



**Life time of soil
moisture
perturbations**

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Life time of soil moisture perturbations in a coupled land-atmosphere simulation

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

In order to evaluate whether the initialization of soil moisture has the potential to improve the prediction skill of coupled climate models at seasonal to decadal time scales, an elaborated AMIP-type experiment was conducted. The experiment design considered soil moisture initialization in different seasons and years, and yields information about the life-time (memory) of extreme yet realistic soil moisture perturbations. Our analyses were focused on root zone soil moisture (RootSM) as it comprises the part of the soil that directly interacts with the atmosphere via bare soil evaporation and transpiration. We found that RootSM memory differs not only spatially but also depends on the time of initialization. Long memory up to one year is evident mostly for dry soil moisture regimes, after heavy precipitation periods or prior to snow covered conditions. Short memory below two weeks prevails in wet soil moisture regimes and prior to distinct precipitation periods or snow melt. Furthermore, RootSM perturbations affect other land surface states, e.g. soil temperature and leaf carbon content, and even induce anomalies with specific memory in these variables. Especially for deep layer soil temperature these anomalies can last up to several years. As long as RootSM memory is evident, we found that anomalies occur periodically in other land surface states whenever climate conditions allow for interactions between that state and RootSM. Additionally, anomaly recurrence is visible for RootSM itself. This recurrence is related to the thickness of the soil layer below the root zone and can affect RootSM for several years. From our findings we conclude that soil moisture initialization has the potential to improve the predictive skill of climate models on seasonal scales and beyond. However, a sophisticated, multi-layered soil hydrology scheme is necessary, to allow for the interactions between RootSM and the deep soil layer reservoir.

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1 Introduction

Until recently, the main application for Earth System Models (ESMs) was the reproduction or projection of long term climate statistics over periods of 30 years or longer (Taylor et al., 2012). However, during the last decade this focus was expanded towards decadal (Meehl et al., 2009) and seasonal predictions (Palmer et al., 2004). On such time scales, not only the quality of model physics and the external forcing play a major role, but also an appropriate initialization of state variables (Pohlmann et al., 2009; Müller et al., 2014). In the climate community, the potential of initialization is investigated focusing mostly on decadal predictions and the state of the ocean (e.g. Keenlyside et al., 2008; Pohlmann et al., 2009; Matei et al., 2012). But especially for short-term simulations like numerical weather forecasts or reanalysis, the land surface has also been identified as interesting target for initializations. Initialization experiments focusing on snow cover (Douville and Royer, 1996; Jeong et al., 2013) and soil moisture (Atlas et al., 1993; Betts, 2004; Fischer et al., 2007; Beljaars et al., 1996; Small, 2001; Kim and Hong, 2007; Koster and Suarez, 2003) are shown to affect the climate state and therefore their initialization can be expected to enhance the predictive skill of an ESM.

The reason for the importance of initialization is the interaction between land surface and atmospheric states, which are rather complex and result in a number of feedbacks (e.g. Bony et al., 2006). Of those, one of the most investigated processes are soil moisture feedbacks (e.g. Dirmeyer and Shukla, 1993; Eltahir, 1998; Seneviratne et al., 2010). They rely on the important role that soil moisture plays in both, the terrestrial water balance as well as the energy balance. On the one hand, soil moisture determines the separation of incoming water fluxes into surface runoff and infiltration. Surface runoff is transported into rivers and leaves a given region. Infiltrated water adds to the soil moisture and might be available for evapotranspiration, again. Thus, soil moisture strongly effects the regional water balance. On the other hand, both energy and water balance, can be effected simultaneously via the evapotranspiration flux.

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Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



climate conditions are more likely to occur if extensive soil moisture anomalies exist in the past season. Additionally, there are several sensitivity studies investigating the effect of soil moisture anomalies on different regions like the North American (Beljaars et al., 1996; Small, 2001; Betts, 2004), African and/or Asian Monsoon regions (Douville et al., 2001; Kim and Hong, 2007) and Europe (Rowntree and Bolton, 1983; Jaeger and Seneviratne, 2011). Often, but not always, prescribing positive soil moisture anomalies is correlated with the simulation of enhanced precipitation in the following season and vice versa. Also the persistence of soil moisture anomalies is investigated in several studies, e.g. Manabe and Delworth (1990); Huang et al. (1996); Koster and Suarez (2001); Betts (2004); Wu and Dickinson (2004); Seneviratne et al. (2006); Dirmeyer et al. (2009); Hagemann and Stacke (2014). Estimates for soil moisture memory range between 1 and 6 months but differ based on the tools and models used to investigate it. Manabe and Delworth (1990) found short memory of 1–2 months for low latitudes with increases up to 5 months in high latitudes, peaking in memory up to 10 months in northern Siberia. For Europe they found memory of 2–3 months, which agrees well with Ferranti and Viterbo (2006). Some similarities exist also with the results of Hagemann and Stacke (2014), especially for regions with short memory. However, they found less memory for northern Siberia and memory longer than one year for desert regions. Most studies, however, do not explicitly compute the soil moisture memory but rather estimate its length based on a prescribed decay function of the soil moisture autocorrelation coefficient for a given lag (often one month) (Huang et al., 1996; Koster and Suarez, 2001; Betts, 2004; Wu and Dickinson, 2004; Seneviratne et al., 2006). The resulting soil moisture memory ranges between 1 and 10 months and shows spatial pattern with long memory in arid regions and high latitudes and short memory for Monsoon influenced regions. Seasonal variations in soil moisture memory were analysed by Dirmeyer et al. (2009). Looking at daily statistics they found considerably less memory, which exceeds one season only for desert or energy limited regions during the respective seasons. Soil moisture memory estimates based on observations are extremely rare, but range roughly in the same order of magnitude

as most modelling studies. Based on 50 measurement sites across the former USSR, Vinnikov and Yeserkepova (1991) computed soil moisture memory ranging from 1 to 5 months.

Most of those studies have in common that they investigated the effect of soil moisture perturbations or soil moisture memory for a very limited time period usually focusing on the next season. Although the results indicate that soil moisture memory might be much longer for several regions, only few information exist about the maximum time period to which soil moisture perturbations can be expected to affect climate simulations. Considering recent projects focusing on seasonal to decadal prediction systems (see MiKlip <http://www.fona-miklip.de/en/> and SPECS <http://www.specs-fp7.eu/>), it would be valuable to learn more about the potential of soil moisture initialization. Particularly, information about the persistence of soil moisture perturbations in ESMs can contribute to decisions about the necessity to initialize soil moisture in short or even long-term predictions.

For this reason we set up an experiment to investigate the life-time of soil moisture perturbations for different seasons. In contrast to previous work by Hagemann and Stacke (2014) the focus is not on the general impact of soil representation on soil moisture autocorrelation length. Instead we analyse the impact of RootSM initialization for different seasons and regions. In our paper we first describe the model characteristics, experiment setup and the applied analysis methods. Following this we present the distribution of soil moisture memory and its variance throughout the year. Next, the origin of soil moisture memory is investigated, and its relation to different soil properties and climate variables is discussed. Finally, we contrast our findings against knowledge gained from previous studies and give directions for further research.

2 Experiment setup and analysis methods

The soil moisture initialization experiment uses the coupled atmosphere/land model ECHAM6/JSBACH (Stevens et al., 2013; Raddatz et al., 2007). All simulations are

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



conducted with a horizontal resolution of T63 ($\approx 1.8^\circ$) and 47 vertical levels for the atmosphere. While most of the setup is identical to the CMIP5 setup (Giorgetta et al., 2013), the standard JSBACH soil module is replaced with the new 5-layer soil hydrology scheme (Hagemann and Stacke, 2014). In contrast to the former bucket scheme, this scheme separates the soil into 5 distinct layers to a maximum depth of about 10 m or the bedrock. The top soil layer is the reservoir for bare soil evaporation. The accumulated moisture in the upper layers within the rooting depth is defined as RootSM and is subject to transpiration. The layers below are associated with the deep zone soil moisture (DeepSM). As the latter is not directly accessible by plants, it can lose water only by drainage or diffusion into upper soil layers. Thus, the deep layers are often equivalent to a long term water storage and were shown to improve the representation of soil moisture memory in JSBACH compared to the standard bucket scheme (Hagemann and Stacke, 2014). It is important to note that the applied version of JSBACH does not consider any melting and freezing processes within the soil. Thus, there is no interaction between water and energy states within the soil column, and soil moisture anomalies can effect soil temperature only via the pathway of evapotranspiration and surface temperature.

