African **M**onsoon **M**ultidisciplinary **A**nalyses
Afrikanske **M**onsun**:** **M**ultidisiplinære **A**nalyser
Afrikaanse **M**oesson **M**ultidisciplinaire **A**nalyse
Analisi **M**ultidisciplinare per il **M**onsone **A**fricano
Afrikanischer **M**onsun: **M**ultidisziplinäre **A**nalysen
Analisis **M**ultidisciplinar de los **M**onzones **A**fricanos
Analyses **M**ultidisciplinaires de la **M**ousson **A**fricaine

The International Science Plan for AMMA

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Preface

African Monsoon Multidisciplinary Analysis (AMMA) is an international project to improve our knowledge and understanding of the West African monsoon (WAM) and its variability with an emphasis on daily-to-interannual timescales. AMMA is motivated by an interest in fundamental scientific issues and by the societal need for improved prediction of the WAM and its impacts on West African nations. Vulnerability of West African societies to climate variability is likely to increase in the next decades as demands on resources increase in association with one of the World's most rapidly growing populations. Vulnerability may be further increased in association with the effects of climate change and other factors linked to the fast growing population.

Recognising the societal need to develop strategies that reduce the socioeconomic impacts of the variability of the WAM, AMMA will facilitate the multidisciplinary research required to provide improved predictions of the WAM and its impacts. This will be achieved and coordinated through 5 international working groups: (i) West African monsoon and global climate, (ii) Water cycle, (iii) Land-surface atmosphere feedbacks, (iii) Prediction of climate impacts and (iv) High impact weather prediction and predictability.

AMMA will promote international coordination of ongoing activities, basic research and a multi-year field campaign over West Africa and the tropical Atlantic. AMMA will develop close partnerships between those involved in basic research of the WAM, operational forecasting and decision making, and it will establish blended training and education activities for African technical institutions and schools.

The AMMA International Science Plan:

- Provides a summary of the key scientific issues and questions that will be addressed by the AMMA programme.
- Describes and promotes a scientific strategy for carrying out the integrative science that is central to AMMA.
- Provides a summary of how the AMMA research and field programme will be organized and implemented.

The international science plan will be updated as the AMMA programme develops in the coming years. A detailed "Implementation Plan" that describes the field observations and planning is in development and will be available in a separate document during 2005.

EXECUTIVE SUMMARY

Introduction to AMMA

African Monsoon Multidisciplinary Analysis (AMMA) is an international project to improve our knowledge and understanding of the West African monsoon (WAM) and its variability with an emphasis on daily-to-interannual timescales. AMMA is motivated by an interest in fundamental scientific issues and by the societal need for improved prediction of the WAM and its impacts on West African nations. Vulnerability of West African societies to climate variability is likely to increase in the next decades as demands on resources increase in association with one of the World's most rapidly growing populations. Vulnerability may be further increased in association with the effects of climate change and other factors linked to the fast growing population such as land degradation and water pollution.

Recognising the societal need to develop strategies that reduce the socioeconomic impacts of the variability of the WAM, AMMA will facilitate the multidisciplinary research required to provide improved predictions of the WAM and its impacts. The international AMMA project has three overarching aims:

(1) To improve our understanding of the WAM and its influence on the physical, chemical and biological environment regionally and globally.

(2) To provide the underpinning science that relates variability of the WAM to issues of health, water resources, food security and demography for West African nations and defining and implementing relevant monitoring and prediction strategies.

(3) To ensure that the multidisciplinary research carried out in AMMA is effectively integrated with prediction and decision making activity.

AMMA will promote international coordination of ongoing activities, basic research and a multi-year field campaign over West Africa and the tropical Atlantic. AMMA will develop close partnerships between those involved in basic research of the WAM, operational forecasting and decision making, and it will establish blended training and education activities for African technical institutions and schools.

At this time scientists from more than 20 countries, representing more than 40 national and pan-national agencies are involved in AMMA. In addition to international structure which has been set up, a network of African scientists linked to AMMA has been established (AMMANET) which will help to consolidate existing collaborations in Africa and to federate initiatives through a pan-African partnership. At this time, funding is largely secured in Europe (mainly in France, Germany, UK & the European Union) up to 2010. Other international efforts are underway to help mobilise the extra funding needed to achieve all the AMMA aims.

AMMA is endorsed by the World Climate Research Programme (WCRP) and continues to develop in association with CLIVAR and GEWEX[1]. AMMA has also been endorsed by two

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[1] All acronyms referred to in the executive summary are included at the end of the summary

projects within International Geosphere-Biosphere Programme (IGBP): IGAC and ILEAPS. AMMA is working with other international projects and programmes to achieve its aims including GCOS, GOOS and THORPEX.

Major Issues

We are currently hindered in providing skillful predictions of WAM variability and its impacts. There are still fundamental gaps in our knowledge of the coupled atmosphere-land-ocean system at least partly arising from lack of appropriate observational datasets but also because of the complex scale interactions between the atmosphere, biosphere and hydrosphere that ultimately determine the nature of the WAM. The monitoring system for the WAM and its variability is inadequate with many gaps in the standard routine network and lack of routine monitoring of some key variables. While the next generation of satellites will undoubtedly help with routine monitoring and prediction efforts, more research is required to validate and exploit these data streams. Dynamical models used for prediction suffer from large systematic errors in the West African and tropical Atlantic regions; current models have problems simulating fundamental characteristics of rainfall such as the diurnal, seasonal and annual cycles. Finally, there is a lack of integrative science linking the work on WAM variability with work on food, water and health impacts. More effort needs to be made to integrate scientists working in these different areas.

Further motivation for a research project concerned with WAM variability and predictability comes from recognizing the role of Africa on the rest of the world. Latent heat release in deep cumulonimbus clouds in the ITCZ over Africa represents one of the major heat sources on the planet. Its meridional migration and associated regional circulations impact other tropical and midlatitude regions, as is exemplified in the known correlation between West African rainfall and Atlantic hurricane frequency. In addition to the large-scale interactions, we know that a majority of hurricanes that form in the Atlantic originate from weather systems over West Africa; however we know little about the processes that influence this and why only a small fraction of these “seedlings” actually become hurricanes.

The WAM system provides an ideal framework for considering scale interactions in a monsoon system: it possesses pronounced zonal symmetry with characteristic jets and associated well-defined weather systems. Research on such scale interactions and in particular those linking dynamics and convection with the land surface will be relevant to other monsoon systems and is needed in order to improve coupled atmosphere-ocean-land models used for weather and climate prediction. In order to carry out this research extra observations are needed.

West Africa is also an important source region for natural and anthropogenic emissions of precursors to key greenhouse forcing agents (e.g. ozone, aerosols). For example, Africa contributes around 20% of the global biomass burning fires. These emissions are modulated by the activity of the WAM but in contrast to other surface impacts they feedback directly on the climate. Long-range transport of trace gases out of West Africa has important implications for the global oxidizing capacity of the atmosphere (which controls the level of many greenhouse gases), global climate change and the transport of key constituents (e.g. water vapour, ozone depleting substances) into the stratosphere. The fires also produce huge quantities of particles, complex mixtures of organic materials and black carbon.

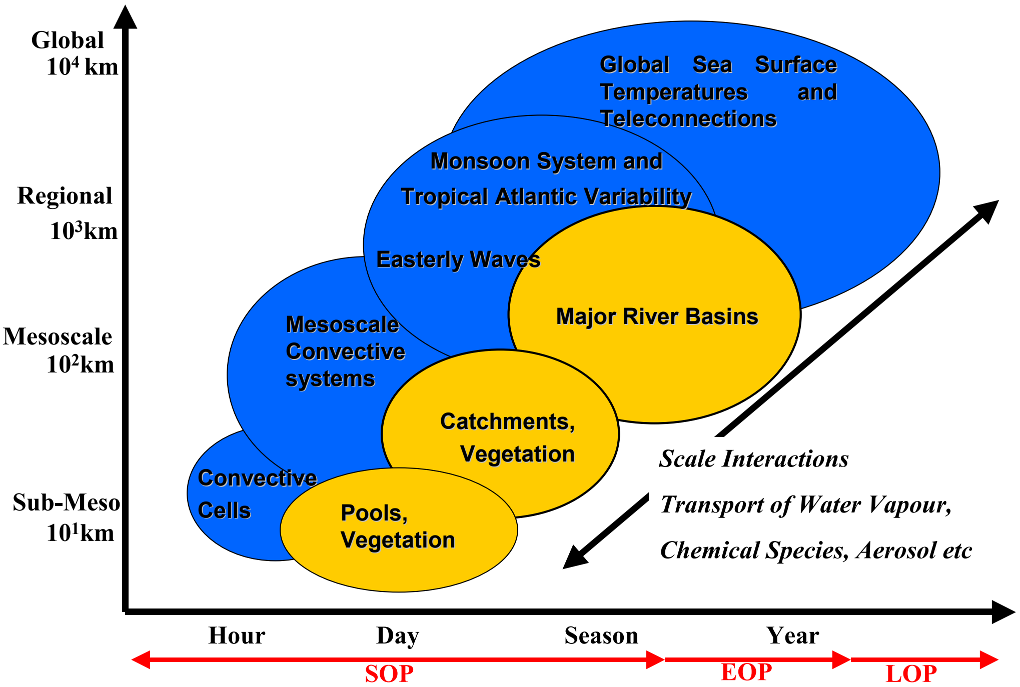
Tropical Africa is the world’s largest source of atmospheric dust. Both the fire aerosols and dust play a major role in radiative forcing and in cloud microphysics, and thus are an important part of WAM system. A key priority is to determine the transport of trace gases and aerosols from the surface to the upper atmospheric layers and the subsequent transport by the WAM. It is thus necessary to study the dynamics and the chemistry of the atmosphere in the same framework.

The AMMA Programme

A project that deals with all the major issues raised above will require a major coordinated international effort involving a multidisciplinary approach to the West African monsoon linking observations, data analysis and modeling on a wide range of space and time scales.

- ***A Multiscale Approach***

To address the multiple scales that characterize the WAM the program is structured around 4 interacting spatial scales (see schematic below): ***(i) Global scale.*** This is the scale at which the WAM interacts with the rest of the globe; emphasis is given to improving our understanding of the role of global SST patterns on WAM variability; seasonal-to-decadal variability are the main time scales of interest ***(ii) Regional scale.*** This is the scale at which we consider monsoon processes and scale interactions; emphasis is given to improving our understanding of the interactions between the atmosphere, land and tropical Atlantic ocean (especially the Gulf of Guinea). It is important to study the role of land surface feedbacks on variability of the WAM at this scale including the key roles of vegetation and soil moisture. The annual cycle and seasonal-to-interannual variability are the main time scales of interest. ***(iii) Mesoscale.*** This is the scale of the typical rain-producing weather systems in the WAM. It is central for studying the variability of rainfields at the seasonal scale and the coupling between hydrology and the atmosphere at the catchment scale. ***(iv) Local scale or sub-meso scale.*** From an atmospheric point of view, this is the convective rain scale; it is central to the hydrology of the Sahel and of small watersheds to the south; it is the main scale of interest for agriculture.

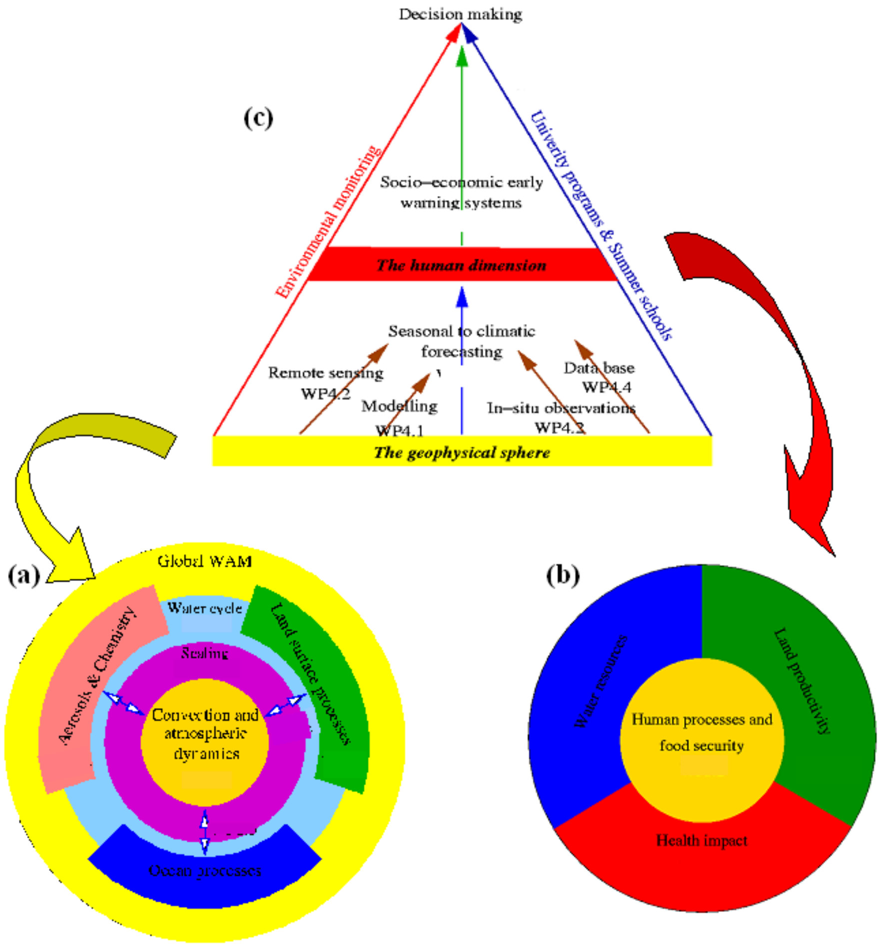


Simplified schematic of key phenomena together with their associated space and time scales. The arrow is included to highlight the importance of scale interactions and transport processes in the WAM.

AMMA emphasizes the importance of improved understanding of how these scales interact and combine to characterize the WAM and its variability, including how these interactions impact sources and transport of water vapour, aerosol and key chemical species (e.g. key greenhouse gases, ozone and aerosol precursors) in the West African region and globally.

