *Journal of Climate*, 23(14):3918–3932.

Owe, M., de Jeu, R., and Holmes, T. (2008). Multisensor historical climatology of satellite-derived global land surface moisture. *Journal of Geophysical Research*, 113(F1):F01002.

Pielke, R. (2001). Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. *Reviews of Geophysics*, (1999).

Redelsperger, J.-L., Thorncroft, C. D., Diedhiou, A., Lebel, T., Parker, D. J., and Polcher, J. (2006). African Monsoon Multidisciplinary Analysis: An International Research Project and Field Campaign. *Bulletin of the American Meteorological Society*, 87(12):1739–1746.

Salvucci, G. D., Saleem, J. a., and Kaufmann, R. (2002). Investigating soil moisture feedbacks on precipitation with tests of Granger causality. *Advances in Water Resources*, 25(8-12):1305–1312.

Schär, C., Lüthi, D., and Beyerle, U. (1999). The Soil-Precipitation Feedback : A Process Study with a Regional Climate Model. *Journal of Climate*, 12:722–741.

Schwendike, J., Kalthoff, N., and Kohler, M. (2010). The impact of mesoscale convective systems on the surface and boundary-layer structure in West Africa: Case-studies from the AMMA campaign 2006. *Quarterly Journal of the Royal Meteorological Society*, (April).

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J. (2010). Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99(3-4):125–161.

Seneviratne, S. I., Lüthi, D., Litschi, M., and Schär, C. (2006). Land-atmosphere coupling and climate change in Europe. *Nature*, 443(7108):205–9.

Sud, Y., Mocko, D., Lau, K., and Atlas, R. (2003). Simulating the Midwestern US drought of 1988 with a GCM. *Journal of climate*, (1988):3946–3965.

Tawfik, A. B. and Dirmeyer, P. a. (2014). A process-based framework for quantifying the atmospheric preconditioning of surface-triggered convection. *Geophysical Research Letters*, 41(1):173–178.

Tawfik, A. B., Dirmeyer, P. a., and Santanello, J. (2015). The Heated Condensation Framework. Part I: Description and Southern Great Plains Case Study. *Journal of Hydrometeorology*, 16(5):1929–1945.

Taylor, C. and Ellis, R. (2003). Linking boundary-layer variability with convection: A case-study from JET2000. *Quarterly Journal of Meteorological Society*, pages 2233–2253.

Taylor, C. and Lambin, E. (2002). The influence of land use change on climate in the Sahel. *American Meteorological Society*, pages 3615–3629.

Taylor, C. and Lebel, T. (1998). Observational evidence of persistent convective-scale rainfall patterns. *Monthly Weather Review*, pages 1597–1607.

Taylor, C., Saïd, F., and Lebel, T. (1997). Interactions between the land surface and mesoscale rainfall variability during HAPEX-Sahel. *Monthly Weather Review*, pages 2211–2227.

Taylor, C. M. (2010). Feedbacks on convection from an African wetland. *Geophysical Research Letters*, 37(5).

Taylor, C. M. (2015). Detecting soil moisture impacts on convective initiation in Europe. *Geophysical Research Letters*, 42:4631–4638.

Taylor, C. M., Birch, C. E., Parker, D. J., Dixon, N., Guichard, F., Nikulin, G., and Lister, G. M. S. (2013). Modeling soil moisture-precipitation feedback in the Sahel : Importance of spatial scale versus convective parameterization. 40:6213–6218.

Taylor, C. M., de Jeu, R. a. M., Guichard, F., Harris, P. P., and Dorigo, W. a. (2012). Afternoon rain more likely over drier soils. *Nature*, 489(7416):423–6.

Taylor, C. M. and Ellis, R. J. (2006). Satellite detection of soil moisture impacts on convection at the mesoscale. *Geophysical Research Letters*, 33(3):L03404.

Taylor, C. M., Gounou, A., Guichard, F., Harris, P. P., Ellis, R. J., Couvreux, F., and De Kauwe, M. (2011a). Frequency of Sahelian storm initiation enhanced over mesoscale soil-moisture patterns. *Nature Geoscience*, 4(7):430–433.