The soil moisture initialization experiment is composed of two sets of simulations. The first set consists of one reference simulation (REF) for the period 1995–2008. For every year and month, restart data is generated by the model and six hourly averages of the RootSM and of the soil moisture for the individual soil layers (LaySM) are stored. From these data, extreme wet and dry soil moisture states are extracted as initial conditions for the second set of initialized simulations (INI). The INI are restarted at the start of every season for the years between December 1996 and September 2005, running freely for three years (see Fig. 1). No INI are started prior to December 1996 as this time is regarded as spin-up. Thus, this experiment yields ensembles consisting of 9 members (one for each year) per restart month (4) and initialization state (2), respectively, accumulating to $9 \times 4 \times 2$ simulations resulting in a dataset of 216 simulation years.

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



In contrast to previous soil moisture initialization experiments (e.g. Betts, 2004; Ferranti and Viterbo, 2006; Fischer et al., 2007; Jaeger and Seneviratne, 2011), the initial soil fields are not defined as a fixed percentage of the reference value nor set to a known critical state like wilting point or maximum soil water holding capacity.

Instead the 6 hourly output for the period of ± 15 days around a given restart time were extracted for every year from REF and merged into one time series. From the time series, the 99th and 1st percentiles of RootSM were identified. These percentile fields serve as extreme wet and dry RootSM initializations, respectively. For LaySM initialization, data from the same time steps were used to be consistent with the RootSM fields. Following this procedure, restart fields were computed for 1 December, March, June and September. While the absolute values of the initialization data are identical for the respective months for every year, it has to be noted that their differences to the reference state vary from year to year. Instead of constant soil moisture perturbations, a distribution of perturbations is generated with minimum perturbation in the year where the reference state is close to the respective percentile and maximum perturbation when the reference climate conditions are opposite to the initial state. In this way, the ensemble does not only consider the internal variability within the model, but additionally takes inter-annual climate variations into account. Furthermore, the perturbations range within model-realistic bounds because they are based on model data. Thus we avoid unrealistic perturbations that would result in causing spin-up behaviour (large model drifts) rather than triggering soil moisture memory.

The analysis is focused on the evaluation of soil moisture memory. In our study we diagnose memory for those time steps where the ensemble mean anomaly (EnsMean) – originating from the initial perturbation – exceeds the ensemble standard deviation (EnsStd). This is determined by the signal to noise ratio (SNR) for a given time step i

$$\text{SNR}(i) = \frac{E[\Delta\theta_j(i)]}{\sqrt{E[(\Delta\theta_j(i) - E[\Delta\theta_j(i)])^2]}}, \quad (1)$$
$$\tau_{lag} = \min_{i=1 \dots n} (i : \text{SNR}(i) > 1), \quad (2)$$

$$\tau_0 = \min_{i=1 \dots n} (i : \text{SNR}(i) \leq 1 \cap i \geq \tau_{\text{laq}}) - \tau_{\text{laq}}, \text{ and} \quad (3)$$

$$\tau_{\max} = \sum_{i=1}^n k(i), \text{ where } k(i) := \begin{cases} 1 & \text{if } \text{SNR}(i) > 1 \\ 0 & \text{if } \text{SNR}(i) \leq 1 \end{cases} \quad (4)$$

where $n = 1095$ is the maximum number of time steps being equivalent to the 3-year simulation period. Further important metrics are the $\Delta\theta_0$ and $\Delta\theta_{\max}$ of a time series. The former is the peak anomaly in the initial memory period and for RootSM usually evident at the first time step. The latter is the 99th percentile in the anomaly time series during all memory periods.

This analysis is demonstrated in Fig. 2 for the RootSM in an arbitrary grid cell and seasonal ensemble. In this example τ_0 for the extreme wet initialization is almost 1 month while the dry perturbation lasts distinctively longer up to about 2.5 months.

The image shows a presentation navigation interface with a dark blue background and white text. At the top is a title bar with the text "Title Page". Below it is a grid of eight navigation buttons arranged in four rows and two columns. The first row contains "Abstract" and "Introduction". The second row contains "Conclusions" and "References". The third row contains "Tables" and "Figures". The fourth row contains two buttons with left and right arrow icons. Below the grid is a wide button labeled "Full Screen / Esc". At the bottom are two more wide buttons labeled "Printer-friendly Version" and "Interactive Discussion".

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



signal than the RootSM. Analysis of memory time series show that in such cases the initial RootSM perturbations need some time to propagate into the deeper layers. This effect is negligible for layers within the root zone, but results in a perturbation delay of over 30 (10) days for 25 % of fifth layer cells for wet (dry) initialization.

The life times τ_0 of these perturbations vary strongly depending on the respective soil layer, initialization season and state. For RootSM the interquartile range of τ_0 varies between 0.5–2 months for March and 0.65–3.5 months for December. Single grid cells (99th percentile) for all seasons show memory up to 10 months. The memory for soil layer moisture increases with depth. The top layer only reaches median values of about one week although for individual grid cells the perturbation signal can be visible for up to 4 months (June and December). The median τ_0 increases to about 5 months in the fifth layer while the interquartile range increases exponentially. Thus, a large ratio of grid cells is still affected by the perturbation after three seasons in the fourth layer and even after two years in the fifth layer. Down to the third layer, the longest τ_0 is found for December initialization shifting to September for deeper layers. For the RootSM and the upper three layers wet initializations correspond to a slightly longer τ_0 than dry ones but for lower layers dry perturbations become much more persistent.

The spatial pattern of the RootSM τ_0 are investigated first by dividing the simulations into two, dry and wet initialized, ensembles (see Fig. 4) including all different seasons. Similar large-scale pattern can be found for both initialization states indicating a generally higher sensitivity for soil moisture perturbations in some parts of the world. Short memory between 2 and 4 weeks is evident for larger parts of Asia, Central Australia and northwestern North America. Regions with medium memory between 1 and 6 months are found for the eastern US, central and eastern South America, the larger part of Europe, Central Africa and southeastern Asia. However, there are distinct difference for the more extreme values. Long memory of up to one year and more is found for wet initialization in the Congo region and Eastern US while it is much more sparse for dry initialization with two spots south of the Amazon catchment and in northeastern China. In return, areas without any memory are more common for dry

Life time of soil
moisture
perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



than for wet initializations. While wet initialization shows no memory for parts of the high northern latitudes as well as the Amazon basin, dry anomalies cannot persist for the southwestern US, the Sahel zone, South Africa, the Arabian peninsula, southeastern Asia, and western Australia. These regions very well coincide with dry conditions. There, dry perturbations have the lowest impact as the soils are usually in a dry state anyway. Thus the perturbations are relatively small and fall within the climate variability. Wet perturbations are much larger and can result in τ_0 of several months.

In a second step, the simulations were sorted with respect to the initialization season but not separated between wet and dry initial perturbations. As already indicated by Fig. 3, the resulting τ_0 distributions show much more variance between seasons than between wet and dry initialization (see Fig. 5). The most prominent features are found for the northern hemisphere. For most parts of the high northern latitudes and central Asia, τ_0 is shorter than one month for March to September initializations. However, with the onset of the boreal winter, τ_0 becomes much more persistent and reaches values up to six months and more. This pattern seems to be related to the regional climate conditions. For March to September, the initialization often precedes periods of higher soil moisture variability. Thus, the computed initial states for the simulations are relatively small compared to variability of the following season, and the perturbation signal decays fast. In contrast, the initial December states are still impacted by the summer soil moisture variability resulting in a large perturbation which by far exceeds the moisture variability during winter. This perturbation is then conserved by the snow cover on top of the soil which hampers the exchange of water and energy between land and atmosphere. Thus, the initial perturbations can persist until next years' snow melt. Another prominent feature are some regions along a band reaching from the African west coast towards India and then following the Asian coast in north-easterly direction. In the September ensemble they show memory up to one year. Almost the same regions are associated with three and six months less memory in the December and March ensembles, respectively, and shorten to less than two weeks in the June ensemble. A similar behaviour is visible for South Africa starting with the March

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



ensemble and South America starting with the June ensemble, although the latter shows shorter memory of $\tau_0 \leq 6$ months. Most of those regions very well resemble areas impacted by monsoon circulation as outlined by Lin et al. (2014). Monsoon periods are characterized by heavy precipitation during one season which amounts to over 50 % of the annual precipitation. Such precipitation results in a very high soil moisture content that completely removes all memory of previous wet or dry anomalies. However, in the seasons after monsoon, precipitation is much lower resulting in low soil moisture variability and longer persistence of anomalies. This is well reflected in the derived memory distribution. For the northern hemisphere, monsoon usually occurs during the summer season thus almost no memory is seen in the June ensemble for western Africa and India. The next season (September ensemble) shows the longest memory of about nine months that lasts until the next monsoon period, while every following seasonal ensemble has memory of three months less, respectively. The same reasoning holds for the southern hemisphere. There the South African monsoon lasts from November till March, resulting in no memory for the December ensemble. The South American Monsoon often lasts even longer until April resulting in short memory for the December and March ensemble as well as a respective cut on the long memory evident in the June ensemble. This analysis reveals that not only the initialization state (e.g. wet versus dry) but also the time of initialization has a large impact on the resulting memory.