- ***Integrative Science and Implementation of AMMA***

Key objectives and planned research activities for each scale have been formulated for AMMA. While it is convenient and appropriate to describe the research plans in terms of these different spatial scales, it is essential for an improved understanding to study the scale and process interactions. The implementation of AMMA is designed in this spirit. The AMMA project integrates the scales at which the geophysical and human processes interact. Furthermore the various disciplines involved in the study of the West African Monsoon need to be integrated to achieve the three overarching aims. This approach has guided the structuring of the scientific objectives.



Implementation of AMMA: Integrative science for the geophysical (a) and human dimension (b) Integration from this knowledge through various tools and for the exploitation by impact studies (c)

From the geophysical perspective, the fundamental science underpinning the AMMA project can be viewed as the various disciplines coming together within broader integrative science topics: i) the interactions between the WAM and global climate from a physical as well as a chemical perspective, ii) the water cycle of the WAM from the regional to the local scale and iii) the coupled atmosphere-land-ocean system and its multiple scales. To feed these integrative topics with sound disciplinary knowledge of the processes and their scale dependence detailed studies of the processes are needed: i) atmospheric processes with a focus on the convective processes which are key to the rainfall production, ii) oceanic processes as they contribute and depend on the WAM, iii) biophysical processes over the continent from the regional to the local scale and iv) aerosol and chemical processes in the atmosphere.

To study the human dimension of the variability and possible trends in the West African Monsoon AMMA aims to address the direct impact of the environmental conditions on three limiting conditions for the African societies: i) Land productivity, ii) water resources and iii) health impacts. This activity will be coordinated to achieve a better understanding of how weather and climate variability impact food security and human processes in the region.

To achieve the AMMA scientific objectives and to master the challenge of multi-scale and multi-disciplinary aspects, a consistent set of tools and methods adapted to the problem of the West African Monsoon will be used: i) models and data assimilation, ii) field campaigns, iii) satellite remote sensing and long-term atmosphere/land/ocean data collection and iv) data base. These activities are key to transferring knowledge from the geophysical community in AMMA to the activities in the human dimension. These tools will collect and consolidate knowledge, integrate the knowledge and materialize the predictive skill gained with this knowledge.

- ***The Field Programme***

AMMA is planned to be a multi-year project and involves 3 nested observation periods. It should be underlined here that the enhancement of observations during these periods will provide a unique opportunity to determine future operational monitoring necessary to improve weather and climate forecasts over the West African region. More than this, a high priority for AMMA is to establish this operational network of observations providing a visible legacy for the international AMMA programme.

- **The Long term Observing Period (LOP)** is concerned with observations of two types: (i) historical observations to study interannual-to-decadal variability of the WAM (including currently unarchived observations) and (ii) additional long term observations (2002-2010) to document and analyse the interannual variability of the WAM.

- **The Enhanced Observing Period (EOP)** is designed to serve as a link between the LOP and the SOP (below). Its main objective is to document over a climatic transect the annual cycle of the surface conditions and atmosphere and to study the surface memory effects at the seasonal scale. The EOP will be 2-3 year duration (2005-2007).

- **The Special Observing Period (SOP)** will focus on detailed observations of specific processes and weather systems at various key stages of the rainy season during three periods in the summer of 2006: (i) the dry season (Jan-Feb), (ii) Monsoon onset (15 May-30 June), (iii) Peak monsoon (1 July – 14 August) and (iv) Late monsoon (15 August-15 September).

- ***Satellites***

Satellite observations will strongly contribute to the objectives of the project by providing key variables of the surface – atmosphere system (e.g. Meteosat/MSG, ENVISAT, TRMM, AURA, AQUA-Train, TERRA). AMMA provides a unique set of integrated atmosphere/land/ocean observations for validation of the satellites. It will also provide the framework to build a reliable monitoring strategy combining satellite and in situ atmosphere/land/ocean networks, to make up for the low density of routine observations in and offshore Africa. Geophysical parameters and their uncertainties will be produced at different scales and gathered in a unique database allowing multiscale as well as multidisciplinary analysis of the WAM and its variability.

- ***Weather and Climate Prediction Models***

Models will be combined with observations to investigate the nature of the WAM at daily, seasonal-to-interannual and decadal timescales, including how the different scales interact. As throughout the AMMA program, the linkages between weather and climate variability will be emphasized. This approach is particularly pertinent to improving models for climate prediction since scale interactions and processes not handled well by GCMs used for climate predictions are best studied in the same GCMs at the weather system scale. Thus, while AMMA recognizes the need for different modeling strategies for studying and predicting weather and climate variability, it will seek to develop a strong synergy between them especially with respect to understanding representation of key scale interactions and systematic errors.

Final comments

AMMA has been carefully conceived to improve our fundamental understanding of the West African monsoon and its societal impacts and to make sustainable improvements to monitoring and prediction of the West African environment. Our activities are embedded within a 'Long-term observing period' (LOP) structure, which will ensure that our intensive activities are directed towards systematic improvements in monitoring and prediction over the coming decades. We will develop and upgrade two important land-based atmospheric monitoring systems (for the upper air and surface fluxes), and over the LOP we will transfer responsibility for these networks to the local African agencies. In addition, ocean monitoring systems surrounding West Africa that have been shown to improve both weather and climate forecasts will continue to provide data to these groups. These networks of observations are of enormous value both to global prediction systems and to local forecasting systems, based in Africa.

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1. MOTIVATION AND BACKGROUND

The interannual and interdecadal variability of the West African monsoon (WAM) is well documented and has motivated considerable research efforts in this area (e.g. Nicholson, 1981; Lamb, 1983; Folland et al, 1986; Fontaine and Janicot, 1996; Le Barbé et al., 2002). The dramatic change from wet conditions in the 50s and 60s to much drier conditions in the 70s, 80s and 90s over the whole region represents one of the strongest interdecadal signals on the planet in the 20th century. Superimposed on this, marked interannual variations in recent decades have resulted in extremely dry years with devastating environmental and socio-economic impacts. Such variability has raised important issues related to sustainability, land degradation, and food and water security in the region.

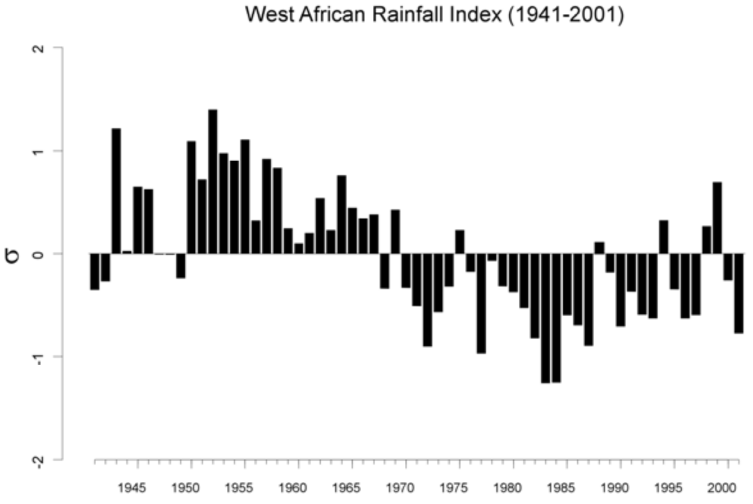


Figure 1.1 Time series (1941-2001) of average normalized April-October rainfall departure for 20 stations in the West African Soudano-Sahel zone (11-18N and West of 10E); following methodology of Lamb and Peppler, 1992).

Vulnerability of West African societies to climate variability is likely to increase in the next decades as demands on resources increase in association with one of the World's most rapidly growing populations. Vulnerability may be further increased in association with the effects of climate change and other factors linked to the fast growing population such as land degradation and water pollution (IPCC, 2001). Motivated by this and recognising the important need to develop strategies to reduce the socioeconomic impacts of climate variability in West Africa, scientists are faced by two major challenges:

1) **To improve our ability to predict the WAM and its impacts on intra-seasonal-to-decadal timescales.**
2) **To improve our ability to assess the impacts of climate change on WAM variability and its impacts.**

We are currently hindered in providing skillful predictions of WAM variability and its impacts. There are still fundamental gaps in our knowledge of the coupled atmosphere-land-ocean system at least partly arising from lack of appropriate observational datasets but also because of the complex scale interactions between the atmosphere, biosphere and hydrosphere that ultimately determine the nature of the WAM. The monitoring system for the WAM and its variability is inadequate with many gaps in the standard routine network and lack of routine monitoring of some key variables. While the next generation of satellites will help, the research that will enable this still needs to be done. Dynamical models used for prediction suffer from large systematic errors in the West African and tropical Atlantic regions; current models have problems simulating fundamental characteristics of rainfall such as the diurnal, seasonal and annual cycles (e.g. WCRP, 2000). Finally, there is a lack of integrative science linking the work on WAM variability with applications such as the areas of food, water and health. More effort needs to be made to integrate scientists working in these different areas.

Further motivation for research concerned with WAM variability and predictability comes from recognizing the role of Africa on global weather and climate. Latent heat release in deep cumulonimbus clouds in the ITCZ over Africa represents one of the major heat sources on the planet. Its meridional migration and associated regional circulations impact other tropical and midlatitude regions, as is exemplified in the known correlation between Sahelian rainfall and Atlantic hurricane frequency (e.g. Landsea and Gray, 1992). In general, our understanding of how the African heat source interacts with the global climate is weak and requires attention (WCRP, 2000). Also, the strong zonal symmetry of the WAM system makes it an ideal framework for considering scale interactions in a monsoon system. Research on such scale interactions and in particular those linking dynamics and convection with the land surface will be relevant to other monsoon systems and it is important to assess whether coupled atmosphere-ocean-land models are able to represent them. In order to carry out this research and to assess the models extra observations are needed.

West Africa is also an important source region for natural and anthropogenic emissions of precursors to key greenhouse forcing agents (e.g. ozone, aerosols). For example, biomass burning in savanna and forest ecosystems over Africa contributes around 20% of the global biomass burning fires. Long-range transport of trace gases out of West Africa also has important implications for the global oxidizing capacity of the atmosphere (which controls the level of many greenhouse gases), global climate change and the transport of key constituents (e.g. water vapour, ozone depleting substances) into the stratosphere. The fires also produce huge quantities of particles, complex mixtures of organic materials and black carbon. North Africa is also the world’s largest source of atmospheric dust. Both the fire aerosols and dust play a role in radiative forcing and in cloud microphysics. Satellite images show that large plumes of African dust and smoke extend over large areas of the Atlantic Ocean during much of the year, reaching into South America, the Caribbean and the North America. Thus, to the extent that these particles affect climate, their effects impact a huge area.

A project that deals with all these issues will require a major coordinated international effort involving a multidisciplinary approach to the West African monsoon linking observations, data analysis and modeling on a wide range of space and time scales. In order to make a significant contribution to the way environmental and climate issues are addressed in West Africa, a strong link will also have to be built with scientists and decisions makers working in the area of applications such as land and water resources management, agricultural and health research.

The present document aims at reviewing the key scientific issues we are facing in dealing with the WAM and at proposing the main lines of an international initiative to address them. Section 2 will introduce the key scientific issues that relate to the WAM, its components and impacts. Section 3 is devoted to presenting the AMMA program and Section 4 reviews the international and programmatic linkages .

2. SCIENCE BACKGROUND FOR AMMA

2.1 Introduction

The West African monsoon (WAM) is a coupled land-ocean-atmosphere system characterised by summer rainfall over the continent and winter drought. The processes that couple the land, ocean and atmosphere take place in association with multiple interacting space and timescales. Many of the key scientific questions that relate to these scale interactions cannot be answered using routinely available observations and reanalysis datasets. This is due to a combination of the sparcity of the routine observing network, the need for specialist observations and the known deficiencies of GCMs used for weather and climate prediction and relied upon for producing reanalyses. Furthermore small spatial and short temporal scales of variability are of great importance for applications and there is a need to characterize and understand how they vary on seasonal-to-decadal timescales. This situation has provided strong motivation for the research and proposed field program within AMMA.

Key research areas are highlighted in the following subsections. First, the key issues that relate to monsoon dynamics and scale interactions are briefly reviewed in section 2.2. This includes a consideration of the processes that influence the large-scale aspects of the West African monsoon and its variability and also its associated weather systems including mesoscale convective systems, easterly waves and tropical cyclones.

As with all monsoon systems the evolving surface conditions are crucially important for determining the nature of the WAM and its variability. In particular, prospects for improved seasonal-to-interannual prediction of the WAM rely heavily on the inherent predictability of these surface conditions as well as our ability to observe key surface variables needed to initialize dynamical models and the ability of these models to simulate their evolution. The scientific issues related to the processes that influence the surface conditions over the land and ocean are reviewed in sections 2.3 and 2.4 respectively.

Africa is a major source of fire aerosols and mineral dust. Given the fact that there are great uncertainties regarding the impact of these particles on weather and climate, there is an important opportunity to address aerosol issues within the AMMA program. Issues related to the mobilization, transport and impacts of aerosol on weather and climate in the West African and Atlantic regions are included in section 2.5.

Tropical Africa is a significant source of natural and anthropogenic precursors of key greenhouse gases (e.g. ozone) and atmospheric aerosols. To date, there is extremely limited information about the chemical composition over West Africa. Also, the extent to which the regional and global radiative forcing and the oxidizing capacity are being perturbed by emissions from West Africa is unknown. Section 2.6 discusses key scientific issues that relate to atmospheric chemistry and the WAM.

Variability of the WAM has a major impact on food and water resources and health in the region. It is becoming increasingly clear that efforts need to be made to link the work on variability and predictability of the WAM to such applications. The key scientific issues related to this are reviewed in section 2.7.

2.2 Monsoon Dynamics and Scale Interactions

2.2.1 The Annual Cycle

The annual cycle of rainfall in the West African region is characterized by a poleward migration of peak rainfall up to about August followed by a more rapid retreat (Fig. 2.2.1). It also includes an apparent “jump” in the location of peak rainfall at the end of June from the coastal region around 5°N to about 10°N (Sultan and Janicot, 2000; Le Barbé et al, 2002). State-of-the-art GCMs used for weather and climate prediction have difficulty simulating the annual cycle of rainfall and associated regional circulations. This raises serious concerns about whether these models can realistically represent the key interactions between the WAM and the rest of the globe that are important for determining interannual-to-decadal variability of West African and regional climates. It is fundamentally important that we improve our understanding of the annual cycle of West African rainfall and the associated regional circulations including in particular the processes that influence rainfall intensity, its meridional migration, onset and the “jump”. Further motivation for this comes from the fact that monsoon onset is considered particularly important for most applications (see section 2.7 below).