Taylor, C. M., Parker, D. J., and Harris, P. P. (2007). An observational case study of mesoscale atmospheric circulations induced by soil moisture. *Geophysical Research Letters*, 34(15):L15801.

Taylor, C. M., Parker, D. J., Kalthoff, N., Gaertner, M. A., Philippon, N., Bastin, S., Harris, P. P., Boone, A., Guichard, F., Agusti-Panareda, A., Baldi, M., Cerlini, P., Descroix, L., Douville, H., Flamant, C., Grandpeix, J.-Y., and Polcher, J. (2011b). New perspectives on land-atmosphere feedbacks from the African Monsoon Multidisciplinary Analysis. *Atmospheric Science Letters*, 12(1):38–44.

Teuling, a. J., Hirschi, M., Ohmura, a., Wild, M., Reichstein, M., Ciais, P., Buchmann, N., Ammann, C., Montagnani, L., Richardson, a. D., Wohlfahrt, G., and Seneviratne, S. I. (2009). A regional perspective on trends in continental evaporation. *Geophysical Research Letters*, 36(2).

Thiery, W., Davin, E. L., Seneviratne, S. I., Bedka, K., Lhermitte, S., and van Lipzig, N. P. M. (2016). Hazardous thunderstorm intensification over Lake Victoria. *Nature communications*, 7:12786.

Thorncroft, C. D., Parker, D. J., Burton, R. R., Diop, M., Ayers, J. H., Barjat, H., Devereau, S., Diongue, A., Dumelow, R., Kindred, D. R., Price, N. M., Saloum, M., Tayor, C. M., and Tompkins, a. M. (2003). The JET2000 Project: Aircraft Observations of the African Easterly Jet and African Easterly Waves. *Bulletin of the American Meteorological Society*, 84(3):337–351.

van den Hurk, B., Doblas-Reyes, F., Balsamo, G., Koster, R. D., Seneviratne, S. I., and Camargo, H. (2012). Soil moisture effects on seasonal temperature and precipitation forecast scores in Europe. *Climate Dynamics*, 38(1-2):349–362.

van der Ent, R. J., Savenije, H. H. G., Schaefli, B., and Steele-Dunne, S. C. (2010). Origin and fate of atmospheric moisture over continents. *Water Resources Research*, 46(9):W09525.

van der Ent, R. V. and Savenije, H. (2011). Length and time scales of atmospheric moisture recycling. *Atmospheric Chemistry and Physics*, 11(5):1853–1863.

van Heerwaarden, C. C. and Guerau de Arellano, J. V. (2008). Relative Humidity as an Indicator for Cloud Formation over Heterogeneous Land Surfaces. *Journal of the Atmospheric Sciences*, 65(10):3263–3277.

Wei, J., Dickinson, R. E., and Chen, H. (2008). A Negative Soil Moisture–Precipitation Relationship and Its Causes. *Journal of Hydrometeorology*, 9(6):1364–1376.

Wolters, D. (2010). Effects of soil moisture gradients on the path and the intensity of a West African squall line. *Quarterly Journal of the Royal Meteorological Society*, (October):2162–2175.

Zeng, N., Neelin, J., Lau, K., and Tucker, C. (1999). Enhancement of interdecadal climate variability in the Sahel by vegetation interaction. *Science*, 286(November).

Zeng, X., Barlage, M., Castro, C., and Fling, K. (2010). Comparison of Land–Precipitation Coupling Strength Using Observations and Models. *Journal of Hydrometeorology*, 11(4):979–994.

