# *AMMA Working Group 3 : Land surface atmosphere feedbacks*

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The interaction between the land surface and the atmosphere is a controlling factor for the development of the west African monsoon. The land surface and the atmosphere are two components of a coupled system, and each influences the other on a range of time and spatial scales. The coupled nature of the system is further complicated by the fact that the different scales are also coupled: small scales influence the larger scale and vice versa. This doubly coupled aspect, together with the wide range of processes implicated, makes the west African monsoon a particularly challenging system to describe and to simulate. The ultimate goal of a fully coupled modeling system with two way interactions between land and atmospheric components and between scales must necessarily be broken down into more manageable tasks that can provide insight into the processes at work. In this integrating working group we present a coherent strategy to draw on the individual modelling and observing efforts taking place elsewhere in the project to address the problems associated with land-atmosphere feedbacks. In a first step we will present the current state of our knowledge on the surface atmosphere interactions followed by a review of currently on-going activities. This will help illustrate the proposed strategy presented at the end.

## 1. Current state of the art

### *1.1 Known characteristic of the intra-annual and inter-annual variability of rainfall*

The changes in the characteristics of the convective systems explain the inter-annual variability of rainfall. Should land-surface processes have an impact on the Africa climate then it needs to be explained how they affect the genesis and evolution of convective systems.
Furthermore the interactions between the surface and the atmosphere are very different in dry periods when the regions is under the influence of a subsidence and during convective phases when the rainfall activates the surface hydrology. To illustrate these strong daily variations in surface processes figure 1 shows observations from the HAPEX-Sahel sites.

A few studies have pioneered this event based analysis of the surface atmosphere interactions :

- Le Barbe and Lebel (1997)
- Polcher (1995)

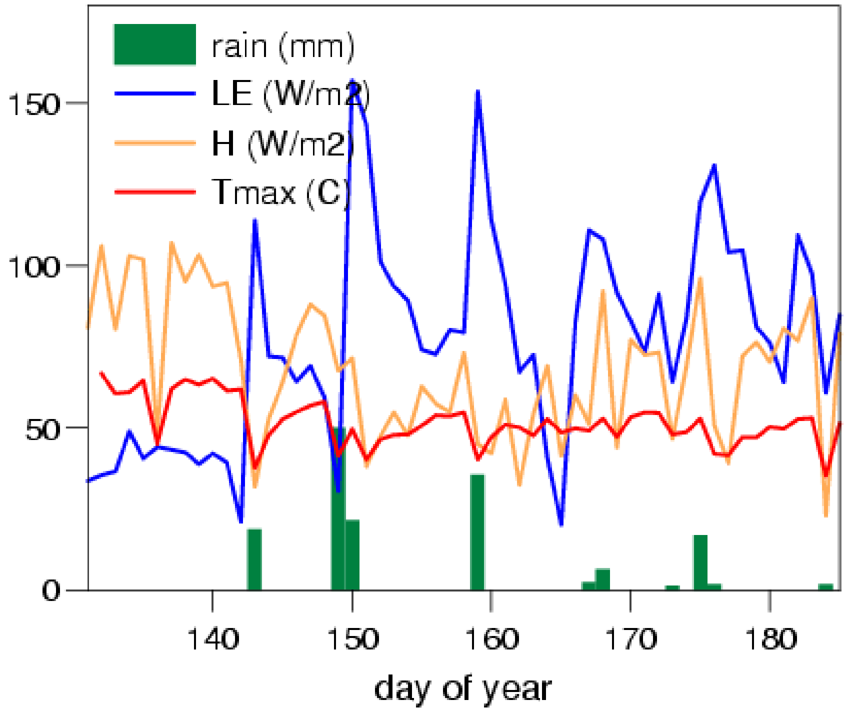


*Figure 1Flux measurements from a Savanna site close to Niamey (Gash et al. 1990)*