Mechanisms have been proposed to explain various aspects of monsoons and their evolution and need to be investigated in the context of the WAM. These include the role of changes in boundary layer θe gradients and inertial instability on the establishment of direct circulations and the location of rainfall (e.g. Emanuel, 1995; Zheng et al, 1999; Tomas and Webster, 1997), the role of dry intrusions on the associated intensity and meridional extent of the rainfall (e.g. Parsons and et al, 2000; Chou et al, 2001; Roca et al, 2005), the role of surface processes including soil moisture and vegetation feedbacks (e.g. Taylor and Lebel, 1998; Chou et al, 2001) and the role of remotely forced circulations including, in particular, those associated with the Asian Monsoon (e.g. Rodwell and Hoskins, 1996).

In order to investigate these mechanisms an accurate description of the annually evolving surface conditions over the land and ocean are required (see section 2.3 and 2.4 below). The way these surface conditions interact with the atmosphere must be investigated through an analysis of surface energy and water budgets, atmospheric convection (moist and dry) and radiation. Alongside this it is important that the regional circulations are analysed including their impact on transport of water vapour and aerosol (see section 2.5).

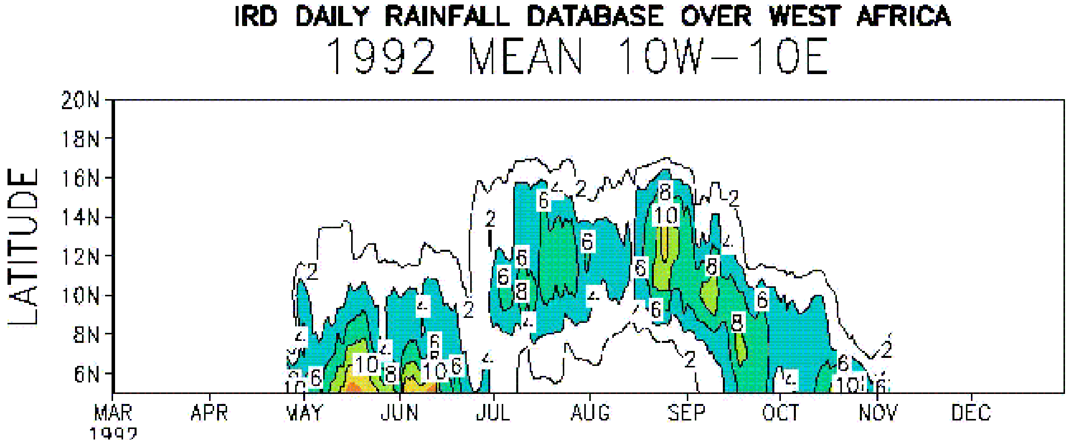


Figure 2.2.1 Seasonal evolution of rainfall in 1992 based on daily rainfall observations between 10W and 10E. Adapted from Redelsperger et al 2002

2.2.2 The Diurnal Cycle

Studies of the diurnal variation of precipitation over West Africa by McGarry and Reed (1978) and Dai (2001) using surface observations indicate a precipitation maximum in the evening. McGarry and Reed (1978) found that between 15 and 20 N thunderstorms were most frequent in the late afternoon or early evening, rain amounts were greatest shortly before midnight, convective cloud cover was most extensive shortly after midnight, and light rainfall most common near dawn. They could not explain this diurnal cycle in terms of a nocturnal low-level jet (although one may exist, as described below), and invoked the natural cycle of MCS development as an explanation. They argued that near-uniformity in the time of maximum rainfall over large areas ruled out squall propagation as an explanation for the diurnal cycle, despite the existence of westward-propagating AEWs and MCSs over the region. In contrast to these surface based studies, Yang and Slingo (2001) used satellite observations that indicated a precipitation maximum that ranged between the evening and early morning. It has been hypothesized that the early morning peak in the vicinity of the Greenwich meridian may be associated with the passage of MCSs triggered earlier by upstream orography but the nocturnal jet that develops in association with the diurnal variations in the heat low may also have a role.

It is important to understand MCS development in terms of the diurnal cycle. The ability of the MCSs to generate midlevel PV anomalies is connected to the heating profile in stratiform regions (Fritsch et al. 1994). Schumacher and Houze (2003) have suggested that the lower stratiform rain fraction over land (Fig. 2.2.5) is connected with the diurnal cooling of the land at night, which tends to truncate the MCS lifecycle. The MCS development will thus likely produce the largest PV anomalies when a process such as a low-level jet overrides the cooling cycle and maintains an MCS through the night. It is therefore important that AMMA include an evaluation of the diurnal cycle with respect to MCS development and maintenance.

Observations and theory show that the heat low circulation and associated moisture transport varies strongly during the day due to the changes in surface heating (e.g. Parker et al., 2005b, Racz and Smith, 1999). As discussed by Parker et al (2005b) the basic diurnal cycle arises through an interplay between the diurnal cycle of the heat low over the Sahara (which drives the circulation) and the diurnal cycle of boundary layer convective turbulence (which tends to suppress the circulation). This coherent diurnal cycle of transport and mixing are key processes that influence the continental water budget. Moist air is advected polewards at low-levels in association with an acceleration towards low pressure. A return flow, characterized by much lower humidity above this exists around 600-700mb following the baroclinic variation of the pressure gradient with height. Theory and models suggest that the peak poleward surge in moisture at low levels occurs in the early morning. However there are almost no available observations to support this hypothesis since operational soundings are usually only launched at close to local noon or occasionally also at midnight. High frequency soundings are required to better document the diurnal evolution of the heat low circulation, establishment of the nocturnal jet and associated moisture transports to support the investigation of the role of these diurnal circulations on the continental water budget and precipitation. These observations should ideally take place during undisturbed periods in order to highlight the coherent diurnal cycle that is unaffected by weather.

Further analysis of the diurnal cycle and its relationship with MCSs and AEWs is clearly needed, as well as the relationship of convection to the diurnal evolution of the boundary layer and low-level flow.

2.2.3 Jets and associated Weather Systems

The WAM is characterized by several key approximately zonal flows that are established in association with the meridional heating contrasts and associated direct circulations (Fig.2.2.2).

The African easterly jet (AEJ) is located in the region of strong low-level θ gradients between the Sahara and the Guinea Coast (e.g. Burpee, 1972, Reed et al, 1977). The tropical easterly jet (TEJ) is an upper-level jet that is established in the equatorward outflow region of the convection and may also be influenced by the outflow of the Asian monsoon. At low-levels south-westerlies from the Atlantic provide most of the moisture for the WAM while polewards of this north-easterlies advect relatively drier Saharan air into the rainy region. These flows impact the regional moisture and energy budgets and the nature of the synoptic and mesoscale weather systems. We currently lack a detailed description and understanding of these interactions and large-scale influences. This is at least partly hindered by the sparcity of the routine upper-air network that is inadequate for resolving these jets and regional circulations. While aircraft campaigns such as that during the JET2000 experiment (Thorncroft et al, 2003) can provide important observations for process studies and the evaluation of model analyses (e.g. Tompkins et al, 2005, see also Kamga et al, 2000) more research is needed in order to recommend what key additional observations are needed as part of a sustained observing system.

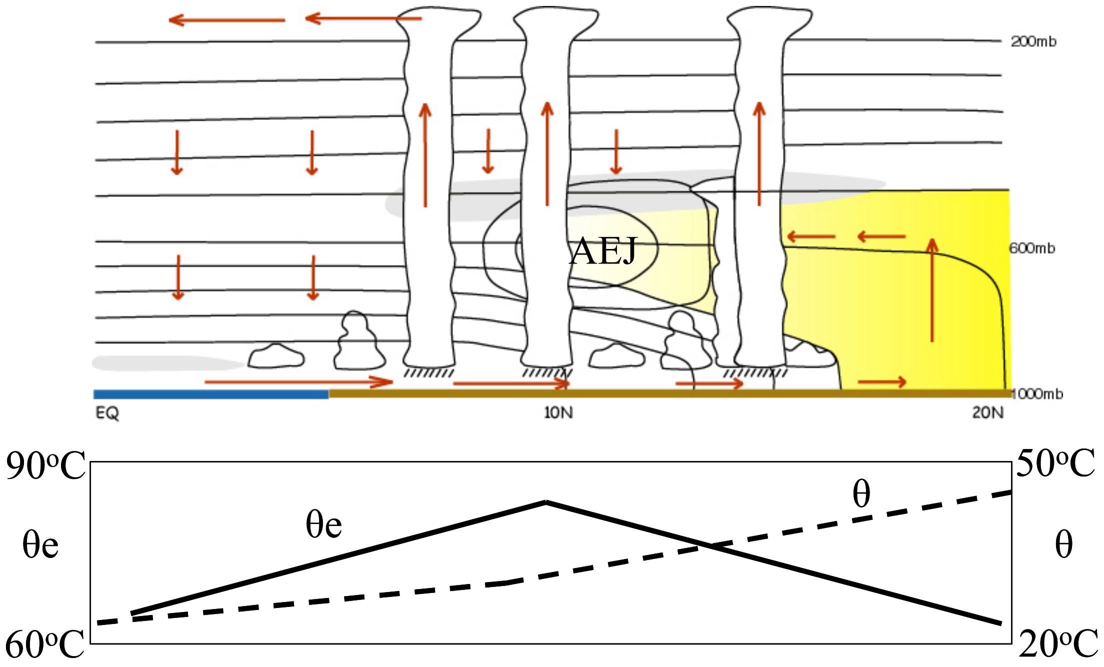


Figure 2.2.2 Schematic of N-S vertical cross section along the Greenwich Meridian, highlighting the heat low-AEJ-ITCZ system and SAL (shaded yellow) and meridional variations in atmospheric boundary layer θ and θe. Adapted from Parker et al. (2005a).

While, from a large-scale perspective the WAM can be described in terms of the annual march of the ITCZ and its associated regional circulations, it is important to remember that the ITCZ represents the sum of many smaller scale weather systems (Fig. 2.2.3). These include mesoscale convective systems (MCSs), (e.g. Houze and Betts, 1981) and synoptic systems such as African easterly waves (AEWs) (e.g. Reed et al, 1977). These weather systems are also known to initiate many of the Atlantic tropical cyclones downstream and thus are an important part of the interactions that take place between West Africa and the Atlantic Ocean. AMMA will strive to provide an understanding of the nature and variability of individual weather systems that comprise the WAM, and will therefore complement similar studies from TOGA COARE and GATE (Rickenbach and Rutledge, 1998; Houze and Betts, 1981).

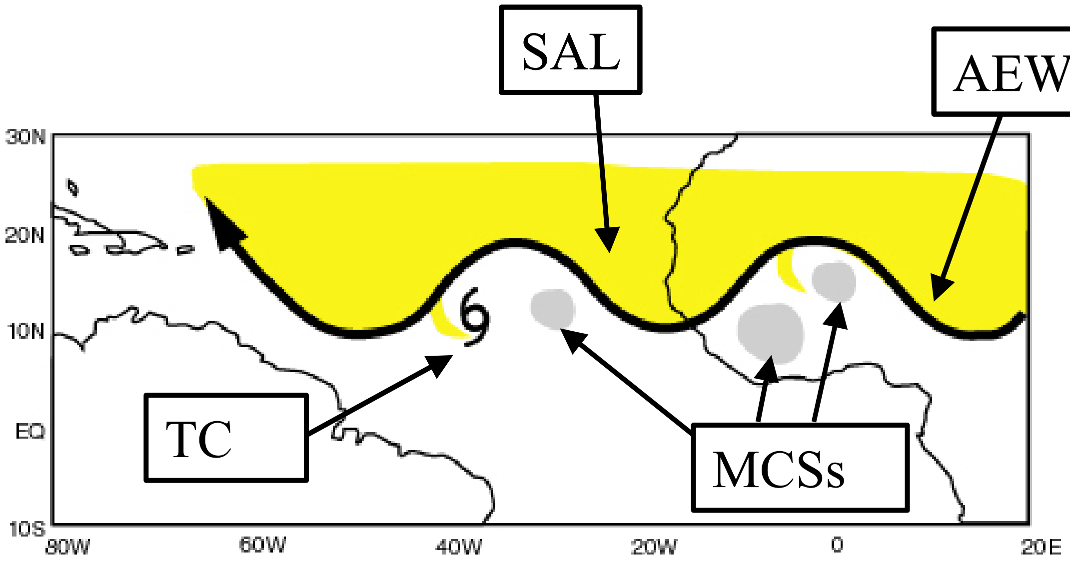


Figure 2.2.3 Key weather systems in the West African and Tropical Atlantic regions. Solid line represents a streamline at the level of the AEJ around 600hPa. Grey shading represents peak rainfall and yellow shading indicates the location of the SAL.

It is important that we have a good description and understanding of these weather systems including how they interact with convection, the surface and the large-scale environment including the jets and monsoon layer winds (c.f. Redelsperger et al, 2002; Diongue et al, 2002). Although these scale interactions are central to the WAM we lack a good description and understanding of how they operate and combine to produce the observed WAM and its variability. The extent to which GCMs used for weather and climate prediction are able to represent these scale interactions, explicitly or through parametrisations requires investigation.

Further motivation for the study of weather systems and their variability comes from applications (e.g. hydrological and crop models) that are sensitive to the temporal and spatial variability associated with these weather systems. The extent to which the statistics of these systems are predictable at seasonal-to-interannual timescales is unknown and should be investigated.

The chemical composition of the free troposphere is intrinsically linked to dynamical as well as chemical processes. Deep convection is important for the transport of aerosols and gases from the boundary layer into the free troposphere and for their subsequent loss by heterogeneous removal processes including washout. Current treatments of these processes in chemistry transport models require significant improvement and will benefit from the muliti-disciplinary studies proposed as part of AMMA. The role of processes such as stratosphere-troposphere exchange and penetration of deep convection into the upper troposphere in determining the chemical composition of the tropical tropopause layer and the transport of trace gases such as water vapour and CFCs to stratosphere still need to be determined. The transport of ozone from the stratosphere, for example across the sub-tropical jet, may also be an important and, as yet, unquantified source of ozone in the troposphere.