In order to identify more general systematics behind the spatial τ_0 distribution, regions of similar soil moisture regimes were defined using the classification described in Seneviratne et al. (2010). The regimes are computed from REF climatology for all four seasons based on the state of soil moisture θ in relation to the wilting point θ_{wilt} , below which no transpiration may occur, and the critical soil moisture θ_{crit} , above which transpiration occurs at the potential rate and is not limited by soil moisture anymore. The regimes are classified into dry ($\theta \leq \theta_{\text{wilt}}$), wet ($\theta \geq \theta_{\text{crit}}$) and transitional ($\theta_{\text{wilt}} < \theta < \theta_{\text{crit}}$) regimes (see Fig. 6). The grid cells are not distributed equally between

the regimes. Instead grid cells in transitional regimes exceed those in others by a factor of 5 (wet cells) to 20 (dry cells).

In spite of the strong differences in sample size, the partition into the three soil moisture regimes appears to be reasonable as they show distinctively different characteristics of soil moisture τ_0 (see Fig. 7). For all seasons, the longest τ_0 is found in dry regimes and the shortest τ_0 in wet regimes. While the dry and wet distributions within the regimes are quite symmetric for the March ensemble, the other ensembles show longer memory for wet perturbations in dry regimes, a symmetric shape for the transitional regime and longer memory for dry perturbations in wet regimes. In contrast to the memory distribution, the $\Delta\theta_0$ distributions show a different relation to the soil moisture regimes. There, the smallest perturbations are evident for dry regimes and the largest for the transitional regime for all seasons (not shown). This already indicates that the size of the initial perturbation cannot be the dominant driver for the initial soil moisture memory. This is confirmed by analysing the spatial correlation between soil moisture τ_0 and $\Delta\theta_0$ for the different regimes and seasons as shown in Fig. 8 (lower panel). The correlations differ for the regimes as well as for seasons and show highest values for June and September in the transitional and wet regime. However, even there the Spearman's rank correlation coefficient does not exceed 0.7. Thus, at most 50 % of the spatial variance in memory pattern can be explained by the size of the initial perturbations. Furthermore, correlations between wet and dry memory are even lower with maximum values of 0.4 in the December ensemble for the transitional regime and almost no significant correlations for the dry regime at all (Fig. 8 upper panel). This indicates that for a given time step and grid cell, the soil might be susceptible for either wet or dry perturbations but rarely for both. Thus, the strength of soil moisture memory seems to depend on dynamically changing land atmosphere interactions rather than static soil or land cover properties.

This statement is supported by the spatial correlations between soil moisture τ_0 and static land surface properties. For most soil parameters (saturated hydraulic conductivity, porosity, pore size index, wilting point, field capacity, matrix potential,

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



vegetation fraction, forest fraction and orographic standard deviation) correlations are low, varying between -0.25 and 0.25 during most seasons or are even insignificant. However, for hydraulic conductivity a low anti-correlation down to -0.36 indicates a longer τ_0 for regions where hydraulic conductivity is low. This effect occurs for transitional and wet regimes and preferably for dry initialization. Rather than just reducing drainage and thus sustaining wet anomalies, the low conductivity also reduces diffusivity and thus limits the ability of the soil to compensate dry anomalies via upward diffusion of moisture from deep and wet layers. Stronger correlations are only found for rooting depth and soil depth down to the bedrock. Rooting depth plays a role mostly in transitional regimes with correlation coefficients up to 0.57 in the June and September ensembles. Since these seasons coincide with the seasons of high memory – perturbation correlation, it can be assumed that the higher rooting depth allows for larger perturbations that cause longer memory. In contrast, anti-correlation between rooting depth and memory is found for wet perturbations in December and March ensemble for the wet regime with values down to -0.34 . During this season, large areas in the wet regime are covered by snow and therefore wet perturbations cannot be easily compensated via transpiration but relying on drainage instead. However, being located in the wet regime it can be expected that the deep soil layers are close to saturation and retain the drainage flux. This effect strengthens with increasing soil layer thickness. Since the overall soil depth is limited, a thicker root zone is likely related to a thinner deep soil zone, leading to the simulated anti-correlation. Correlations with total soil depth are only important for wet perturbations. They are mostly positive (up to 0.45) because deep soils provide a stable reservoir from which water can rise upwards via diffusion to sustain the wet anomaly. Of course, this is only possible for those grid cells where the wet perturbations exist in all layers and not just in the root zone. Consequently, this correlation is only observed in seasons and regions where no strong anti-correlations with hydraulic conductivity exist.

Together with the observed seasonal dynamics in soil moisture memory, these correlations demonstrate the limitations in explaining soil moisture memory with static

soil properties alone. Instead, the contribution of favourable climate states appears to be equally important to form persistent anomalies.

4 Interaction of perturbations between soil moisture and other state variables

As already pointed out by earlier studies (Seneviratne et al., 2006; Rowntree and Bolton, 1983, and others), soil moisture anomalies also lead to alterations in other – originally not perturbed – state variables due to feedback mechanisms (see Sect. 1). However, it is not yet clear to what extent the memory within a state variable is affected by such feedbacks. While assuming that memory is a specific characteristic for a given state, the overall memory of a coupled system of interacting states might differ distinctly from the sum of its parts. For this reason, the induced anomaly and memory statistics in other land surface states are analysed in the following.

The largest impact of soil moisture perturbations is expected for surface and soil temperatures due to the tight coupling of water and energy fluxes via the latent heat/evapotranspiration flux. Indeed, induced perturbations are evident there (Fig. 9, left). The $\Delta\theta_0$ are largest for the surface and top layer with median values of 1.1 K (–1.4 K) for dry (wet) initialization which decrease towards zero in the deepest layer. The extremes range between –10 and 9.5 K for the surface and still reach ± 0.5 K near the bottom of the soil column. While the interquartile range of the anomaly is consistent with the initial soil moisture perturbation for all layers, e.g. warm anomalies for dry initialization and cold anomalies for wet initialization, extreme values with opposite anomalies exist. The memory in soil layer temperature is much shorter than for moisture. Starting from few a days at the surface, the median τ_0 and its interquartile range increase with increasing depth towards a median of about 0.5 months in the fourth layer (Fig. 9, right). In the fifth layer, the value decreases again as a large fraction of the grid cells does not show any initial memory. The extremes, however, increase exponentially from three weeks at the surface to over two years in the lowest layer. Wet and dry initialized ensembles behave similar to each other, however the interquartile

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



range for the 4th and 5th layer is respectively about 0.5 and 1 months longer for wet initializations than for dry.

Induced perturbations are not only evident for surface and soil temperature, but do also occur in other land surface variables. Concerning the initial memory period (see Fig. 10, line symbols) induced perturbations result in anomalies in the range of ± 1 hPa for surface pressure, ± 0.005 m for snow water equivalent, -0.001 to 0.002 kg m⁻² for specific surface humidity, -2.5 to 9.5 kg m⁻² for vertically integrated water vapour and ± 0.003 kg m⁻² for the leaf carbon content (see Table 1 for details). However, the τ_0 associated with these anomalies is rather short for all states but leaf carbon content where τ_0 lasts up to 4 months (see Table 2). In order to identify a systematic behaviour in these effects, the anomaly-memory relations are divided into wet and dry initializations. It becomes visible that the dry and wet perturbations in dry and transitional soil moisture regimes mostly result in either positive or negative anomalies. For the wet soil moisture regime, however, positive as well as negative anomalies are visible for any perturbation. The τ_0 does not seem to be correlated with the $\Delta\theta_0$ for any state but leaf carbon content. Here the largest anomalies correspond to the longest memory and occur in the transitional regime, while both, dry and wet regimes show shorter memory and smaller anomalies. For the dry regime this is probably due to the low amount of plant cover whereas in the wet regime there is no water limitation and therefore leaf carbon content becomes insensitive to variations in soil moisture.

Taking into account the full time series (Fig. 10, filled symbols), the change in memory indicates that there are not only initial, induced perturbations with an associated memory, but anomalies recur again at later time steps. For some variables, these anomalies show even larger magnitudes than the initial ones. The accumulated memory τ_{\max} for most variables rises from a few days to about one month, and the memory for leaf carbon content doubles to 6 months. Snow water equivalent τ_{\max} stays low around one week for all regime-initialization combinations as does the leaf carbon content τ_{\max} for dry perturbations in the dry soil moisture regime. While the sign of the anomalies corresponds to the expectations for some variables, e.g.