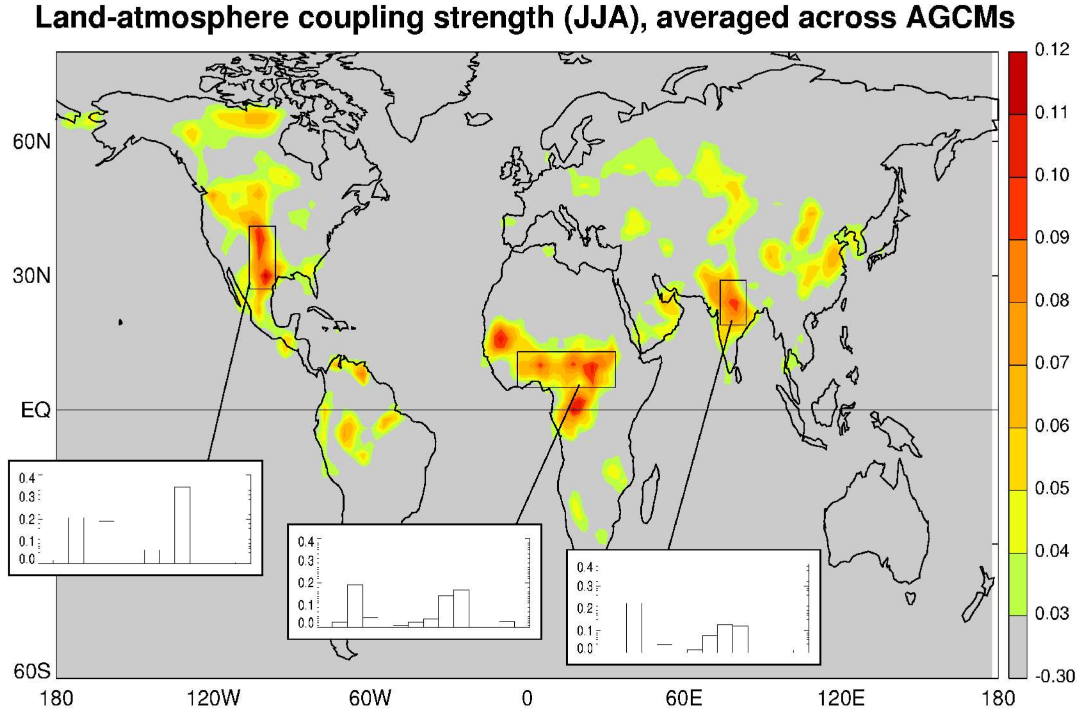
### *1.2 Observations of the surface atmosphere interactions*

**Convective scale:**
Observations from a dense rain gauge network show that relative to a dry area, a recently wetted zone tends to be favoured by increased rainfall in the following storm (Taylor and Lebel 1998). The observations are consistent with a positive feedback mechanism operating at the scale of individual convective cells (~10 km). This hypothesis is supported by modelling results which show a strong sensitivity of convection embedded within a squall line to boundary layer moisture anomalies, particular at short length scales (Clark et al 2004).

**Synoptic scale:**
Satellite observations indicate that the land surface exhibits notable variability at the synoptic scale, associated with the passage of convective systems and easterly waves. The modulation of rainfall by waves at this scale generates strong variability in near surface soil moisture, and hence surface fluxes. The variability in surface heating can generate anomalous heat low circulations which may influence subsequent convection and the evolution of the waves (Taylor et al 2005).

### *1.3 Known uncertainties in models*

Our ability to model these feedbacks appears to be still very poor as there is no consensus between models if the feedback exists and how strong it should be. The recent paper by Koster et al. (2004) has shown that the African region is a hot spot for surface atmosphere coupling (see figure 2). But the regional bar graphs also shows that this strength of the coupling is very different from one model to another. Thus any modelling study performed on the surface atmosphere interactions has to question itself where the model used is situated within this spread and what arguments can be brought forward to indicate that it is more credible than other models.



Land-atmosphere coupling strength (JJA), averaged across AGCMs

*Figure 2: From Koster et al., Regions of strong coupling between soil moisture and precipitation (2004), Science, Vol. 305, 1138-1140.*

This means that AMMA needs to provide better understanding of the processes responsible for the surface atmosphere coupling so that the models can be tested. Credible models should at least be able to reproduce the identified mechanisms.