(a) African Easterly Waves

African easterly waves are important in West Africa due to their association with daily rainfall (e.g. Reed et al, 1977, Fig.2.2.4) and also downstream in the tropical Atlantic where they can serve as precursors for tropical cyclones (e.g. Avila and Pasch, 1992). Despite their importance, fundamental gaps exist in our knowledge and understanding of the evolution of AEWs as they move across Africa and the Atlantic; especially how they interact with convection and other physical processes. For example, composite analyses of AEWs (e.g. Reed et al, 1977, Diehdiou et al, 1999) have shown that AEWs are associated with a coherent modulation of the rainfall but the processes that explain this modulation and its variability are not well understood. Because of the marked meridional contrasts in temperature and humidity that exist over West Africa, synoptic-scale advections of temperature and moisture may be expected to impact the nature of the clouds and convection including MCSs. These relationships require investigation through improved analysis of the synoptic environment and associated convection characteristics.

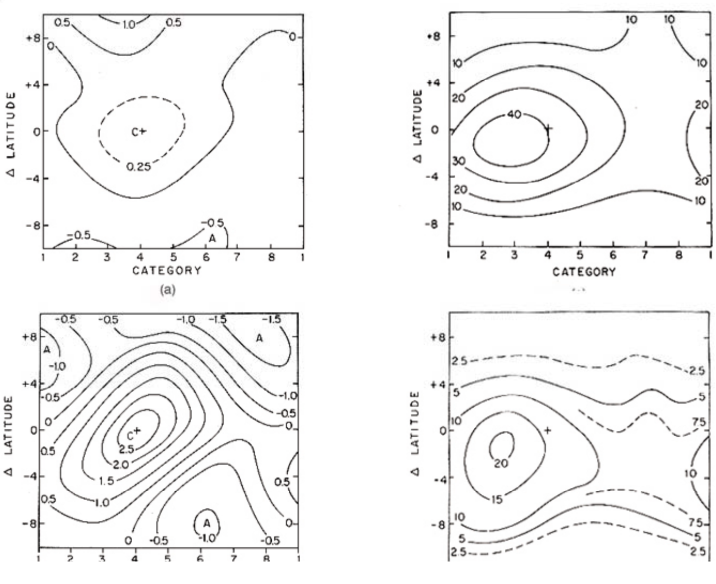


Figure 2.2.4 Composite AEW structures from phase III of GATE (after Reed et al, 1977). (a) and (b) are relative vorticity at the surface and 700hPa respectively with a contour interval of 10-5s-1. (c) and (d) show percentage cover by convective cloud and average precipitation rate (mm day^{-1}) respectively. Category 4 is location of 700hPa trough and the "0" latitude is 11^{o}N over land and 12^{o}N over ocean.

AEWs are often described as developing via a mixed barotropic-baroclinic instability mechanism in association with the meridional gradients in potential vorticity (PV) in the core of the AEJ and meridional gradients in low-level θ (e.g. Burpee, 1972, Thorncroft and Hoskins, 1994, see Fig. 2.2.2). While this theory has received considerable acceptance its application to real events has barely been explored. The extent to which it is appropriate to describe these weather systems as waves or isolated vortices generated by convective heating, whether they have a finite amplitude origin or develop through a local instability and ultimately their interactions with convection and surface conditions (e.g. Taylor and Clark, 2001) are all areas that need to be investigated.

As shown by Reed et al (1988) and more recently by Thorncroft and Hodges (2001), AEWs are associated with vorticity anomalies that have two distinctive tracks. One track is located at low-levels on the poleward side of the AEJ and is linked to perturbations that develop in the vicinity of the low-level meridional theta gradient. The second track is located closer to the level and latitude of the AEJ and is linked to perturbations that develop in the vicinity of the negative meridional gradients in PV. Little is known about the variability of these storm tracks and how they impact the WAM and downstream tropical Atlantic.

(b) Mesoscale Convective Systems

Since MCSs provide a majority of the rainfall over West Africa (e.g. Mathon et al., 2002; Lebel et al., 2003) it may be argued that the WAM is strongly linked to the statistics of these MCSs and that the variability in the WAM in turn is linked to variability in these statistics. In this context it is important that we improve our understanding of the 2-way interactions between the MCSs and the synoptic environment in which they develop including the AEWs, the jets, low-level monsoon and Saharan air flow and surface conditions. The extent to which MCSs can become organized, the processes that lead to this and the consequences for the 2-way interactions with the synoptic environment require investigation. Such investigations must take account of the whole life cycle of the MCSs including initiation, propagation and decay. MCSs forming over Africa and moving offshore were studied extensively in GATE (Houze and Betts 1981). However, the GATE data set was limited to ship based radars. In COPT81 the first Doppler radar data were obtained in west African MCSs (Chong et al. 1987). Much was learned from these early studies. However, they lacked airborne radars and polarimetric radars from which a more complete dynamical and microphysical description could have been obtained. In addition there were no lightning measurements. To relate the African MCSs to the AEJ and AEWs modern observational technology is needed.

A key motivation for this work is the need to represent the large-scale impacts of MCSs in climate and forecast models. In this respect, major areas for investigation include how deep convection is initiated, the propagation of fast-moving systems through model meshes and the momentum, heat and moisture transports due to organized convection. The improved representation of convective processes in chemistry-climate models is also an aim.

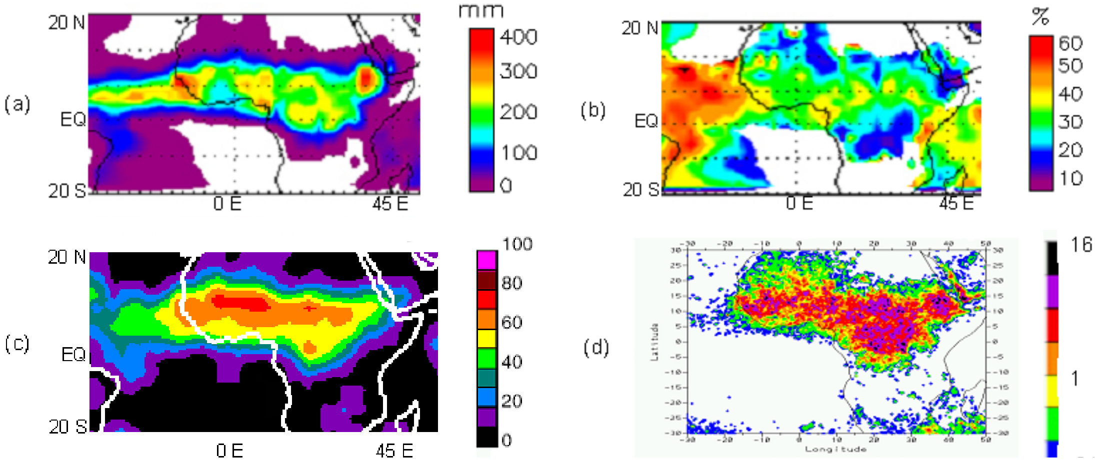


Figure 2.2.5 TRMM based MCS climatology over Africa and tropical Atlantic for June-July-August (JJA). (a) Total JJA rainfall from the TRMM Precipitation Radar (PR). (b) Stratiform fraction of the JJA rainfall. Panels (a) and (b) were obtained by the methods of Schumacher and Houze (2003) and were provided by C. Schumacher. (c) Percentage of MCSs detected by the TRMM PR that had extensive ice scattering in the 85 GHz channel of the TRMM Microwave Sensor (TMI). Panel (c) was obtained by the methods of Nesbitt et al. (2000) and was provided by S. Nesbitt. (d) Average lightning flash density (flashes per month) for June-July-August derived from the Lightning Image Sensor on TRMM (provided by W. Petersen).

modelling effort needs to be designed. In particular, it is necessary to document accurately the momentum transport responses on both the convective scale and mesoscale. To establish the impact on the large-scale flow, there is a need to document the detailed water budget of mesoscale convective systems of the West African monsoon. Gamache and Houze (1983), Chong and Hauser (1989) and Caniaux et al (1994)estimated water budgets of African MCSs over the ocean and land. But these single cases based on limited measurements need to be verified and documented in more precise relation to the AEJ and AEWs and in the context of the larger continental water cycle described below (section 2.3).

(c) Tropical Cyclones

Although we know that most tropical cyclones that develop in the so-called main development region in the Atlantic originate from weather systems originating in West Africa, we lack a good understanding of the processes that organize the systems and modulate their intensity once they enter the oceanic environment.

Recent research has suggested that the Saharan Air layer (SAL) may significantly impede the development of incipient tropical waves or disturbances and can even weaken pre-existing tropical cyclones (Dunion and Velden 2002). The SAL develops over the Sahara in association with dry convection that creates a well-mixed aerosol-laden layer that can extend up to 600hPa. The low static stability results in a prominent negative PV anomaly that characterizes the anticyclonic shear side of the AEJ (Thorncroft and Blackburn, 1999). The SAL retains its Saharan characteristics as it moves over the ocean and can reach as far west as the Caribbean Sea (~7000 km from the west African coast) (Reid et al, 2002). Geostationary satellites reveal that the combination of the SAL's synoptic-scale dry, dusty air and associated vertical wind shear below 700hPa inhibit the occurrence of the deep atmospheric convection essential for tropical cyclone formation (Fig. 2.2.6). The anticyclonic vorticity associated with the SAL may also be expected to be detrimental to spin-up of tropical cyclones. What is not well understood is the relative importance of these processes in limiting the development of tropical weather systems.

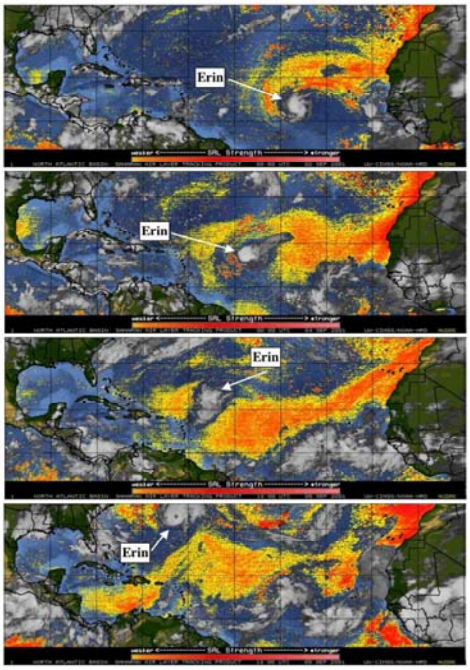
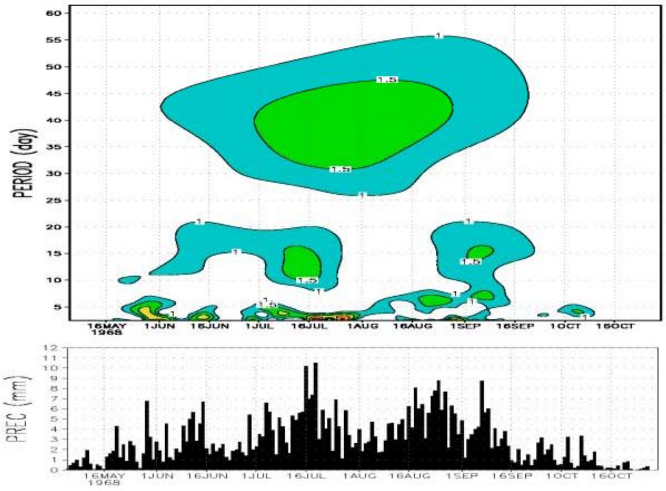


Figure 2.2.6 GOES SAL tracking imagery time series showing Hurricane Erin's interaction with the SAL.

On smaller spatial and temporal scales, it is well-known that the amplification of vorticity at the surface is vital in marking the onset of tropical cyclogenesis. Proposed mechanisms for vorticity generation include stretching in association with deep convection and diabatic heating within an existing low- and/or mid-level circulation (e.g., Fritsch et al. 1994; Rogers and Fritsch 2001), the merger of multiple mid-level vortices (e.g., Ritchie and Holland 1997), axisymmetrization of vorticity associated with convective flare-ups from a parent vortex (e.g., Montgomery and Enagonio 1998) or a combination of these. Observations of wind and temperature fields at high temporal and spatial resolutions, over land as well as over the water, are needed to be able to document the structural changes that occur to tropical weather systems when they experience convective outbreaks to address which of the processes listed above is important for amplifying low-level vorticity, and to determine the possible role of the Saharan air layer in limiting their development.

2.2.4 Intraseasonal Variability

Figure 2.2.7 illustrates that West African rainfall can vary significantly on intraseasonal timescales (e.g. Janicot and Sultan 2001). Two main periodicities can be distinguished, a 10-25-day signal (a "supra-synoptic" timescale with a peak around 15 days) and a 25-60-day signal (an "intra-seasonal" timescale with a peak around 40 days). We know very little about such variability, its causes and predictability, and its relationship with the WAM and associated regional circulations. Several possible mechanisms have been proposed and required investigation. The 10-25-day periodicity appears to be dominant and this signal can be decomposed into two independent modes of convection (e.g. Mounier and Janicot 2004): a quasi-stationary one centered on the Guinean coast, may be linked to convectively coupled Kelvin waves (e.g. Wheeler and Kiladis 1999) and/or to coupled land-atmosphere interactions (e.g. Grodsky and Carton 2001), and a westward propagative one along the Sahel latitude and the northern tropical Atlantic, which seems to originate over Central Africa. The 40-day signal, although less recurrent than the 15-day signal, can significantly modulate the West African rainfall and it has been suggested that equatorial Kelvin and Rossby waves initiated by anomalous heating/cooling in the equatorial West Pacific linked to MJO may be responsible for convection variability over West and Central Africa at this timescale (e.g. Matthews 2004). It has been more generally shown (e.g. Wheeler el al. 2000, Yang et al. 2003, Roundy and Frank 2004) that the tropical north African region is impacted by Kelvin waves, equatorial Rossby waves and the mixed Rossby-gravity waves but we do not currently know if and how these impact the WAM. It has also been suggested that land surface processes can contribute to intraseasonal variability of the WAM at the mesoscale (e.g. Taylor and Lebel 1998).