Acronyms

AAP	Afternoon Accumulated Precipitation
AEJ	African Easterly Jet
AEW	African Easterly Wave
AIRS	Atmospheric InfaRed Sounder
AMMA	African Monsoon Multidisciplinary Analysis
AMSR-E	Advanced Microwave Scanning Radiometer - Earth Observing System
ASCAT	Advanced SCATterometer
BL	Boundary Layer
CAPE	Convective Available Potential Energy
CIN	Convective Inhibition
CMORPH	NOAA CPC MORPHing technique
ERA-Interim	European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis Interim
ET	Evapotranspiration
GCM	General Circulation Model
GLC2000	Global Land Cover data set
GLEAM	Global Land Evaporation Amsterdam Model
HAPEX-Sahel	Hydrology-Atmosphere Pilot Experiment in the Sahel
ITCZ	Inter-Tropical Convergence Zone
ITF	Inter Tropical Front
LCL	Lifting Condensation Level
LFC	Level of Free Convection
LST	Local Standard Time
MCS	Meso-scale Convective System
MSE	Moist Static Energy
PERSIANN	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks
SMAP	Soil Moisture Active Passive
SMOS	Soil Moisture and Ocean Salinity
SMPC	Soil Moisture - Precipitation Coupling
SST	Sea Surface Temperature
TMPA	The Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis
UTC	Universal Coordinate Time

List of Figures

List of Tables

Acknowledgements

At the first place I would like to thank all the members of my supervision board, i.e. Martin Claussen, Stephan Bakan, Cathy Hohenegger, Chiel van Heerwaarden, Juergen Bader and Alexander Loew for your responsive guidance, support and encouragement throughout the PhD.

I would like to especially thank Cathy, Chiel and Stephan for joining my panel board urgently, during the PhD process. I sincerely appreciate your willingness to support me at the very important final phase of my PhD. Thank you for your time, valuable advices and fruitful discussions. Chiel, I am also very much grateful for your positive evaluations of my work. It was very important for me, and every time it burst me with a great extra portion of motivation. Martin, I would like to also thank you sincerely for your professional approach to solving problems and finding always the best and most optimal solution for everyone. Thank you very much for your support through my whole PhD!

I would like to also acknowledge Juergen Boehner and Lars Kaleschke for serving as commission members.

I would like to express my special appreciation to Francoise Guichard, a research scientist in CNRM department of Meteo France, for her willingness to help me in the scientific advising, for always finding time for a phone call and for her priceless advices and comments! I am also very grateful to the whole Mesoscale Meteorology Group of CNRM, and in particular to Fleur Couvreux and Emmanuel Poan for the fruitful discussions, and creating particularly warm atmosphere during my short visit to CNRM. I am expressing my gratitude also to Sonia Seneviratne and Benoit Guillod from the Department of Environmental System Science at ETH Zurich for their competent help, and discussions we had. Thank you very much to the Meteorology and Air Quality group at Wageningen University for hosting me, having a fruitful discussion after my talk and sharing good ideas that I could also implement.

I am very much grateful to my BSc adviser Alexander Mahura and his colleague Roman Nuterman from the DMI in Copenhagen for spending their weekend time at work listening to my presentation and giving me very useful and detailed comments and ideas. Alexander, thank you very much for following my research path, and always being there for me!

I am thankful to my colleagues at MPI-M, and especially to the whole Land Department for discussions and support. I would like to especially thank Thomas Raddatz for his never ending ideas, willingness to discuss and his time.

Thank you to the whole IMPRS team, and of course to dearest Antje Weiz for her great support and her Big Heart! I am grateful to all my student colleagues for discussions we had, your advices, and your great mood and motivation through the my PhD time. Especially I would like to thank Andreas Veira, Dorothea Mayer, Ulrike Port, Jessica Engels, Gernot Geppert, Beniamino Abis, Guido Cioni, Josiane Salameh and Christopher Hedemann for their support and care. A special thanks go to my dearest friends and closest people - Christian Klepp and Miriam Ferrer-Gonzalez for being always there for me in bad and good times. I love you guys!

Finally, I will never find enough words to express my sincere gratefulness to my dearest parents, my father Yuri Petrov and especially to my mother Svetlana Petrova. Having a tough life because of the weekly dialyse procedures, my mom always finds energy and strength to support me in tough moments. Being trained as a nuclear physicist, she was even advising me on the best statistical solutions for some of my problems! I absolutely adore her strength, wisdom and care! I love you both!