### *1.5 Open questions*

Based on the current state of our knowledge a list of key open questions can be established.

- How does the land surface integrate the atmospheric input (principally, radiation and turbulent fluxes and precipitation) at different scales ?
- What are the spatial characteristics of the land surface state resulting from the atmospheric forcings ?
- How does the spatial signature of the land-atmosphere exchanges agregate to influence the state of the atmosphere and the associated convection and rainfall ?
- What is the effect of heterogeneities in surface exchange on mesoscale convection ?
- How does temporal heterogeneity in the surface state affect the atmosphere above (the memory effect) ?
- How important are these effects relative to external influences such as the sea-surface temperatures ?
- How are the feedback processes simulate at the mesoscale by convection resolving models represented at the global scale ?

# 2. Ongoing activities

## *2.1 Identifying the main modes of spatio-temporal variability of the continental land surface and comparison of observations (U. Bourgogne)*

### Spatio-temporal variability of surface state

Analyses have been performed on monthly Normalized Difference Vegetation Index (NDVI) data over 1982-2002 (similar results are obtained at a 10-day time-scale). Two leading components have been highlighted using an Independent Component Analysis : the first one (IC1) describes NDVI variability over the Sahel from August to January, the second one (IC2) depicts a dipole pattern between the Sahelian and Guinean regions during the northern summer, followed from October to January by a north-south signal propagation. Correlations and composite analyses reveal linkages with well-known patterns of rainfall and OLR anomalies, partly driven by large-scale sea-surface temperature anomalies. IC1 is related to broad coherent anomalies of rainfall and OLR over the sub-continent at summertime; they result from variations in the Intertropical Front latitudinal location and in convection intensity within the inter-tropical convergence zone (ITCZ) that are partly teleconnected with SST anomalies in the East tropical Pacific and Mediterranean. IC2 reflects a north-south dipole in rainfall and OLR due to variations in the latitudinal location of the ITCZ, as a response to modifications of the Atlantic inter-hemispheric gradient.

### Relationships between autumn land surface state and the following summer rainfall

These relationships have been explored through composite analyses, cross-correlations analyses and Granger causality analyses with NDVI and sigma_0 data over the period 1992-2000. Results suggest that the theoretical 'inter-season' memory held by deep-soil moisture reservoirs and deep-rooted plants from autumn to spring is possible. Indeed, over the study period, the wettest Sahelian rainy seasons were preceded by positive anomalies of soil-vegetation water content over Guinea from winter to spring. These winter to spring anomalies are partly related to the 2nd Guinean rainy season. They strengthen the meridional gradient of soil-vegetation water content over the sub-continent in winter and spring; this gradient is thought to partly control the gradient of entropy and then the monsoon.

### Intraseasonal evolution of Sahelian vegetation

Analyses have also been performed regarding the intra-seasonal evolution of the Sahelian vegetation (i.e. phenological main stages) and its variability. Over the Sahelian band, the median photosynthetic activity onset and cessation dates respectively occur during the 1st 10-day period of July and the 2nd 10-day period of November. The onset date shows low inter-annual variations. Years of 'low' photosynthetic activity are usually characterized by slow photosynthetic activity increase, weak NDVI levels (e.g. 1984, 2002) while years of 'high' photosynthetic activity featuring delayed cessation, steep growth and high NDVI levels. These types of seasonal courses are strongly dependent on those of rainfall; the amount recorded during the 3rd decad of August (i.e the one preceding the NDVI maximum) appears crucial for the overall quality of the vegetative season.

## *2.2 Surface influence on inter-annual variability of the monsoon in a climate model (CNRM)*

The main objective in this topic is to explore the impact of different soil moisture (SM) boundary conditions or initial conditions on dynamical seasonal hindcasts of the West African monsoon (WAM) using the ARPEGE-Climat atmospheric GCM driven by observed sea surface temperatures (SST). Besides a control experiment with interactive SM, two sensitivity experiments will be performed in which more realistic boundary conditions or initial conditions will be used. Each experiment consists of an ensemble of ten 10-year simulations over the 1986-1995 period, allowing us to assess both the variability and the predictability of the WAM.