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



wet initialization resulting in positive anomalies for leaf carbon content and negative anomalies for surface temperature and vice versa, other variables (snow cover, surface pressure) react with anomalies in both directions. More details for the overall memory and anomalies in soil moisture and temperature are displayed in Fig. 11. For soil moisture, there are almost no differences between the magnitudes of $\Delta\theta_0$ and $\Delta\theta_{\max}$. Thus, anomalies during later memory periods are usually smaller than at the beginning, indicating that no positive feedbacks or new equilibria are triggered by the initial perturbations. However, τ_{\max} for all layers is increased by 1–1.5 months for the median and up to 4 months for the 75th percentile. The largest increase is visible for the upper extreme of RootSM memory with 15 months. Extreme anomalies for soil temperature behave similarly to initial anomalies and become smaller for deeper soil layers. Changes in magnitude range between -5 and 3 K for the surface and vary around ± 0.3 K in the deep layers. The separation between positive and negative anomalies in response to the initial soil moisture perturbation is not as distinct anymore for the upper three layers. The accumulated median memory is at least 1 month for all layers and interquartile range as well as extremes increase even stronger than for the initial memory. For the 75th percentile, τ_{\max} exceeds τ_0 by 1 (8) month for the first (fifth) layer. The differences between wet and dry initialization are less extreme compared to τ_0 statistics but still a slightly longer memory is found for wet initialization in the lowest layer.

These analyses demonstrate that memory occurrence and anomaly recurrence are not limited to soil moisture and the closely linked soil temperature. Instead, the soil moisture perturbations affect most of the land surface system although to a different extent. However, the mechanism responsible for the recurrence of anomalies in the different variables cannot be identified from these analyses.

5 Anomaly interaction pathways between state variables

In technical terms, the recurrence of state variable anomalies indicates that the anomaly mean and the anomaly standard deviation for a given location are not just two steadily decreasing and increasing curves at whose intersection the memory ends. Instead one or both of them show temporal variations which result in the anomaly becoming visible ($\text{SNR} \geq 1$) again. In the following, this possible recurrence is explored on grid cell level by investigating the relation of SNR time series (see Eq. 1) between different state variables. Here, we focus on leaf carbon content and (deep layer) soil temperature as longest accumulated memory was computed for these variables. In order to find suitable grid cells for the analysis, we applied a number of conditions, namely the difference between τ_{\max} and τ_0 being > 600 days and the amount of recurring memory periods ≥ 3 . Only such grid cells were analysed that comply with these conditions. Additionally, they were ranked according to the similarity between the length of their memory periods as we expect more robust results for regularly recurring anomalies.

For all state variables except soil moisture, the anomaly recurrence is simple to explain. For example, soil moisture perturbations affect leaf carbon content and can result in anomalies with a distinct memory (see Sect. 4). However, leaf carbon content follows a yearly cycle and can become insensitive to soil moisture anomalies during certain time periods, i.e. when soil moisture is below the wilting point or above the critical soil moisture. The latter case occurs in the example for leaf carbon content shown in Fig. 12 (right). Here, the anomaly vanishes during periods of maximum leaf carbon in the reference simulation. In case the soil moisture perturbation still exists after the peak, a new anomaly is triggered and leaf carbon memory recurs. Similarly, soil temperature anomalies do not depend on soil moisture anomalies alone, but also on evapotranspiration anomalies. These are only triggered when several climate conditions (e.g. downward radiation, surface humidity) are favourable (not shown). Thus, temperature anomalies emerge as long as these conditions apply but, as surface

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



temperature memory is short, are interrupted whenever the favourable conditions fade. In both cases, the recurrence of state memory is possible only because soil moisture memory lasts long enough until conditions for anomalies become favourable again.

As there is no state variable that demonstrated longer memory than soil moisture, another explanation is needed for its memory recurrence. Still, there are several possible explanations for this phenomenon: The first hypothesis is based on feedbacks between different state variables. As shown in the previous section soil moisture perturbations induce anomalies in other variables. However, the induction may have a certain lag time and furthermore the memory of the anomalies differs between the various states. Thus, it would be possible that a soil moisture anomaly induces a temporally lagged anomaly in another state with a different memory. While the soil moisture anomaly is already decayed, the induced state anomaly might still exist and – in case there is a feedback loop between both – induces a secondary anomaly in soil moisture. This effect would be visible as wave-like variations in the ensemble anomaly mean. Secondly, the soil moisture anomalies might be stable over long time periods, but its memory could be temporally hidden during periods with pronounced variability in interacting variables. This would become visible as a rather steady and slow decline of the anomaly mean curve which would be overlain by periodical increases in the ensemble anomaly standard deviation.

For soil moisture, the best example is found for a grid cell at -2.8°N and 13.12°E (West Africa, Republic of Congo) during wet initialization in September. Its ensemble mean anomaly and SNR timeseries are shown in Fig. 13 for soil moisture and soil temperature in the different soil layers. At this location the depth of the bedrock is prescribed with 5.6m while root depth extents down to 2.8m. This means that the water content of the lowest soil moisture layer as well as about 50 % of the fourth layer is not directly accessible to plants for transpiration. Consequently, the SNR soil moisture curves (Fig. 13, right) exhibit very different temporal dynamics for the soil layers. In the upper three layers, which are within the root zone, the initialized perturbation decays within 1 (2) months for the first (third) layer. It recurs at yearly

Life time of soil
moisture
perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



intervals for a three months period, although only the recurrence after 12 months shows memory for all three layers while for later recurrences SNR stays below 1. In between those intervals the SNR curves are subject to high-frequency variations. The increasing length of memory and less variable SNR signal reflect the increasing soil layer thickness with depth in these layers. The root zone moisture as a whole also reflects the yearly intervals of increased SNR, but shows much less high-frequency variability. The SNR is above 1 for most of the time series. In contrast to the upper layers, the fourth and fifth layer, which represent the water reservoir below the root zone, show the slowly decaying SNR signal of the initial perturbation without any short-term variability. Comparing the SNR curves to the anomaly time series (Fig. 13, left), the same slow decay is visible for the anomalies in the two lowest layers. Above, distinct wet anomalies mark the annual recurrence of memory while in between small wet and dry anomalies are visible. The intra-annual anomalies usually show a small time lag for deeper layers indicating that the anomaly is migrating from the top layer into the deeper layers. However, the annual anomalies are already visible in the third layer before they start in the second or first one. Therefore, the wet anomalies could be related to water percolating downwards from above that is retained here due to the higher water content of the lower layers. Alternatively, it is even possible that water is migrating upwards via diffusion due to the positive water anomaly in the lower layers leading to an strengthened gradient between those layers. For the actual grid cell, the second case is more probable as the wet anomalies coincide with the minima of the REF precipitation climatology. Thus, the anomaly and memory recurrence within the RootSM results from interactions with the uninterrupted period of memory in the deep moisture layers below the root zone.

Additionally, the vertical profile of soil temperature memory is analysed for the same grid cell (Fig. 13, bottom). Similar to soil moisture memory, variability for soil temperature is higher for the thin top layers and lower for the thick, deep layers. Three events of increased memory are visible that correspond to the memory recurrence in soil moisture. Even though variability in the top layer is very high, a distinct downward

Life time of soil
moisture
perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



movement of the memory signal is visible, starting with short periods of a few days in the top soil layer. The downward movement shows a short time lag in memory occurrence for every layer together with a longer memory of the single events due to the increasing layer thickness. Additionally, the accumulation of anomaly and memory is visible in the lower two layers. Here, the vertical structure of the signal reflects the migration of the induced temperature anomalies from the top layer downwards. As the memory increases with depth and layer thickness, the rather short-lived anomalies of the top layer accumulate to a distinct and steady anomaly in the lower two layers. This top-down movement is not only supported by the pattern of the anomaly time series (Fig. 13, left), but follows from the model physics. In this version of JSBACH, phase changes of moisture within the ground are not considered and there is no interaction between moisture and temperature within the soil column. The only existing link between both is the latent heat flux/evapotranspiration at the soil surface. Thus, the first part of the hypothesized anomaly and memory transport between variables is realized here, as changes in RootSM induce anomalies and memory in the deep layer soil temperatures. However, there is no feedback evident from the temperatures to the moisture state. Thus, in this experiment the recurring soil temperature anomalies are most likely caused by recurring soil moisture memory but not vice versa.