Modulus wavelets analysis (top)

Daily rainfall over Sahel (bottom)

Janicot et Sultan 2001

Figure 2.2.7 Wavelet analysis and time-series of daily rainfall data for the Sahel (Janicot and Sultan, 2001)

Recent work has also suggested that large-scale westward propagating waves exist at 6-9-day timescales distinct from synoptic AEWs (e.g. Diedhiou et al. 1999). They are more intermittent, develop north of the AEJ, and are characterized by a similar phase speed but a higher wavelength (about 5000 km). They are associated with significant fluctuations of the AEJ wind speed consistent with the development of large westward moving anticyclonic cells north of this jet. There is however no currently accepted explanation for these waves and little is known about their significance for the WAM or downstream tropical Atlantic.

Finally the relative contributions to intraseasonal variability from external and internal processes required investigation through closer analysis of the rainfall characteristics, surface conditions and regional circulations. Scale interactions must also be better known, looking at how AEJ, and African weather systems and MCS distribution can be modulated by and can impact intraseasonal variability of convection, and how this timescale variability can be modified by the large scale dynamics and climate anomalies like El Nino events for instance.

2.2.5 Interannual Variability

The marked interannual variability of WAM seasonal rainfall totals was emphasized in Section 1 (see Fig. 1). This interannual variability results from the above subseasonal rainfall behavior changing sufficiently from year-to-year to produce widely differing seasonal totals. For the Gulf of Guinea coastal region, the interannual variability dominates the rainfall time series for most of the last century (e.g., Rowell et al, 1995; Ward, 1998) even though this part of West Africa was also strongly affected by the 1970-1990 drought (Le Barbé et al., 2002). Further north across the Soudan and Sahel zones, this interannual variability is superimposed strongly on pronounced multidecadal rainfall trends since 1940 (e.g., Fig. 2.1; Tarhule and Lamb, 2003). A major challenge for AMMA is to perform the research required to improve our ability to monitor and predict WAM variability on this interannual time-scale that is so vital for society.

(a) Role of Sea Surface Temperatures

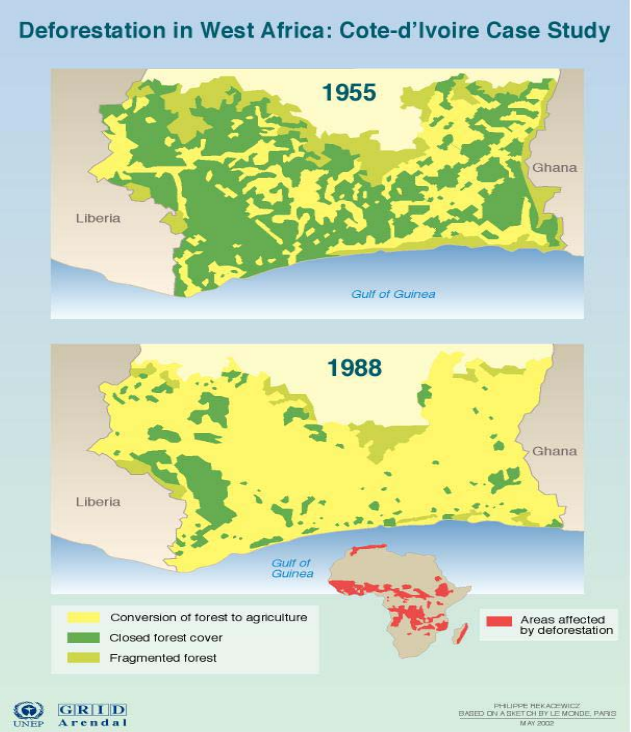
The research of the last 30 years has established that the interannual variability of WAM seasonal rainfall exhibits distinct spatial modes of behavior, and that some of those modes are forced by large-scale sea surface temperature (SST) anomaly patterns. WAM seasonal rainfall anomalies tend to be of either (a) opposite sign between the Sahel-Soudan zone and Gulf of Guinea coastal region (i.e., a “dipole”; Lamb 1978a; Nicholson, 1980) or (b) the same sign across all of the Subsaharan West Africa (Nicholson, 1980). The dipole rainfall behavior has been linked to the interannual variability of tropical Atlantic SST anomaly patterns (e.g., Lamb, 1978 a, b; Lamb and Peppler, 1991, 1992; Rowell et al, 1995, Ward, 1998). Sahel-Soudan drought accompanied by Gulf of Guinea wetness is associated with cold (warm) SST anomalies north (south) of 10°N, and vice versa. Within this context, Gulf of Guinea rainfall is strongly related (positively) to SST anomalies in the adjacent eastern equatorial Atlantic. In contrast, the extension of drought conditions all the way from the Sahara Desert to the Gulf of Guinea coast has been found to coincide with El Niño events in the tropical Pacific Ocean (e.g., Folland et al, 1986; Palmer, 1986; Palmer et al, 1992; Rowell et al, 1995; Ward, 1998; Giannini, et al, 2003).

Specific studies differentiating interannual from multidecadal timescales of WAM rainfall as well as their interactions have also been carried out (Ward 1998, Janicot et a. 2001, Giannini et al. 2003). The multidecadal decreasing trend of WAM rainfall is closely linked to the change of the north-south interhemispheric gradient of SST and especially to the long-term warming in the Indian ocean. On the other hand, at the interannual timescale, the tropical Atlantic SST dipole pattern is connected to out-of-phase rainfall anomalies in the Sahel and Guinean Coast regions, whereas a clear connection with ENSO is revealed for years with the same sign rainfall anomaly in the two regions. The connection with ENSO at interannual timescale has strengthened since 1970 while the tropical Atlantic dipole impact on WAM rainfall has weakened. It has been suggested that the impact enhancement of El Nino events has been induced by the multidecadal scale SST pattern that leads to an indirect effect of this SST pattern on WAM rainfall.

The above results provide the basis for the seasonal prediction of WAM rainfall from the expected evolution of tropical Atlantic and Pacific SST anomaly patterns during the months leading up to the monsoon season. Both statistical and numerical modeling approaches have been employed with mixed success. A major challenge that persists is the difficulty of predicting the evolution of the tropical Atlantic SST anomaly pattern prior to and during the WAM season. This situation is reviewed further in the next section below, from oceanographic and sea-air interaction perspectives. In contrast to the above dominant role that tropical Atlantic and Pacific SST anomaly patterns have been found to play for the interannual variability of WAM rainfall, the contributions of land-atmosphere interactions now are considered to be of subordinate (but possibly amplifying) importance on this time-scale (e.g., Giannini et al, 2003).

(b) Role of Land Surfaces

While it is generally accepted that sea surface temperatures have a major role in determining interannual-to-decadal variability of the WAM, the role of the land change is more difficult to quantify. We are hindered in investigating the role of the land due to the lack of appropriate large-scale multi-year observations of land surface conditions and low confidence in our ability to model the complex land surface boundary condition. A current hypothesis is that anthropogenic factors such as conversion of forest to agriculture and overgrazing have played an important role in the rainfall variability observed during the last century (e.g. WCRP, African Climate report, 1999). The land cover of West Africa underwent dramatic changes over the past 50 years and its effects need to be considered not just locally, but also remotely. For example the primary forest in Ivory Coast covers about one-fifth the surface it was in the 60’s (Fig. 2.2.8).



Sources: *Le Monde*, Institute of Research for the Development (IRD), 1996 ; United Nations Environment Programme (UNEP), International Soil Reference and Information Centre (ISRIC), *World Atlas of Desertification*, 1997.

Figure 2.2.8 Example of deforestation in West Africa – emphasizing the changes here in the Ivory Coast between 1965 and 1988. Adapted from *Brou et al. 1997*

In order to assess the role of the land on these timescales it is necessary to consider the significance of potential feedbacks. Fundamentally, rainfall anomalies are expected to result in anomalies in the surface conditions, notably through impacting soil moisture and vegetation. These surface anomalies will impact the energy and water budgets. It is important to investigate whether, through such impacts, the rainfall anomaly is perpetuated through a positive feedback process. A positive feedback process has been shown to operate at the mesoscale (e.g. Taylor and Lebel, 1998) and there is also some evidence to suggest that the seasonal WAM rainfall is impacted by the rainfall at the end of the previous rainy season (e.g. Philipon and Fontaine, 2002). In agreement with this, recent modelling studies that include such feedbacks suggest that the interannual 'memory' effect plays a significant role in reddening the spectrum of interannual rainfall (e.g. Zeng et al., 1999, Wang and Eltahir, 2000) and may have contributed to the large decadal drying trend observed in the Sahel last century.

The extent to which land processes act to enhance or weaken the interannual-to-decadal variability of the WAM forced by SSTs and the extent to which they can influence the variability independently should be explored. It is also important to assess whether, through impacting the regional climate, land processes can influence the SSTs themselves. If they do, this could significantly limit predictability of SSTs and, in turn, the WAM.

In recent decades, land use change in the West African region has been dramatic, driven by population growth, economic development and climate variability. There is controversy regarding the extent and intensity of these changes, but recent modeling studies (Taylor et al., 2002) show that land use change is likely to have contributed to a reduction in Sahel rainfall since 1960 and will tend towards increasing drought conditions as the population grows.

2.3 Land Surface Processes

Observations obtained from the operational network, satellite and previous experiments such as HAPEX-Sahel (Goutorbe et al., 1997) have provided a complex picture of the variability and long-term evolution of the land conditions and water cycle over West Africa. The marked tendency in vegetation changes over West Africa since the 1950's is the result of several factors: lower rainfall, land use change and demographic pressure. Lower rainfall has an impact on natural vegetation as well as on cultivated lands. The distribution of natural eco-systems closely follows the latitudinal pattern of rainfall over the region. In the Sahel, the descent of the isohyets of about 200 km towards the south (Lebel et al., 2003) lasted sufficiently long (almost 30 years from 1970 to 1997) so that vegetation was profoundly affected even though eco-systems display a certain resistance capacity to water stress. Recurrent seasonal rainfall deficits, associated with smaller crop yields, also led the farmers to clear bush lands and fallows in order to extend the cultivated lands. Independently of this climate-related process, the high growth rate of the population (in Niger the birth rate is still approaching 4%, one of the highest rate in the world) is a concurrent cause for the degradation of natural eco-systems and extension of cultivated lands, where runoff coefficients are significantly larger than on tree-savanna eco-systems.

A needed preliminary subject of study is thus to evaluate how climate-related and human related processes have concurred in the past and could concur in the future to impact the land cover of the region. Then studying the influence of such vegetation changes on the water cycle – and, more largely, the interactions between the vegetation changes and the modification of the hydrological cycle – constitute a major scientific challenge for AMMA. This must involve improved analysis of the land surface conditions on a range of space and time scales and an improved analysis and understanding of the internal processes that characterize the land surface feedbacks.

The ultimate deliverable of this research is to provide scenarios for the future of water resources and agriculture in West Africa (see below section 3.4.2). Land surface studies will thus aim at improving i) our knowledge of land cover change over the region – which involves an important observational program – ii) the characterization of the influence of land cover change on the water partitioning at the surface and iii) our understanding of land surface-atmosphere interactions.

2.3.1 Land cover

The land cover of West Africa underwent dramatic changes over the past 50 years over the Sahel but also to close regions (large deforestation in countries along the Golf of Guinea) which impacted the West African monsoon (see 2.2.5 & fig. 2.2.8). In certain parts of the Sahel, the natural vegetation has totally disappeared and crops account now for 70% of the total land use against less than 25% in the early 1950's (Loireau, 1998). These changes are not well documented at the regional scale and we are lacking a synthetic view that could serve as a realistic basis for both atmospheric modeling sensitivity analyses and hydrological modeling. It is therefore essential to collect the numerous aerial photographs and satellite images that could provide large scale maps of man-induced land cover change over West Africa. Monitoring the seasonal cycle of the vegetation for different biomes and climatic conditions is another requirement: on the one hand, it is important to quantify how the vegetation reacts to rainfall deficits or excesses; on the other hand, the seasonal cycle of vegetation controls the water and the carbon cycles as well as the emissions of various chemical species.

At the same time it is important to set up long term observing systems, especially because the vegetation displays inertia with respect to rainfall variability. These observations will have to be conducted in close coordination with hydro-meteorological observations. Local eco-physiological studies have also to be undertaken in order to study the competition between species under various condition of water stress and to better understand what is conditioning the equilibrium of a given eco-system. Such a study was carried out for a tiger-bush system during HAPEX-Sahel, showing how the space organization of the bushes and the water dynamics controlled by the slope concur to maintain the dynamical equilibrium of this kind of eco-system. Similar studies should be encouraged for other types of eco-systems.

Land cover studies directly connect to the human dimension of a program like AMMA. As stated above, the increasing demographic pressure is an important factor in forest clearing and in the acceleration of the fallow/cultivation rotation. Thus land cover studies should be carried out in association with demographers and economists.

2.3.2 Water partitioning

The continental water cycle was profoundly affected by the rainfall deficit of the past 30 years (see figures 2.3.1 and 2.3.2 below). The rainfall deficit, expressed as a percentage, usually translated into a twice as large streamflow deficit over the large rivers of the region (Lebel et al., 2003). At small space scale, on the other hand, an increase of the runoff coefficients was observed, involving an increase of the level of some Sahelian aquifers. This is thought to be the result of the changes in the land cover. This decadal scale signal is but one illustration of the competing influences of climate variability and changing surface conditions in shaping the variability of the water cycle at the surface. This is a research area that is typically multi-scale in time and space.

The lack of a consistent regional observing system and of multiscale studies leaves us with a piecewise vision of how the hydrologic processes act to enhance or smooth out the rainfall variability, and how this affect the water resources. It is consequently necessary to build up a combined strategy of observations and modeling that will allow monitoring and representing the variability of the continental water cycle over a broad range of space and time scales: local, meso and regional.

(a) Local Scale

This scale refers to hydrologic units in the order of a few km^2. It has to be studied in order to provide insight into the processes driving the partitioning of rainfall between runoff, aquifer recharge and evapotranspiration. The interaction with vegetation is particularly important to consider at this scale (see 2.3.3 below). This has to be done for different climatic conditions from dry in the North to more humid in the South.