This 10-year period has been chosen to take advantage of the recent GSWP2 project that has been used to produce a global SM reanalysis. Given the lack of both in situ and satellite SM observations, GSWP2 is aimed at producing global SM datasets by driving land surface models with 3-hourly atmospheric analyses and monthly land surface parameters available on a 1° by 1° horizontal grid. The ISBA land surface model of CNRM has participated in GSWP2 and the resulting SM data set is in principle the climatology that would have been simulated by ARPEGE-Climat if it was a perfect atmospheric model. Unfortunately, this is not true for two reasons: 1) the GSWP2 land surface parameters are not the default boundary conditions used in ARPEGE-Climat, 2) the baseline GSWP2 atmospheric forcing shows a systematic overestimation of precipitation in several regions.  These difficulties explain some delay in our WP1.3 activities, but this delay should not affect the other WP1.3 contributions.

The first step has been the production of a global SM climatology over the 1986-1995 period with the ISBA land surface model. The GSWP2 soil and vegetation parameters have been replaced by the ECOCLIMAP data base used in the ARPEGE-Climat model. Moreover, the baseline GSWP2 precipitation forcing has been replaced by an alternative product in which empirical satellite and wind corrections have been removed. The resulting water budget simulation has been evaluated after converting the ISBA runoff into river discharge with the help of a river routing model. While the results are globally satisfactory, the simulation of the West African river discharges shows serious problems. Besides uncertainties in the precipitation forcing, some deficiencies in the ISBA land surface model (such as the lack of floodplain parametrization) probably contribute to the significant discrepancy between simulated and observed discharges over the Niger river basin.

The second step has been the production of the control ensemble experiment with interactive SM. The ARPEGE-Climat model has been driven by observed monthly mean SSTs over the whole 1986-1995 period. The control experiment consists of 10 simulations initialized in September 1985 from different initial conditions derived from a previous experiment. The analysis will focus on the summer monsoon season, whose predictability will be assessed both with a perfect model approach and against real observations. Given the 18-month timescale of the milestone, the sensitivity experiments with prescribed GSWP2 SM boundary conditions, and then prescribed GSWP2 SM initial conditions before the onset of the monsoon season, should be performed before the end of 2005. This constraint means that we won’t be able to improve the GSWP2 SM climatology over West Africa before starting these experiments. This remark does not mean that the sensitivity tests will not affect the monsoon variability and predictability, since the prescribed SM conditions will be however probably much more realistic than the ARPEGE-Climat SM climatology.

### *2.3 Case study mesoscale model simulations for the study region (U. Leeds)*

Preliminary simulations of atmospheric circulations over the region and their sensitivity to soil moisture have been made using the Met Office Unified Model. These have focused on case studies from the JET2000 experiment. On one day during that experiment (August 28th), an aircraft flew over mesoscale areas of recent rainfall adjacent to rather dry conditions. Model diagnostics have been compared to aircraft data and the analysis suggests that the spatial variability in near surface soil moisture may explain structures in and above the planetary boundary layer. Another case study at the larger scale is in its initial stage. The work is expected to reach its milestone at 12 months, and thus will feed into detailed flight planning for the SOP.

### *2.4 Evaluation of fluxes associated with circulations at the diurnal time scale (IBIMET)*

Based on approaches used in mid-latitudes, theoretical modeling will be performed assessing the impact of idealized surface flux variability on the dynamics of heat lows and the evolution of easterly waves. The impact of surface heating and moisture variability on atmospheric circulations, and their interaction with larger-scale dynamics through momentum and heat fluxes over low latitudes, will be assessed in the presence of a strong meridional circulation.

Initial work has focused on the development of an analytical model to analyze how small a horizontal variation in surface heating can be and still produce a significant mesoscale circulation, how the heat and momentum fluxes associated to mesoscale flows can penetrate deeply into the mid-troposphere, and how they modify tropospheric relevant climate parameters, such as the atmospheric static stability. The theoretical model is almost ready, but further study is necessary to verify the results and to finalize the model for more complex situations. In order to accomplish this one of the contributors is now visiting the Dpt of Atmospheric Science at the Colorado State University working in the Prof R.A. Pielke’s Research Group. More complex theoretical modelling using some numerics is planned for the near future. Progress towards the 18 month milestone has been somewhat delayed due to the late arrival of funding for the project.