The grid cell analysis demonstrates the possibility of memory interactions between variables although no indication was found for a closed memory interaction loop that feeds back into soil moisture again. Instead, anomaly recurrence in RootSM seems to depend on the existences of deep soil layers below the root zone. In order to conclude whether this is true for the model in general or just for the one grid cell, we divided all grid cells in three groups depending on the thickness of the soil column below the root zone. For these groups, the frequency distribution of memory recurrence was calculated for every soil moisture regime and is displayed in Fig. 14. Indeed the curves differ distinctively between grid cells without any deep soil layers and grid cells with either thin (≤ 1 m) or thick deep soil layers. It can be seen, that memory recurrence is generally more frequent for dry soil moisture regimes than for wet ones.

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Additionally, the impact of the deep soil thickness is strongest for dry regimes and almost not visible for the wet regimes. The figure also shows the impact of different seasons and initializations on the memory recurrence. The seasonal variations are mostly not distinguishable, but the wet initialization shows systematically less memory recurrence than the dry initialization. For the transitional regime, the major part of the impact is seen for the recurrence range of 5–200 days where all three sets of deep layer thickness are well separated. In the dry regime there are no differences between thin or thick deep soil layers, but a large offset to the cells without any deep soil layers. Consequently, the deep soil moisture storage seems to play a prominent role for the memory characteristics within the RootSM in all but the wet soil moisture regime. Still, there is a significant part of the land surface where memory recurrence is caused by other processes, e.g. in the wet soil moisture regimes and all the grid cells without any deep soil layers. There are indications, that the second hypothesis, the steadily declining anomalies interrupted by periods of high variability, is realized as well. An example on grid cell scale is shown in Fig. 12 (left). Here the anomaly is above the mean level of ensemble standard deviation over the whole three years. It even increases periodically due to recharge from the deep soil layer. However, during the rainy seasons, the ensemble standard deviation increases strongly and overlays the mean, thus, dividing the memory signal into several separate periods. However, a more comprehensive analysis of this effect and other possible reasons for memory recurrence on global scale is beyond the scope of this study as it would need a different experiment setup.

6 Summary

The presented soil moisture initialization experiment was designed to reveal information about the life-time of extreme – yet realistic – soil moisture perturbations in a coupled climate model. For the root zone, those lifetimes range from days up to one year and, thus, are consistent with the range of memory found by other studies

(e.g. Manabe and Delworth, 1990; Hagemann and Stacke, 2014; Ferranti and Viterbo, 2006).

The distribution of memory shows a systematic relation with soil moisture regimes and is consistent with large-scale physical characteristics. A prominent example is the soil moisture memory for monsoon regions, which is extremely low during the monsoon period as any soil moisture perturbations are negligible in face of the heavy precipitation. A similar result was reported by Seneviratne et al. (2006) who computed the global soil moisture autocorrelation pattern based on an ensemble of eight atmospheric general circulation models. Their simulations started in June and lead to a memory pattern very similar to the pattern of the June ensemble in our study. However, memory in the period after the monsoon is among the longest found globally and lasts until the next years' monsoon season starts again. Thus, monsoon regions are actually regions of significant memory if considered after the main precipitation period. Similarly, we see long memory in the high-northern latitudes in the December ensemble as perturbations are preserved because land atmosphere interactions are hampered by snow cover. These regions coincide with the long memory regions identified by Manabe and Delworth (1990). But again, the date of initialization is critical, since snowmelt and summer precipitation reduce the memory after the winter period, as seen in the other seasonal ensembles. Only limited agreement can be found between our memory pattern and the soil moisture autocorrelation length shown by Hagemann and Stacke (2014), although the same Earth System Model (ESM) was used. While for South America and the high northern latitudes some similarities are visible, the extremely long memory exceeding one year for most arid regions cannot be confirmed. This might be due to their use of autocorrelation diagnostics which the authors themselves report to be problematic in very dry and very wet regions. On average, longest memory is visible for dry soil moisture regimes and shortest for wet regimes. Within these regions it shows only low dependency on the type (dry/wet) of the initial perturbation. In terms of temporal variance, long memory is more common

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



in dry periods following distinct rainy seasons and during extensive periods with snow cover.

Although soil moisture memory is often associated with static soil properties like soil depth (e.g. Asharaf and Ahrens, 2013; Hagemann and Stacke, 2014) we find that soil moisture memory is a dynamical feature which strongly depends not only on the size of a given anomaly, but also on favourable climate conditions. Even the size of the initial perturbations can only explain up to 50 % of the spatial pattern of memory while static parameters like soil depth, rooting depth or hydraulic conductivity display even weaker correlations.

Furthermore, soil moisture perturbations affect other land surface states due to different interactions. Strongest impacts are seen for leaf carbon content whose anomalies are associated with a memory of up to 6 months in transitional soil moisture regimes. While the effect on surface temperature is very short-lived and shows much high-frequency variation, the respective anomalies migrate through the soil column into deeper layers and there accumulate to considerable memory that can even exceed the simulation period of three years.

However, we also find that RootSM memory can emerge again after the initial memory was already lost. In most cases this is related to the existence of a deep soil moisture storage below the root zone. As all soil layers interact with each other, anomalies which were already faded in upper layers might recur. This is caused by anomalies still existing in lower layers that either modify percolation or – in case of wet anomalies – can even migrate wet anomalies via upward diffusion. This effect is most common in dry and transitional soil moisture regimes but quite insensitive to the initialization date and type.

From this, we can conclude that memory is not just a property of a single variable but it is modified by the interactions of states in a coupled system. Between different states, only one interaction direction is clearly visible in our simulation, going from soil moisture towards soil temperature and leaf carbon content, respectively. However, we do see two-sided interactions between soil moisture in different layers, namely root zone and

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



deep soil. As deep soil memory exists for the full three year simulation period for some regions and feeds back to root zone memory, the predictive potential of soil moisture initialization might be much longer than previously expected. Thus, soil moisture has the potential to play an important role in seasonal predictions. However, it has to be noted that in the current version of JSBACH, phase changes within the soil column are not yet considered and, thus, water and energy balances are not connected. However, this process is implemented in the next version (Ekici et al., 2014). It leads to a tight moisture-temperature coupling and might result in significant two-sided memory interactions within the two long-memory states. Whether this will result in long-term stabilization or rather in a quick compensation of anomalies is difficult to predict and needs to be tested.

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Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Giorgetta, M. A., Jungclaus, J., Reick, C. H., Legutke, S., Bader, J., Böttinger, M., Brovkin, V., Crueger, T., Esch, M., Fieg, K., Glushak, K., Gayler, V., Haak, H., Hollweg, H.-D., Ilyina, T., Kinne, S., Kornblueh, L., Matei, D., Mauritsen, T., Mikolajewicz, U., Mueller, W., Notz, D., Pithan, F., Raddatz, T., Rast, S., Redler, R., Roeckner, E., Schmidt, H., Schnur, R., Segschneider, J., Six, K. D., Stockhause, M., Timmreck, C., Wegner, J., Widmann, H., Wieners, K.-H., Claussen, M., Marotzke, J., and Stevens, B.: Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5, JAMES, 5, 572–597, doi:10.1002/jame.20038, 2013. 1749

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Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Life time of soil moisture perturbationsT. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Seneviratne, S. I., Koster, R., Guo, Z., Dirmeyer, P. A., Kowalczyk, E., Lawrence, D., Liu, P., Lu, C.-H., Mocko, D., Oleson, K. W., and Versegny, D.: Soil moisture memory in AGCM simulations: Analysis of global land-atmosphere coupling experiment (GLACE) data, *J. Hydrometeorol.*, 7, 1090–1112, doi:10.1175/JHM533.1, 2006. 1747, 1758, 1766
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Table 1. Area-weighted mean values of $\Delta\theta_0$ (upper part) and $\Delta\theta_{\max}$ (lower part) for different soil moisture regimes and initializations.