(b) Mesoscale

At a larger scale a key research area is to study the upscaling properties of the various hydro-meteorological fields (rainfall, runoff, aquifer levels) and to develop hydrological parametrisations at the meso-scale that can be used either as a component of coupled hydrological-atmospheric models or as separate hydrological models used in a forced mode. It must be noted that the deficit of high resolution observations of rainfields has not permitted us until recently to conduct in-depth studies of how the various scales of rainfall variability impact on the hydrological cycle. The data collected during HAPEX-Sahel and the ensuing long term monitoring period in the Niamey region has provided a first opportunity to characterize more accurately the rainfall variability over the central Sahel (Ali et al., 2003) and how it relates to atmospheric patterns (Lebel et al., 2003) and to hydrologic variability (Peugeot et al., 2003). Similar observations are needed for the Sudano-Sahelian and the Guinean climates.

Despite its initial goal, HAPEX-Sahel came short from providing all the observations and understanding needed to correctly assess the water partitioning at the mesoscale in the Sahel. Most studies (e.g. Seguis et al., 2002; Peugeot et al., 2003) have been devoted to a better representation of the small scale processes driving the deep percolation to the aquifers and controlling the evapotranspiration from a vegetation most often water stressed. AMMA should thus focus on mesoscale studies, for a number of reasons: i) as shown in a simulation study carried out by Lebel and Vischel (2004) rainfall variability seems to have its larger effect on runoff in a range of scales comprised between 30 and 100 km; ii) vegetation is rapidly evolving over most of West Africa and local studies are not sufficient to apprehend both how vegetation changes impact on water partitioning and how long lasting periods of rainfall deficit impact on vegetation ; iii) at the mesoscale aquifers behave as an integrator of all the smaller scale variabilities affecting the surface processes and thus the water budget is more likely to be closed at the this scale, based on aquifer monitoring; iv) as detailed below in section 2.3.4, feedbacks of the continental water onto the rain systems dynamics seems to be especially sensitive at the mesoscale thus the importance of assessing the pattern of surface soil moisture at this scale. Of course the upscaling from the local scale to the mesoscale happens through a different hierarchy of mechanisms depending on the eco-system and rainfall conditions. This is why concomitant mesoscale studies must be promoted for different regions of West Africa from the dry Sahel to the north to humid Savannas in the South. The typical scales that need to be documented are approximately known for rainfall (1 to 100 km) and runoff (1 to 10000 km^2) thanks to the long term monitoring carried out in the framework of the *Observatoire de Recherche en Environnement* (ORE) CATCH over the Niamey degree square and the Ouémé catchment in Benin (14200 km^2). This is far less clear for the aquifers whose characteristic scales may change depending on surface and underground conditions. Regional studies are thus a needed complement to mesoscale studies.

(c) Regional Scale

To obtain a regional vision of how the water cycle reacts to land cover changes and large scale rainfall variability it is necessary to document the regional gradient in rainfall and vegetation, and their interaction with the aquifers. Because a large part of West Africa is not permanently drained at the surface, rivers do not provide a comprehensively integrated surface component of the water budget. Aquifers are thus the most efficient integrators able to provide a validation for coupled vegetation/hydrology models. It will thus be a challenge of the AMMA field program to collect existing data on the aquifers and to setup specific measurement on the mesoscale sites in order to be able to upscale aquifer parameters from the local to the regional scales. New geophysical techniques developed in recent years may prove very helpful in that respect. Regional monitoring and modelling is also required in order to link the various mesoscale observations and models obtained for various hydro-climatic areas. This requires a blending of satellite and ground based observations, involving a combined strategy in observation and validation. Similarly to the mesoscale the understanding of feedbacks at the regional scale (see 2.3.4 below) requires to be able to estimate the various components of the regional surface water budget. This is of course easier written than done, but AMMA provides for the first time the opportunity to have scientists and institutions from the various West African countries bringing their data and competence into a large international coordinated effort needed to address such complex environmental issues.

2.3.3 Interactions in the continental water cycle

(a) Hydrology and vegetation

The interactions between vegetation and hydrology play a key role in the variability of the continental water cycle – not considering at that stage the coupling with the atmosphere. This was documented at the local scale (for a tiger bush eco-system, Galle et al., 1999; Seghieri and Galle, 1999) and at the mesoscale for the Niamey region (Monteny et al., 1997), but here again we are lacking a clear vision of how these interactions are playing at a regional scale. In addition to using satellite data bases to study how the rainfall variability over the whole region shaped the development of the vegetation at the seasonal scale over the past years, an action is needed to promote concomitant hydrological and vegetation observations in order to help developing hydrological models incorporating a dynamic vegetation. Dynamic land surface models are a necessary tool to investigate both these internal processes and the coupling with atmospheric processes, especially since the interactions between the vegetation and the atmosphere through the water cycle are pretty much scale dependent. While, as shown in Fig. 2.3.1, the rainfall deficit of the 1970s and 1980s produced a twice as large streamflow deficit over most of the large basins of West Africa (Lebel et al., 2003), it was also shown on many smaller catchments that the streamflow has indeed increased at the end of the dry years, due to land surface modifications (Seguis et al., 2004). Natural vegetation clearing and its replacement by crop lands, resulted in higher runoff coefficients which more than compensated the rainfall decrease. In the Niamey area for instance, the average annual rainfall in the mid 1990s was about 170 mm smaller than in the 1950s-1960s, that is an about 25% decrease; at the same time however the runoff from small endoreic catchments appeared to be 70% larger in the mid 1990s than during the wet 1960s years. A preliminary modeling study carried out by Seguis et al. (2004) showed that in the hypothesis of unchanged vegetation conditions, the runoff would have in fact decreased by about 50%. On the other hand, in case of unchanged rainfall, then the runoff would have increased by 275%. There is thus an apparent contradiction between the changes observed in the water cycle at the regional scale and the changes observed at the local scale. Because eco-systems and hydrological systems react and interact at longer time scales than the typical scales of atmospheric forcing, a better understanding of how the relative weight of the various terms of the water cycle are scale dependent requires a long term observation strategy that will have to be an important part of AMMA. Such an observation program will also contribute to the knowledge about vegetation patterns which is important for determining biogenic emissions of trace gases.

(b) Local / Convective Scale

The main interaction of interest at that scale is that between the vegetation and the water cycle. While the resistance and the resilience of plants to water stress are mostly the result of a forcing process that will be investigated as part of 2.3.1, the degree to which modifications of the vegetation at the scale of a catena may affect runoff is still a question open to research. The interactions between topography, vegetation and runfoff/infiltration partitioning are clearly different in humid regions and in semi-arid eco-systems –characterized by a rapid drying out of bare soil patches and concentration of water in flatter areas where the vegetation is denser, with a prevalence of trees. These interactions need to be studied dynamically, based on small spatial scale/ long term observations, including flux measurements that are not easy to carry out over several seasonal cycles. Several target areas will thus have to be selected for such studies with the aim of developing/testing coupled vegetation/hydrology models, in the direction followed by Boulain (2004; see also Boulain et al., 2005).

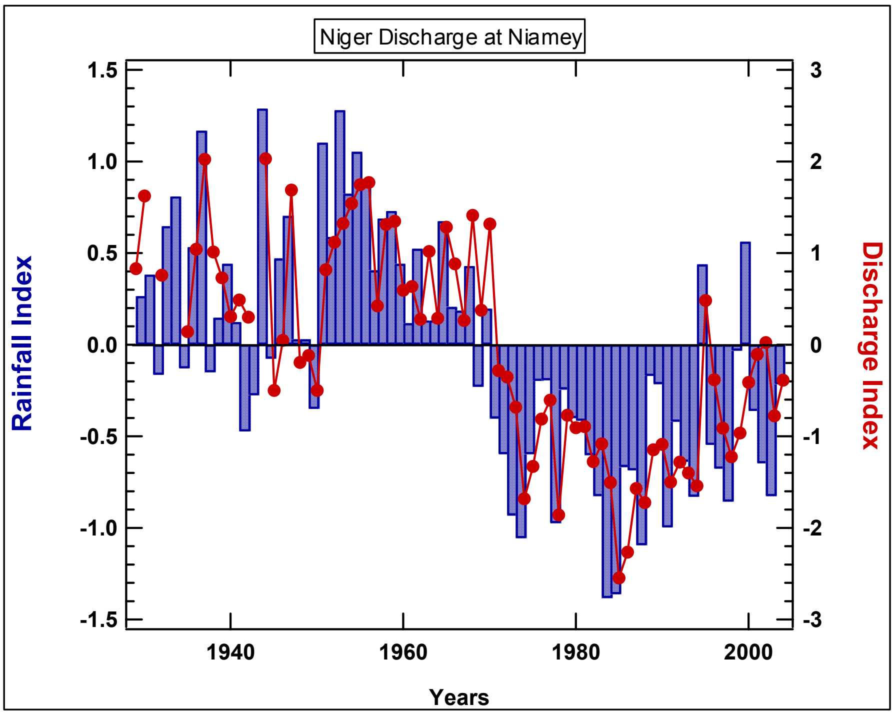


Figure 2.3.1. Annual fluctutations of the standardized rainfall and streamflow series for the Niger catchment at Niamey. Note that the two series match each other when the streamflow axis is multiplied by a factor 2.

(c) Mesoscale

As stated earlier in section 2.3.2, the mesoscale (typically in the range 10-100 km) is the scale at which rainfall variability and surface water partitioning are in closest interaction. One reason for this is precisely because vegetation patches and heavy rain patches are often of comparable scales. The pattern of interactions between these patches can be studied only over areas encompassing a sufficiently large number of these patches. The difficulty here is that, while mesoscale studies of the water balance is feasible from classical ground sensors – albeit some significant uncertainties – a detailed monitoring of the vegetation at the mesoscale for several seasonal cycles is a tremendous task that can be achieved only be an association of ground monitoring over 1 km-scale plots with remote sensing data. In soudanian regions where high altitude clouds are frequently present during the season of vegetation growth, satellite monitoring from visible sensors is challenging and the use of microwave sensors is required. In Sahelian regions the work carried out for more than 20 years over the Gourma region in Mali (25,000 km^2) is a good example of the capacity of such combined strategies to produce the data set needed for running regional scale models of vegetation growth (see e.g., Jarlan et al., 2002; 2003).

(d) Regional

There are mostly two areas of interest regarding the regional impact of the interactions in the coupled surface-atmosphere systems: i) the overall monsoon dynamics, which is the focus of 2.2b (see also 2.3.4 below) and the water cycle through the large scale advections of water vapour from region surrounding the West African continent and the recycling of the continental evaporation, through the vegetation. Little work exist on the estimation of the regional evaporation over West Africa and AMMA, launched in the context of new satellite missions like MSG and AQUATRAIN, provide a unique opportunity to combine satellite and ground information in order to compare estimated values from measurement to the evaporation in large scale models. Another topic of interest is to study how known rainfall biases in GCMs are translated into the various components of the regional water cycle and how this might in return maintain rainfall biases. In a very general way regional evaporation studies are trailing far behind rainfall studies and should be encouraged.

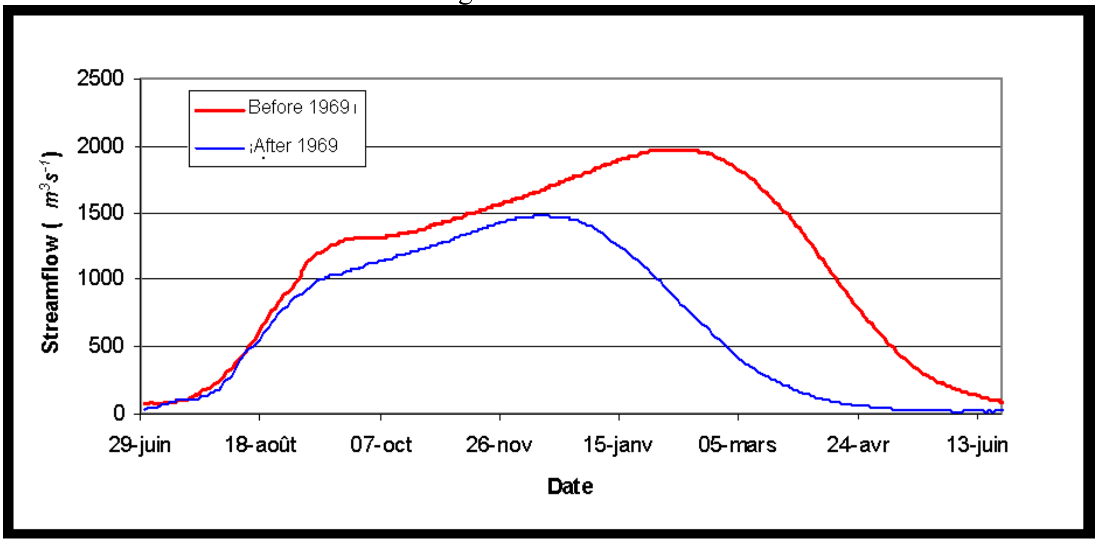


Figure 2.3.2. Modification of the seasonal cycle of the Niger discharge at Niamey, due to the change of the rainfall regime over the catchment after 1969.

2.3.4 Feedbacks between the land surface and atmosphere

A number of modeling studies have shown a strong sensitivity of rainfall in West Africa to land surface properties. In simulations where natural tree and grass cover is removed over large areas, there is a tendency for lower rainfall (e.g. Charney 1977, Xue and Shukla 1993). This is associated with both an increased albedo on the southern flank of the Sahara likely to suppress ascent, and weaker evaporation rates unable to maintain a thermodynamic profile conducive to moist convection. To what extent the natural loss of Sahelian vegetation induced by the recent drought may have enhanced or prolonged the dry conditions remains an open question.

At shorter space and time scales, West Africa is considered to be a region with relatively strong coupling between soil moisture and rainfall (Koster et al 2004). Observational evidence of a positive feedback between rainfall and soil moisture was presented by Taylor and Lebel (1998), suggesting rather surprisingly that a feedback was operating on a length scale ~ 10km: vegetation-humidity gradients induced by rainfields heterogeneity are a likely explanation of the persistency in rainfield patterns observed in the Sahel. It is however challenging that regional modelling studies are currently not able to reproduce these observations: large scale dynamic features of the atmosphere tend to prevail over smaller scale heterogeneities developing in the boundary layer as a result of vegetation humidity gradients. However, idealised modeling studies (Clark et al 2003) showed that convection within a squall line was particularly sensitive to boundary layer moisture anomalies at this scale, leading to a tendency for MCS to reinforce pre-existing soil moisture patterns at the scale of an individual convective cell. It is possible that the mesoscale feedbacks between soil moisture and the atmosphere have an impact at larger scales. Mesoscale convective systems produce swaths of surface soil moisture which, in the sparsely-vegetated Sahel at least, will dominate surface evaporation patterns for several days afterwards. Mesoscale convective systems are found preferentially in certain phases of easterly waves, providing a mechanism for generating synoptic scale soil moisture variability. Taylor et al (2005) showed that such patterns can induce heat low circulations and feed back on the waves themselves.