### *2.5 Implementation of models and design of experiments assessing soil moisture – convection feedback loops (CNRS and U. Perugia)*

Work towards this milestone involves a complementary approach which will combine understanding based on simulations with both a cloud-resolving model and a single column model.

**Single column model (SCM)**

Current work is focused on analysis of the SCM convection and surface parameterisations when coupled in the GCM. More specifically, over West Africa, the GCM has problems with the limited northward extension of the simulated monsoon precipitation. Present analyses seem to indicate that the problem is mainly due to the insufficient evaporation provided by the surface scheme. A thorough analysis of the surface scheme is being undertaken and improvements should be tested by month 9. The implementation of the SCM should begin after that.

**Cloud-resolving model (CRM)**

Work till now has involved setting the CRM code up for on the ECMWF cluster. The code has been changed in many places in order to produce radiative-convective simulations and these changes need to be re-implemented in a fashion compatible with the MPI implementation that is running on the HPC facilities cluster. Progress has also been made on reading into the model pre-existing experiments to avoid lengthy spin-up simulations.

### *2.6 Development of satellite tools to identify moisture related heterogeneities (CEH)*

It is crucial for a number of flight plans during the SOP and the analysis of all observations related to the surface atmosphere interactions to be able to locate areas of high surface soil moisture from recent (hours to days) rainfall. To this end, operational tools based on near-real time satellite imagery are being prepared. Following rainfall, anomalies from a fortnightly mean diurnal cycle of cloud-free land surface temperature and albedo produce a characteristic cool, dark signature. A short report based on data from 2000 has been produced illustrating typical surface signals during the pre-onset phase of the SOP, and this has been communicated to WP4.2. The use of near-real time Meteosat Second Generation data (provided by the LandSAF) is currently being explored. It is hoped that a preliminary version of the system will be ready in time for the forecasting dry run in month 8 of the project. This will permit an assessment of its utility ahead of the SOP.

## 3. Proposed structure for future activities

In order to further our understanding of the surface atmosphere interactions and to integrate the currently on-going activities we propose a scientific strategy which approaches the problem progressively. We break into the coupled system by considering one-way influences, first from data-derived atmospheric states to the land surface, then from the land surface response back to the atmosphere. Integrating the work done in work packages 4.1, 2.3 and 2.1 of AMMA-France and AMMA-EU, the approach is first to force land surface models with atmospheric data – including data collected in the SOP/EOP, and then in turn to force atmospheric models with the surface states generated by these land surface modelling experiments. The approach is presented in illustration 1. The objective is to learn enough from this offline coupling approach to understand better the fully coupled system. The final outcome of this exercise is to compare the coupling simulated by mesoscale models with the one assumed in surface, planetary boundary and convection parameterizations of large scale models. This confrontation will provide the knowledge needed to understand the relative impact of surface processes in the evolution of the monsoon and the potential impact of surface perturbations.