	Dry regime		Transitional regime		Wet regime	
	Dry	Wet	Dry	Wet	Dry	Wet
leafmass [kg m^{-2}]	-2.5×10^{-4} ; 1.8×10^{-5}	8.7×10^{-6} ; 4.5×10^{-4}	-3.6×10^{-3} ; -9.4×10^{-4}	5.6×10^{-4} ; 2.7×10^{-3}	-1.1×10^{-3} ; 3.4×10^{-4}	-2.5×10^{-4} ; 9.4×10^{-5}
prsurf [hPa]	-1.56; 0.21	0.11; 0.59	-0.96; 0.66	-0.29; 0.69	-0.97; 2.03	-0.30; 0.70
snow [m]	-3.9×10^{-4} ; 0.0	-4.8×10^{-3} ; 5.7×10^{-4}	-2.9×10^{-5} ; 2.5×10^{-3}	0.0; 2.6×10^{-3}	-1.3×10^{-3} ; 5.9×10^{-3}	-1.2×10^{-3} ; 3.2×10^{-3}
humiditiespec [kg kg^{-1}]	-7.9×10^{-4} ; 3.1×10^{-4}	6.2×10^{-4} ; 1.7×10^{-3}	-9.9×10^{-4} ; -4.2×10^{-4}	6.6×10^{-4} ; 1.3×10^{-3}	-3.5×10^{-4} ; 5.1×10^{-5}	-2.5×10^{-4} ; 1.3×10^{-4}
watervapor [kg m^{-2}]	-2.43; 9.36	0.62; 1.85	-1.77; -0.23	0.48; 1.23	-1.27; 1.43	-1.99; 1.01
leafmass [kg m^{-2}]	-9.3×10^{-5} ; 4.0×10^{-4}	2.4×10^{-5} ; 1.2×10^{-3}	-4.1×10^{-3} ; -1.0×10^{-3}	1.0×10^{-3} ; 3.2×10^{-3}	-9.7×10^{-4} ; 5.5×10^{-4}	-1.1×10^{-3} ; 7.7×10^{-4}
prsurf [hPa]	-0.66; 2.64	-1.17; 1.40	-0.98; 0.22	-0.85; 1.81	-2.23; 2.52	-1.06; 3.95
snow [m]	-2.4×10^{-3} ; 2.6×10^{-4}	-5.7×10^{-3} ; 1.4×10^{-3}	4.0×10^{-4} ; 5.1×10^{-3}	3.4×10^{-4} ; 7.3×10^{-3}	-7.6×10^{-5} ; 0.01	2.3×10^{-4} ; 0.01
humiditiespec [kg kg^{-1}]	-4.5×10^{-4} ; 2.1×10^{-3}	5.7×10^{-4} ; 2.6×10^{-3}	-1.2×10^{-3} ; -1.5×10^{-4}	-1.6×10^{-4} ; 8.2×10^{-4}	-8.0×10^{-4} ; 4.0×10^{-4}	-1.5×10^{-3} ; 1.4×10^{-4}
watervapor [kg m^{-2}]	-2.59; 8.47	0.60; 10.05	-3.30; 1.31	-2.79; 2.26	-4.25; 3.79	-5.40; 0.22

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Table 2. Area-weighted mean values of τ_0 (upper part) and τ_{\max} (lower part) in months for different soil moisture regimes and initializations.

	Dry regime		Transitional regime		Wet regime	
	Dry	Wet	Dry	Wet	Dry	Wet
leafmass	0.02; 0.42	0.05; 0.76	1.14; 3.74	1.39; 3.88	0.12; 0.93	0.06; 0.41
prsurf	0.04; 0.07	0.03; 0.10	0.06; 0.13	0.07; 0.18	0.04; 0.12	0.05; 0.13
snow	0.0; 0.03	1.6×10^{-3} ; 0.07	0.0; 0.06	0.0; 0.05	7.0×10^{-3} ; 0.09	0.0; 0.09
humidityspec	0.04; 0.13	0.08; 0.57	0.06; 0.14	0.09; 0.18	0.04; 0.07	0.04; 0.05
watervapor	0.04; 0.11	0.07; 0.10	0.05; 0.08	0.05; 0.09	0.04; 0.05	0.04; 0.04
leafmass	0.02; 0.65	0.47; 2.14	2.23; 5.63	2.67; 6.21	0.50; 2.44	0.28; 1.67
prsurf	0.71; 0.95	0.74; 0.91	0.76; 1.04	0.79; 1.12	0.69; 0.99	0.75; 0.95
snow	0.0; 0.10	1.6×10^{-3} ; 0.14	0.0; 0.15	0.0; 0.15	0.01; 0.38	0.0; 0.29
humidityspec	0.69; 0.98	0.75; 2.07	0.89; 1.06	0.89; 1.29	0.73; 0.93	0.64; 0.96
watervapor	0.55; 0.83	0.68; 0.92	0.76; 0.91	0.77; 0.88	0.70; 0.86	0.68; 0.84

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

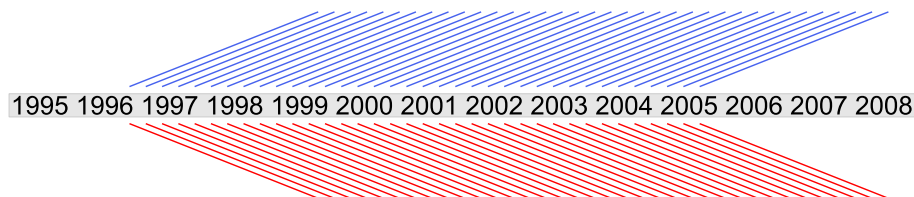



Figure 1. Schematic of the soil moisture initialization experiment setup. The grey bar indicates the time line of reference simulation (REF) while the blue and red lines indicate the extreme wet and dry initialized simulations (INI), respectively.

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

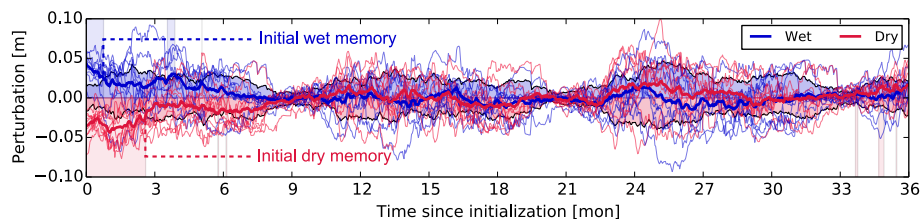


Figure 2. Example for soil moisture perturbation at grid cell scale (June ensemble, grid cell near Hamburg, Germany). The thick blue and red lines indicate the ensemble mean wet and dry perturbation, respectively. The thin lines are single ensemble members and the filled area displays the ensemble standard deviation.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

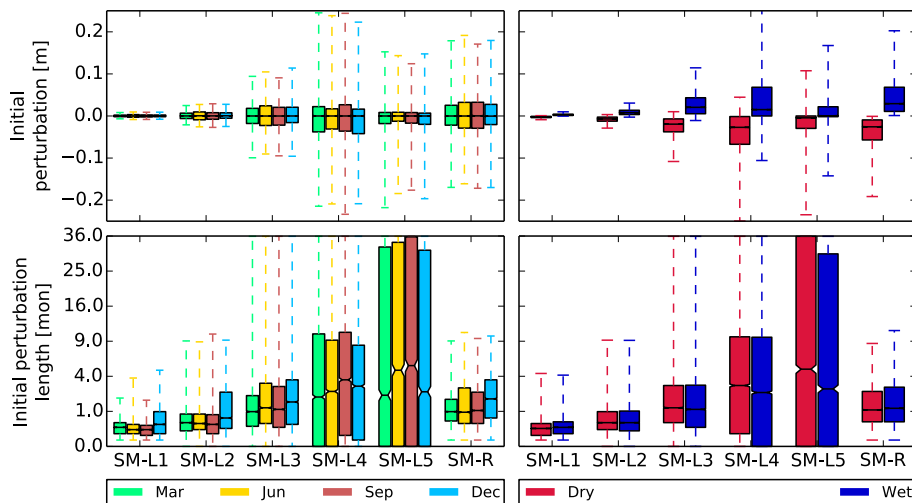


Figure 3. Initial perturbation $\Delta\theta_0$ (upper panels) and perturbation length τ_0 (lower panels) statistics subdivided into seasonal ensembles (left) as well as into wet and dry initialized ensembles (right). Metrics are shown for soil layer moisture (SM-L[1-5]) and the root zone soil moisture (SM-R). The whiskers indicate the 1st and 99th percentiles respectively, the box indicates the interquartile range and the notch indicates the median. Note the exponential axis for τ_0 .