There are thus two main axis of research for AMMA. First, given the typical length scales (5-15 km) identified by Taylor and Lebel (1998), it would be appropriate to obtain high resolution series of rainfall measurements covering these scales for different climate conditions from the South to the North of the region. These measurements should include flux, soil moisture and vegetation observations (at a minimum the design of the rainfall observations will have to incorporate flux and soil moisture observations set up for the local studies). However, observing feedback mechanisms is not straightforward as it relies on knowledge of the spatial and temporal variability in soil moisture and surface fluxes. These properties can not be observed by ground measurements only, and therefore will need to be obtained from a combination of validated satellite data and land surface models. However, with an understanding of soil moisture variability, observed atmospheric features could be interpreted in terms of the coupled land-atmosphere system, and numerical models used to assess the sensitivity of the atmosphere to realistic surface forcing. Such an approach may help to understand, for example, the role of the land surface in the genesis and decay of MCS, monsoon onset, and the observed relationship between rainfall at the end of one year and the intensity of the subsequent monsoon (Phillipon and Fontaine 2003). It is clear however that a specific investigation of this latter relationship should be encouraged in AMMA. Up to now only crude statistical studies were carried out on this topic, due to the nature of the available data (low spatial and temporal resolution). With a much better documentation of the seasonal cycle of both the vegetation and the water cycle over densely instrumented mesoscale areas spanning the eco-climatic gradients of the region one can hope to gain some understanding of how vegetation may store water from one monsoon cycle to the next and possibly play a role in its intensity. Here again, ground observations – even though unique – will not be sufficient to obtain the required regional vision, and assimilation of new satellite data coming from AQUATRAIN, MSG and MODIS must be given high priority.

The second axis of research is thus clearly in the area of modelling. Provision has to be made to incorporate small scale surface observations in mesoscale atmospheric models in order to test their influence on the MCS dynamics in these models. Simulation of realistic humidity gradients, when no appropriate observations are available is another venue to explore for carrying out these tests of models.

2.4 Atlantic Ocean Processes

As discussed in section 2.2.5(a) above, WAM variability has been linked to SST anomaly patterns on a wide range of space- and time-scales. Of particular importance here is the marked interannual variability of rainfall in West Africa, known to be strongly influenced by variability in global sea surface temperatures (e.g., Folland et al, 1986; Palmer, 1986; Rowell et al, 1995; Giannini et al, 2003). Also, the substantial multi-decadal rainfall variability experienced in the Sahel during the 20th century has been associated with an interhemispheric SST anomaly difference (e.g., Ward, 1998; Giannini et al, 2003).

Recent work on interannual variability has re-emphasized the importance of the cross-equatorial SST gradient in the Atlantic and, in particular, the contribution to this gradient from SST variability in the Gulf of Guinea (e.g. Lamb and Peppler, 1992; Ward, 1998; Fontaine et al, 1999). Less attention has been directed at the upwelling region off the west coast of Africa between about 10N and 20N and it's effect on the WAM. As with the upwelling region in the Gulf of Guinea, it is also to be expected that atmospheric circulation anomalies associated with SST variability in this upwelling area can impact on the WAM. Data and modeling are required to determine if such a relation exists and has an important impact on the WAM.The upwelling zone represents the eastern boundary of a band of high SST variability that extends across the Atlantic at approximately the same latitudes as the upwelling zone (Huang et al., 2004). Research has shown that this band together with the ENSO cycle contributes to rainfall variability in the Caribbean Central American region (e.g. Enfield and Alfaro, 1999; Giannini et al., 2000). The 10N to 20N latitude band represents the Main Development Region (MDR) for tropical storms. Molinari and Mestas-Nunez (2003) have shown that decadal variability in SST in the MDR is correlated with the NAO and tropical storm formation.

Thus, current seasonal-to-interannual predictions of the WAM and its variability rely heavily on our ability to provide skilful predictions of tropical Atlantic SSTs. Unfortunately, at present, neither observations nor models are fully adequate to characterize quantitatively the variability and predictability of SSTs in the tropical Atlantic. The problem is rooted in prediction inadequacy for the average state and the seasonal cycle that propagates through to the interannual time-scales (see Fig. 2.4.1).

The heat stored in the upper ocean, represented by the sea surface temperatures (SSTs) and the depth of the oceanic mixed layer (MLD), strongly affects the atmosphere, its weather and climate. The processes that determine the SST and MLD depend on the time-scale of interest : for seasonal to interannual variability the mechanisms involved are mainly thermodynamic and dynamic interactions with the atmosphere and the upper ocean circulation and temperature structure (e.g. thermocline depth), but for decadal and longer term variability the mechanisms involve the deeper ocean too (to depths of hundreds and even thousands of metres). At present a detailed understanding of how these processes act to determine the mean state and the variability of the tropical Atlantic climate system is not available. Through observations and modelling it is important to assess the extent to which SSTs and upper ocean heat content can be understood in terms of the local heat balance, and to investigate the relative roles of ocean dynamics, atmospheric circulations (including those that are remotely forced) and land processes in determining the SSTs and their variability. A better understanding of these processes and their impacts combined with modelling studies will help to assess the predictability of Atlantic SSTs.

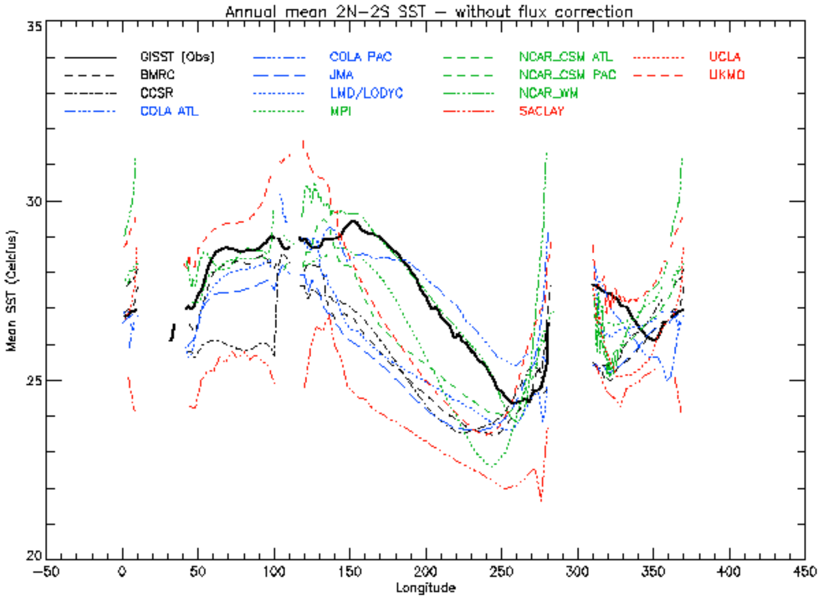


Figure 2.4.1 Coupled model systematic error in equatorial SST simulation: simulation (after Davey et al, 2002)

2.4.2 Annual Cycle of Tropical Atlantic SSTs

The annually varying sea surface temperatures (SSTs) in the Atlantic (see Fig. 2.4.2) are a key factor in determining the annual cycle of the WAM. The relatively cool SSTs that develop in the Gulf of Guinea during the boreal spring and summer are particularly important. They help to establish the marked meridional contrasts in low-level θe between the continent and the ocean, important for establishing the direct circulations and continental rainfall. Less is known about the effects of the upwelling region off Senegal on the WAM. The period of low SSTs is out of phase with the Gulf of Guinea (i.e. lowest temperatures are in winter). Thus, the potential exists for this region to have an effect on both the termination and initiation of the WAM. Cool SSTs arise through a combination of processes including equatorial and coastal upwelling (enhanced by the shallow thermocline in the Eastern Atlantic), radiation and evaporation (Mitchell and Wallace 1992; Waliser and Somerville 1994; Philander et al 1996). The extent to which the annually varying SSTs in the Atlantic help to drive the WAM and the extent to which they are coupled with the evolving regional circulations, clouds and convection is not well understood and requires investigation. Moreover, the mean state of the atmosphere and ocean in this region is determined through a coupled interaction involving local and remote influences. The ingredients needed to achieve the presently observed balance are not clear. The inability of most, if not all, coupled models to simulate the mean equatorial SST field (Fig. 2.4.1), circulation (ocean and atmosphere) and convection over the tropical Atlantic is a clear example of the deficiencies in our understanding of the regional interactions.

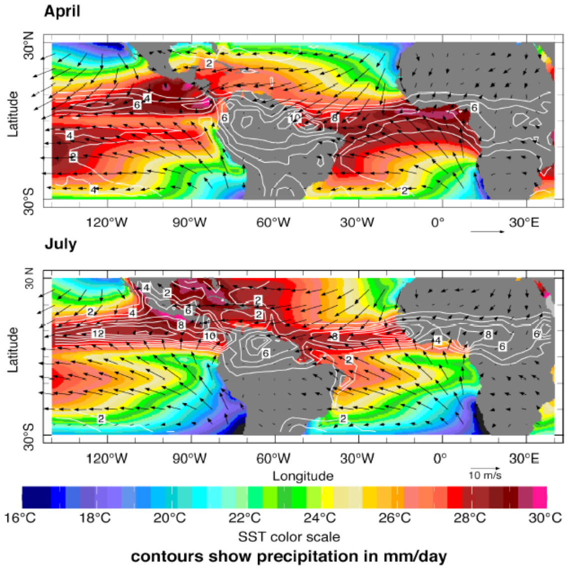


Figure 2.4.2 The distribution of rainfall (white contours in mm/day), SST (colours in ^{o}C according to scale) in the tropical Atlantic and adjacent land and ocean regions. Rainfall data are from GPCP, SST data from NCEP, and wind data from NCEP/NCAR CDAS-1.

2.4.3 Long time-scale Variability of Tropical Atlantic SSTs

The state of our understanding of the mechanisms that determine the observed SST variability at interannual and longer time-scales in the tropical Atlantic is also incomplete affecting our ability to discern the importance of local and remote processes, and the role of passive (uncoupled) and interactive (coupled) processes in both atmosphere and ocean. Unlike the tropical Pacific, seasonal-to-decadal variability in the tropical Atlantic is not dominated by any single mode such as ENSO. Rather, this region is subject to multiple competing influences of comparable importance. Locally, the climate of the tropical Atlantic region is strongly impacted by two features of the SST field: first, the atmosphere is sensitive to fluctuations in the cross-equator SST gradient. The response involves anomalous cross-equator flow, particularly in boreal spring, directed toward the hemisphere in which the SST is anomalously high (e.g. Moura and Shukla, 1981). Changes in the cross equatorial SST gradients are mainly related to large scale SST anomalies in the trade wind regions of both hemispheres. Because each hemisphere can exert its own control on this phenomenon, the nature of the gradients is rather complex. Secondly, there is evidence of ENSO-like variability in the equatorial Atlantic with equatorial SST anomalies in the central/eastern part of the basin playing a key role (e.g. Zebiak, 1993). The variability in cross-equator gradient in SSTs has already been shown to be linked to variability in the Atlantic ITCZ and West African rainfall (e.g. Lamb, 1978a) but the impacts of the ENSO-like variability are less well studied. It is important that the processes involved in determining these two modes of variability be considered along with the mechanisms that explain their impacts on West African rainfall variability.

The longer time-scale variability in the tropical Atlantic is also sensitive to remote influences of ENSO and the NAO. While the NAO is essentially an extratropical phenomenon, its reach extends into the tropics and it can have a substantial influence on SSTs in the tropical North Atlantic (e.g. Cayan, 1992, Sutton et al, 2002). SSTs in a similar region are also influenced by ENSO events. A weakening of the north-east trades in boreal winter leads to a reduction in the cooling of the ocean by evaporation and subsequent positive SST anomalies in boreal spring (e.g. Curtis and Hastenrath, 1995). This ENSO-related Atlantic variability has been shown to be linked to rainfall variability over North-Western Africa (e.g. Ward, 1998).

Despite the importance of the Gulf of Guinea SSTs for the WAM the oceanic circulation, its variability in this region and the effects of surface advection on surface characteristics are not well known. While the mean currents are well identified, and in spite of the FOCAL/SEQUAL experiments (1982-83-84) their behavior in the Gulf of Guinea and their variability is still poorly documented. For example, our knowledge of the relative contribution to the current variability of different physical processes (as vertical and horizontal advection, equatorial waves, remote processes…) is still limited. In boreal spring-summer, the equatorial upwelling is directly associated with the underlying Equatorial UnderCurrent (EUC). The EUC exhibits a very complex dynamic and its eastern termination is still not understood. For example the two recent EQUALANT cruises, carried out in boreal summer 1999 and 2000, have shown a strong one-year-interval variability of the EUC at 10°W, and revealed its disappearance east of 0°E (Bourles et al, 2002) along with important differences in SST at 10W. Furthermore, the effect on SST of the low sea surface salinity (SSS) encountered in the Gulf of Guinea, due to high precipitation and to rivers discharges, has to be assessed. Actually, due the barrier layer effect, SSS may influence SST (Pailler et al., 2000), and it has been shown in the Pacific that SSS variability may play a key role in El Niño events (Johnson et al., 2000).

In summary, large uncertainties exist in our understanding of the processes that cause SST variability in the tropical Atlantic on time scales from seasonal-to-interannual. Currently these uncertainties prevent improvement of the C-GCMs that are needed to forecast the characteristics of the WAM.

2.5 Aerosols

Africa is the world’s largest source of biomass burning aerosols and mineral dust. Satellite imagery shows huge plumes of dust and smoke emerging from Africa and spanning the entire tropical Atlantic during much of the year. Figure 2.5.1 shows that despite differences in the detail of the retrievals from various satellite sensors, they all consistently indicate that these plumes are the most widespread, persistent, and dense seen on Earth.