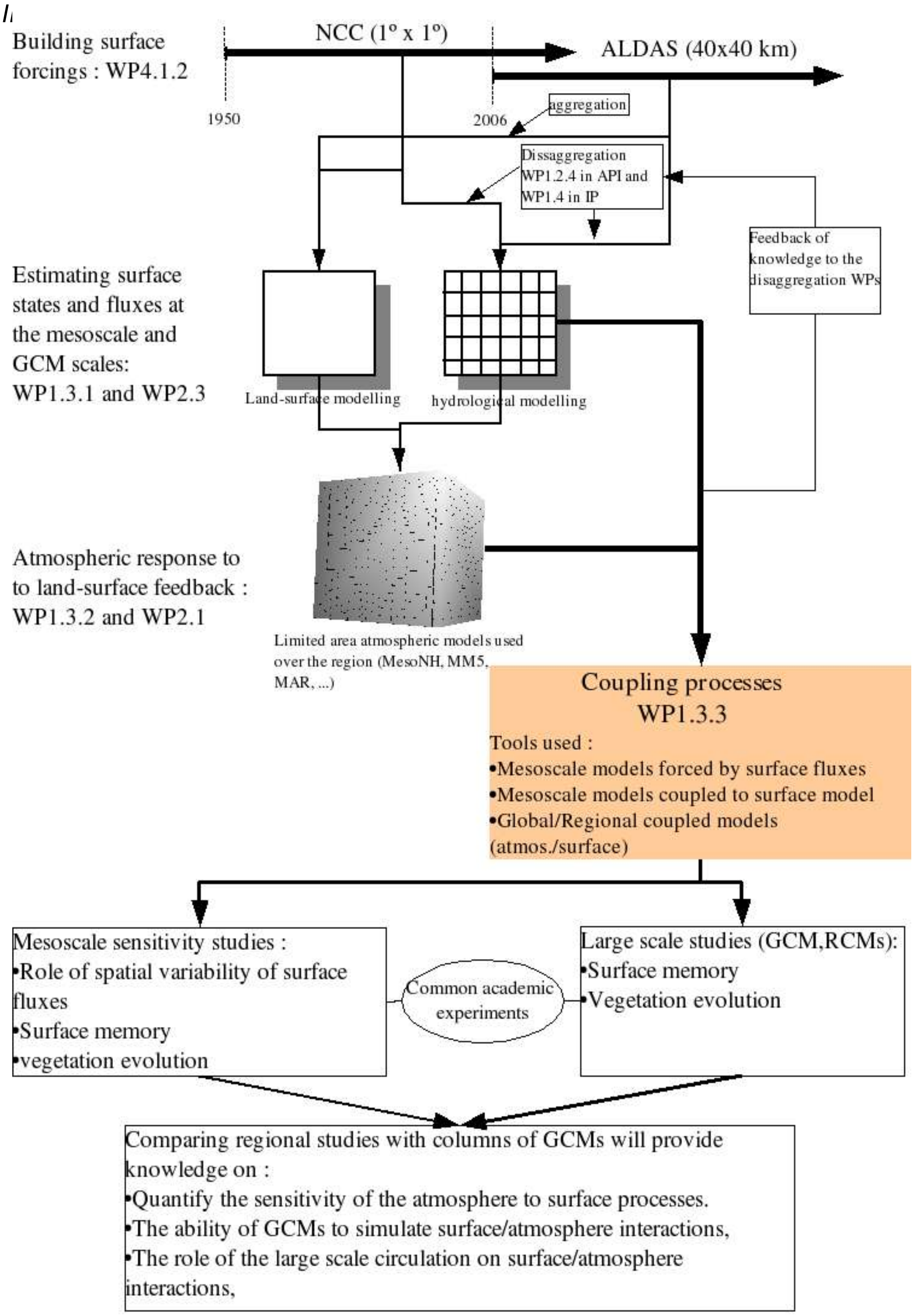


*Illustration 2: A proposed strategy for surface atmosphere interactions.*

To help clarify the steps to be taken and the relation with other AMMA activities involved, this scientific strategy can be split into 3 activities :

- Land surface processes and atmospheric forcing, which details the plans for use of observations and experiments with land surface models.
- Atmospheric response to land surface processes, which discusses the experiments to be performed with atmospheric models at the mesoscale.
- Coupling processes confronts the mesoscale and the large scale view of the coupling processes in order to asses the role of surface processes in the West African Monsoon.

The planed observations will also allow to identify directly some processes key in the surface atmosphere interaction and which which then constitute benchmarks to evaluate models.

- How does soil moisture influences atmospheric circulations (“dry”) - from mesoscale daytime breezes possibly associated with initiation of convection to initiation/amplification of easterly waves.
- How does soil moisture affects initiation, propagation and structure of MCS.

### *3.1 Land surface processes and atmospheric forcing*

The objective of this activity is to use the land surface model experiments carried out in part in WP2.3 and WP4.1 of AMMA-France and AMMA-EU to assess the role of atmospheric conditions on land surface processes, to perform case study experiments based on forcing data from the EOP and SOP, and in turn to provide surface conditions for the atmospheric model experiments in WP 1.3. This subject has strong links with WP2.3, where land surface models are developed and tested with observed surface conditions. Here the emphasis is on the impact of the atmosphere on surface processes and in particular the role of spatial heterogeneities of the atmospheric forcing.