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

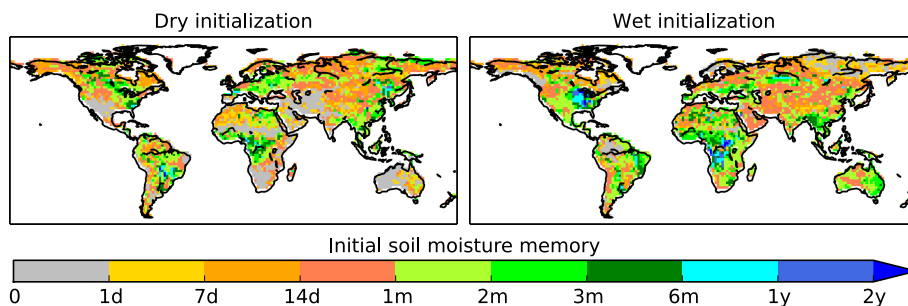


Figure 4. Initial perturbation length for root zone soil moisture in dry (left) and wet (right) initialized simulations. The letters d, m and y indicate days, months and years, respectively.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Life time of soil
moisture
perturbations**

T. Stacke and
S. Hagemann

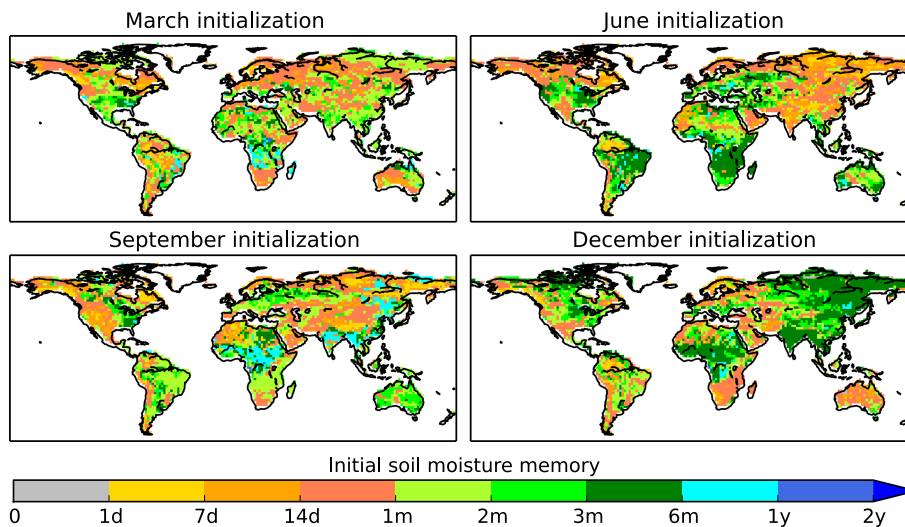
[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Figure 5. Ensemble mean τ_0 for all (dry and wet) simulations initialized in a given season.

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

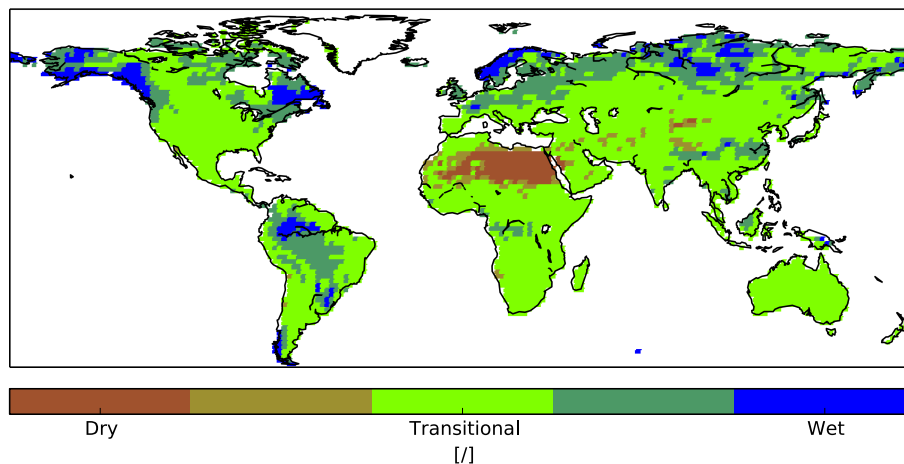
[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Figure 6. Soil moisture regimes based on REF climatology. Transient colors mark grid cells switching between the transitional and wet/dry regimes seasonally while the others remain in their category for the whole year.

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

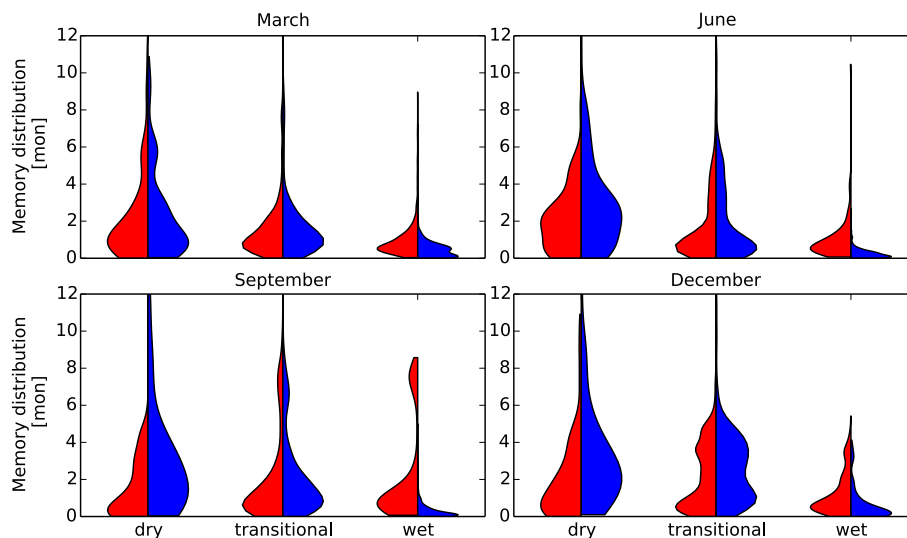
[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Figure 7. Violin plots of τ_0 distribution for dry (red) and wet (blue) initialization in the three soil moisture regimes for the four seasonal ensembles.

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

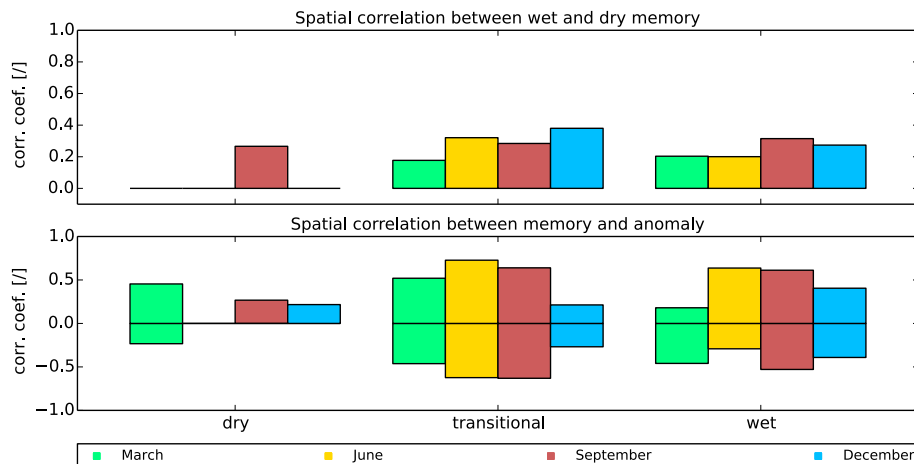


Figure 8. Spearman rank correlation coefficient for different soil moisture regimes and seasons. The upper panel shows the spatial correlation between wet and dry τ_0 . The lower panel shows the spatial correlation between τ_0 and the respective $\Delta\theta_0$. Only significant correlations are included.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

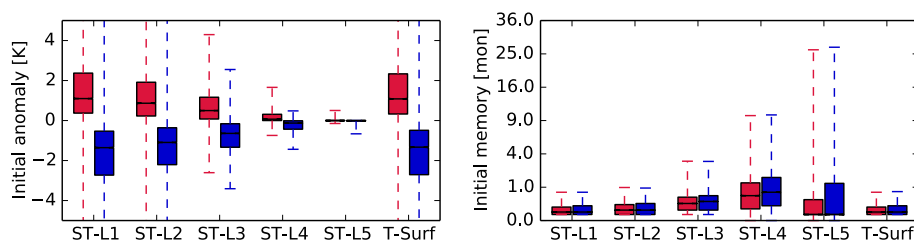


Figure 9. Global statistics for $\Delta\theta_0$ (left) and τ_0 (right) in soil layer (ST-L[1-5]) and surface temperatures (T-Surf) in the wet (blue) and dry (red) initialized ensemble simulations. The whiskers indicate the 1st and 99th percentiles respectively, the box indicates the interquartile range and the notch indicates the median. Note the exponential axis for the memory statistics.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

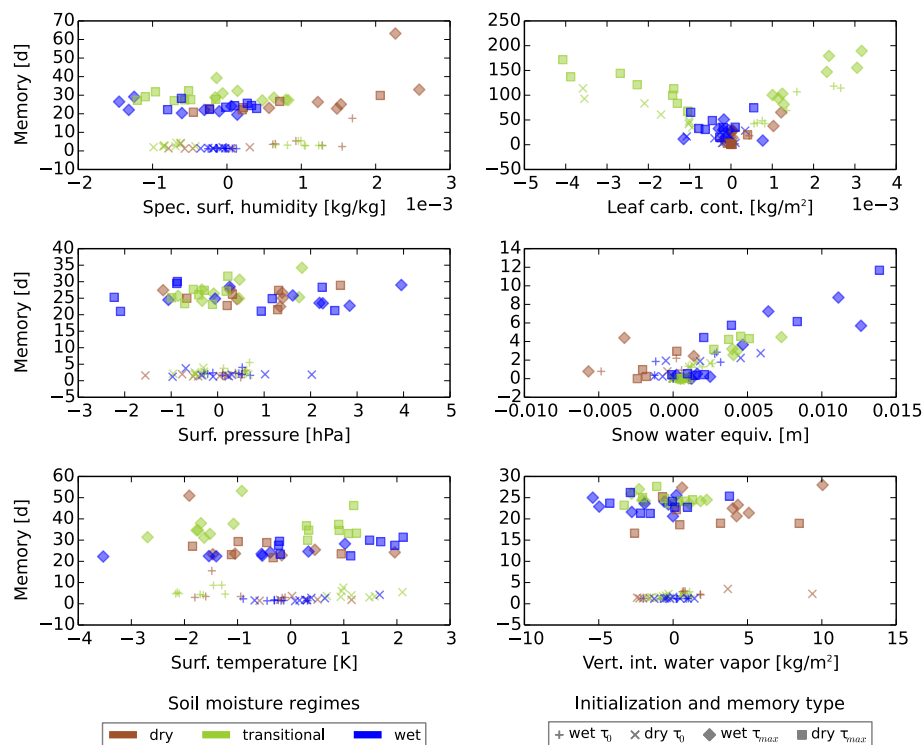


Figure 10. Scatter plots of induced anomaly – memory relation in surface states. The colours indicate the soil moisture regime. The marker symbols refer to the soil moisture initialization state and the memory metric.

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

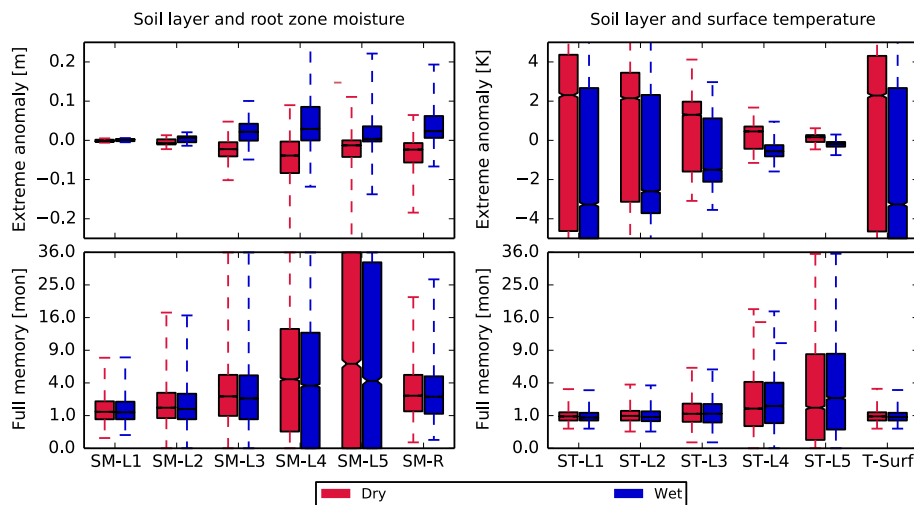


Figure 11. Global statistics for extreme anomalies during the full time series (top panels) and accumulated memory (bottom panels) in soil layer moisture (left side) and temperature (right side) in the wet (blue) and dry (red) initialized ensemble simulations.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)

[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

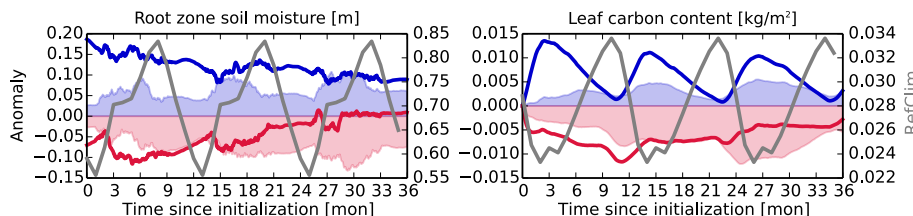


Figure 12. Ensemble mean anomaly (coloured lines) and standard deviation (shaded area) for root zone soil moisture (left) and carbon content in leaves (right) with the respective climatologies (grey) from the reference simulation. Blue colours indicate wet initialization and red colours indicate dry initialization. Time series are from a grid cell at -2.8° N and 13.12° E.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

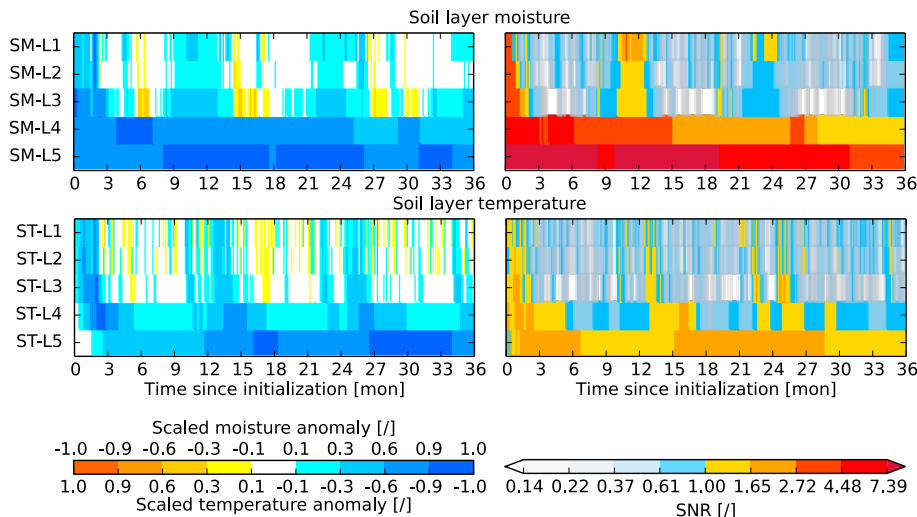


Figure 13. Time series of ensemble mean $\Delta\theta_0$ and SNR for a grid cell at -2.8°N and 13.12°E (Republic of Congo) of the wet initialization September ensemble. The upper and lower panels show soil moisture and soil temperature, respectively, for all soil layers. The anomaly notation is mirrored for the soil temperature. Note, that the SNR color spacing is logarithmic in order to display the ratio similar to a normal distribution. All yellow and red patches in the right panels indicate time periods defined as memory.

Life time of soil moisture perturbations

T. Stacke and
S. Hagemann

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

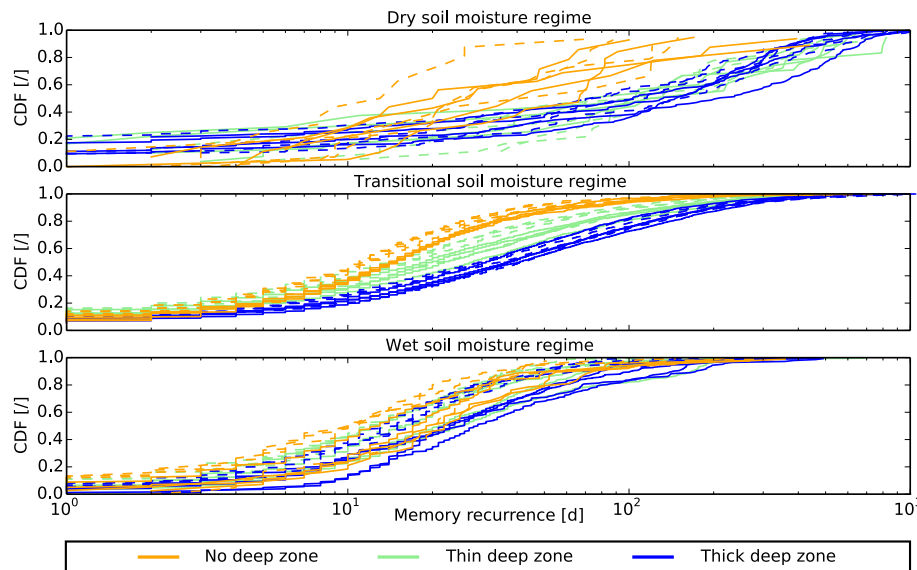


Figure 14. Cumulative density functions of recurring memory for grid cells with different deep zone thickness below the root zone soil moisture (orange, green and blue colours) in all soil moisture regimes. Different initial states (wet and dry) and seasons are merged into the plot where wet and dry initializations are indicated with dashed and solid lines, respectively.