Before tackling a fully coupled problem at mesoscale it is important to understand the behaviour of the different components of the system. This necessitates an offline coupling approach for which the first step is to force land surface models with the best flux observations available. The land surface models described and developed in 2.3 will then be interrogated for their surface flux heterogeneity at the mesoscale, a property thought to be partially forced by the atmosphere and of critical importance for the subsequent atmospheric response. The work to be done in this subsection can be broken down into three steps:

1) Initial experiments with land surface models using a range of idealised forcing heterogeneities to gauge sensitivity.
2) Preparation of input data emanating from SOP/EOP for case study experiments (link with WP4.1).
3) Analysis of the change in surface conditions owing to the land surface response to this forcing: in particular its heterogeneity.

### *3.2 Atmospheric response to land surface processes*

This activity contains the second half of the experimental design for the investigation of land surface-atmosphere feedback, in which an atmospheric mesoscale model, which resolved explicitly the African convective systems, is forced by fluxes of heat and water vapor produced with the land surface model experiments to be defined under 1.3 and carried out in 2.3. To prepare the fully coupled approach with GCMs single column models will also be tested in their response to surface fluxes. While a comprehensive treatment of the full coupled problem at all scales is still judged to be beyond the scope of this investigation, much can be learned from an exercise where we simulate the atmospheric response to a land surface state which is itself a response to imposed atmospheric conditions. The degree of consistency between the atmospheric model and the original atmospheric input data will provide insight into a number of important phenomena, including:

- The role of small scale surface heterogeneity in modifying the mesoscale atmospheric response.
- Identify the large scale situation which allow the surface heterogeneities to express themselves in the local atmospheric processes.
- The importance of surface memory effects on the local level.

In parallel with the mesoscale modelling work, work with GCMs on the regional scale is ongoing, and some of the same questions will be addressed at these larger space and timescales. In particular the memory effect can also be investigated on a seasonal basis at large scale. The evolution of vegetation cover both on seasonal and interannual timescales is also of central importance to AMMA, both in terms of climate feedback and changes in land use.

The ultimate goal of this research is to gain insight into surface/atmosphere feedbacks at a scale at which they can be explicitly simulated to to a large extent. This will provide invaluable information to sensitivity of large scale models to surface processes.

### *3.3 Coupling processes*

**This activity integrates the accomplishments of the previous two sub-WPs and extends them to the global scale.**

The experiments which can be done at the mesoscale are limited by the fundamental hypothesis that the local surface/atmosphere interactions do not affect the large scale forcing. This is inherent in the convection resolving models used as the large scale forcing is imposed.

On the other hand GCMs and RCMS represent the surface/atmosphere feedbacks under the premise that small scale heterogeneities do not impact these interactions. Even if the parameterizations of surfaces, boundary layers and clouds integrate some notion of heterogeneity their interactions assume that spatially homogeneous fluxes are exchanged. In the case of RCMs the large scale forcing is imposed as in mesoscale models. Thus they offer an interesting intermediate tool in this integration of scales.

In order to make progress in the understanding of the land-surface atmosphere feedbacks it is essential to confront these contrasting views and produce a more fundamental understanding of these key processes of the West African Monsoon.

This will be achieved through the following steps :

1. Identify the rain producing systems which are explicitly represented in mesoscale models and the properties of which can be studied in GCMs and RCMs. This will set the metric used to compare the models results at the various scales.
2. Design model experiments based on the mesoscale studies and observations which can be performed at all scales. It is likely that these experiments will be of a more academic nature but they need to be inspired by the results at the mesoscale.
3. Based on the results of the mesoscale models the results of the GCMs can be evaluate and their sensitivity to surface processes assesed.
4. Based on this knowledge and the enhanced confidence in the sensitivity of GCMs the relative role of surface processes and sea-surface temperatures can be evaluated.