Dust and biomass burning aerosols are believed to play an important role in climate forcing (Kaufman et al., 2002). The quantitative assessment of their climate impact is, however, difficult and highly uncertain because of our lack of knowledge about many aspects of the physical, chemical, and radiative properties of these materials and their temporal and spatial variability (IPCC, 2001). For example, the large aerosol optical depths in the region exert a significant influence on the surface radiation budget, by modulating the latent and sensible heat fluxes and the surface temperature over both the land (section 2.3) and ocean (section 2.4). Thus, to the extent that dust and smoke impact weather and climate, these effects should be investigated over N. Africa and the tropical Atlantic.

Although the effects of dust and smoke have been studied in previous field programs, the AMMA operating region is advantageous for many reasons. First of all, this area shows the largest column loading (Fig 2.5.1) of both dust and biomass burning at different times of the year. Biomass burning typically occurs from November-February during the dry-period, while dust events occur year round, but most intensively during June-August. This temporal variability of the biomass burning and mineral dust aerosols allows investigation of the two aerosol species both as individual components, and mixtures of the two species.

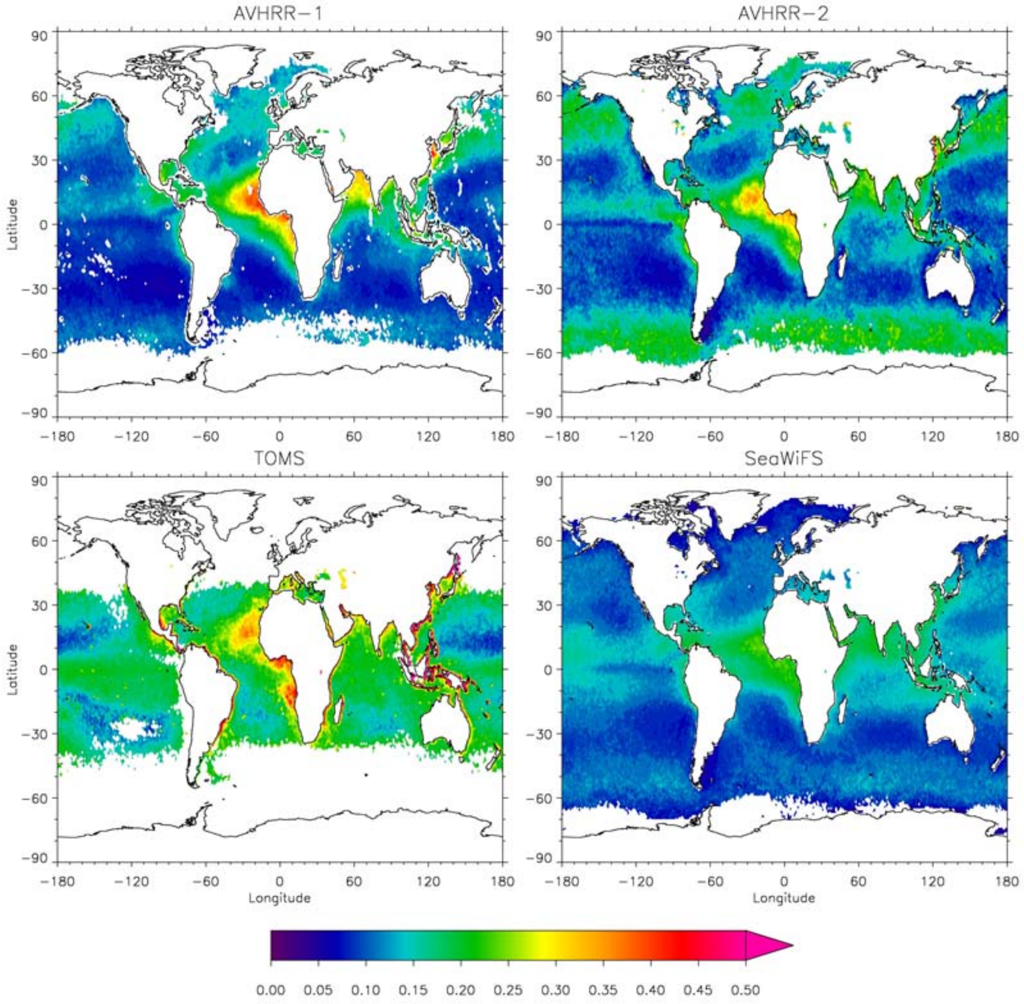


Figure 2.5.1 Averaged aerosol optical depth (AOD) (550 nm) over ocean for the period Sep 97-Dec 00. Values are given with minimum of data for ten months. Maximum AOD is 0.72, 1.00, 1.68, and 0.28, respectively for AVHRR-1, AVHRR-2, TOMS, and SeaWiFS (from Myhre et al., 2004).

2.5.1 Mineral Dust.

Mineral dust can have a significant impact on the Earth's radiation budget. Over the ocean, the scattering of solar radiation back to space by dust can produce a strong local cooling effect, as large as –130 Wm^{-2} (Haywood et al., 2003). Over land or reflective cloud, dust can have either a positive or negative radiative effect on solar radiation depending on the surface albedo and the aerosol single scattering albedo (Liao and Seinfeld, 1998). Dust also absorbs long-wave terrestrial radiation and can cause a warming in a manner analogous to greenhouse gases (Haywood et al., 2003). The effect of aerosols upon the surface radiation budget is even more significant. For example, Haywood et al., 2003 estimate an instantaneous change in the surface solar radiation of up to -209Wm^{-2} during a heavy dust outbreak, with consequences for sensible and latent heat fluxes and surface temperatures over both land and ocean (sections 2.3, and 2.4). The SHADE experiment (Tanre et al, 2003), held off the coast of West Africa during September 21-28, 2000, shows that the diurnal mean net radiative impact of African dust, if extraploated to the entire Earth, would be approximately -0.4 W m^{-2}. However it is difficult to generalize such studies to global scales because of the many uncertainties about dust emissions and the highly variable and poorly characterized properties of dust (Sokolik et al., 2001). As a result of these many factors, the net effect of dust could range from cooling to warming (IPCC, 2001; Ramaswamy et al, 2001).

Dust also seems to play a role in indirect forcing. Over the Mediterranean, African dust strongly modifies cloud properties, possibly suppressing precipitation (Rosenfeld et al., 2001). Dust could also affect clouds through ice nucleation processes. A recent field experiment in southern Florida (CRYSTAL FACE) (Sassen et al., 2003) shows that African dust particles are effective ice nuclei (IN) capable of glaciating altocumulus clouds at relatively warm temperatures (–5.2° to – 8.8°C). Rosenfeld et al. (2001) obtained comparable IN results with African dust over the Mediterranean. Because of the widespread dispersal of African dust to the Atlantic, Europe, the Middle East and the Indian Ocean, soil dust could play a strong role in modulating climate over large areas through this indirect effect.

Dust transport is extremely sensitive to climate variability in North Africa. Measurements on Barbados show that dust transport to the Caribbean can vary greatly from year-to-year (see Fig. 2.5.2) and that these variataions are highly correlated with Soudano-Sahel rainfall (Prospero and Lamb, 2003). Because of drought, the dust transport during the past several decades was 2-4 times greater than during the predrought period during the 1940s to 1960's (Prospero and Lamb, 2003). This variability is comparable to, or greater than, that of pollution aerosol emissions in Europe and North America over this time period. Thus if dust itself has an impact on climate processes, then any feedback involving the dust will have been strongest in the last several decades. This variability could also impact weather processes on smaller scales ranging from individual clouds (through the modification of cloud nucleation processes) to the development of tropical cyclones as discussed in section 2.2.3.

There is considerable debate about the impact of humans on dust mobilization. Much-quoted estimates range up to 30 to 50% (Tegen and Fung, 1995) although recent estimates suggest a much smaller impact, under 10% (Tegen et al., 2004). These estimates are highly questionable but, nonetheless, IPCC [2001] states "… that there is no evidence that the naturally occurring component [of dust] has changed since 1750, …". While there are clearly some areas in North Africa where humans have exacerbated dust mobilization, most of the major dust sources are in areas so remote that humans could only have played a minor role in mobilization (Prospero et al., 2002; Brooks and Legrand, 2000). AMMA's strong emphasis on land-surface-processes and hydrology, offers a unique opportunity to look into the role of humans on "desertification" and dust mobilization.

2.5.2 Biomass Burning Aerosols

There is great interest in biomass burning aerosols because of the presence of black carbon (BC), a strong absorber of atmospheric solar absorption. Atmospheric BC reduces solar radiation reaching the surface and it strongly absorbs upward-welling radiation (Ramanathan et al., 2001). The net effect is to reduce heating of the surface and increase heating in the atmosphere. These effects are profoundly different from weakly absorbing aerosols such as sulfate.

On a global scale, biomass burning and fossil fuel combustion are both major sources of both organic compounds and BC (Ramanathan et al., 2001). In West and Central Africa biomass burning emissions are three times greater than fossil fuel combustion emissions. This is a strong contrast to other regions where fossil fuel products are usually overwhelming [Global Environment Outlook 2000, UNEP's Millennium Report on the Environment, Ed. Earthscan, 1999.]. The seasonal biomass burning cycle in Africa is well defined. The burning in the AMMA region takes place in winter and defines the northern most extent of fire in Africa. As the year progresses, the burning moves southward into central and southern Africa [Figure 2.5.5]. Biomass burning in southern Africa has been studied in the recent Southern African Regional science Initiative (e.g. Swap et al., 2002), but the vegetation and agricultural practices differ between northern and southern Africa and hence the physical and optical properties of biomass burning aerosols may differ significantly.

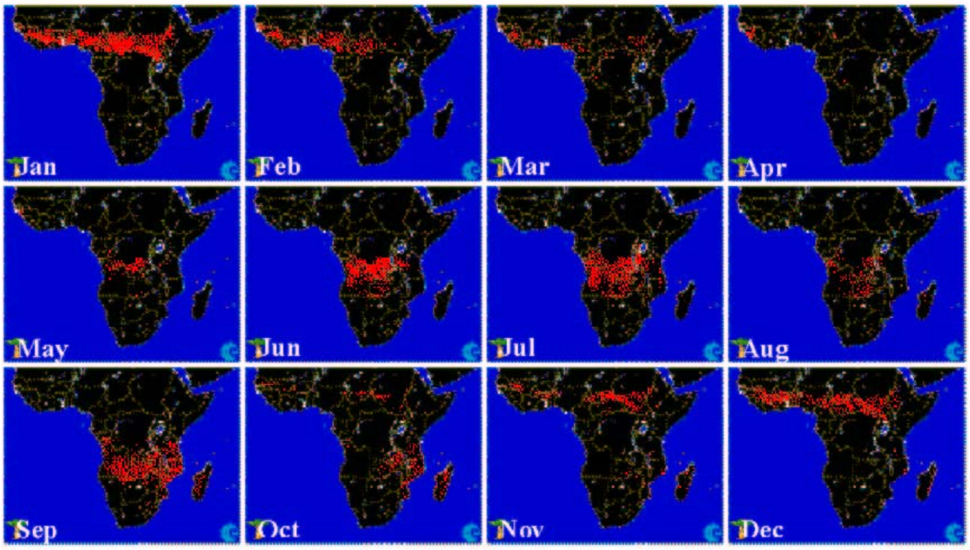


Figure 2.5.5. Satellite data showing the annual shift in biomass burning activities in Africa.

The impact of biomass burning on climate is difficult to quantify because of the extremely complex character of biomass burning aerosols. Fires produce a wide spectrum of organic aerosol products ranging from volatilized organic compounds, to pyrolized materials, to BC. In addition, many gaseous fire reaction products subsequently condense into aerosols. Over central Africa in the EXPRESSO field program during the November 1996 burning season, water soluble organic compounds (e.g., formate, acetate, oxalate, etc.) accounted for 46% of the total particulate organic carbon (Ruellan et al., 1999). In addition there is a substantial contribution from other soluble inorganic ions which are either produced in the combustion process or entrained from the surface. The presence of this wide range of soluble species suggests that these products can serve as effect cloud condensation nuclei [CCN] although the CCN response could be quite complex, depending on air parcel history. In AMMA biomass burning aerosol studies would take place during winter (SOP-0). The circulation system at this time of year produces a complex vertical structure with oceanic air masses at the lower levels and dry, dust laden air at higher levels. Thus the aerosol properties can change greatly depending on altitude and wind trajectory.

A major aim is to obtain a better understanding of the role of biomass burning aerosol emissions on cloud microphysics in the continental tropical zone and to assess the direct and indirect radiative impact of aerosol and cloud layers at regional scale. The fact that the fires take place close to the ITCZ suggests that biomass burning aerosols and other emissions can be transported to great altitudes and exported over great distances. Understanding the interaction of the source processes and the transport is a major objective. A further item for investigation is to attempt to quantify the effect that mixing of biomass burning aerosol and mineral dust has on the physical and radiative properties. The presence of mineral dust could reduce the impact of biomass burning emissions on climate. Additionally, the CCN properties of an internal mixture of dust and biomass burning aerosols is likely to be significantly different to that of an external mixture, which again has implications for climate change.

2.6 Atmospheric chemistry

The West African monsoon region is believed to be critical for global atmospheric chemistry and yet no systematic observations of the chemical composition over the region have been made. West Africa is an important source region for many trace gases, of both biogenic and anthropogenic origin, which play a crucial role in the cycle of oxidants in the troposphere. Natural emissions are dependent on vegetation type, soil moisture and temperature so are expected to change with changing climate. Further the deep convection associated with the monsoon can transport these precursors and their oxidation products to the upper troposphere and lower stratosphere, where they can then be rapidly transported on regional and global scales. Many of these products also lead to secondary organic aerosols which affect the radiative budget both directly and indirectly through their impact on cloud properties (see Fig. 2.6.1).

2.6.1 Sources of trace gases

Although anthropogenic pollution, resulting from the use of fossil fuels and human activities in general, have increased considerably in high population density areas in the tropics (Asia, South America, and locally in Africa), the main sources of trace gases and aerosols result from the biosphere-atmosphere system. The soil is a source of nitrogen compounds; vegetation, in both natural and disturbed ecosystems, produce hydrocarbons; and the combustion of biomass, mainly through anthropogenically induced fires, produce in varied proportions almost all the chemically or radiatively active trace gases and aerosols.

Plants emit a great number of volatile organic compounds (VOC) such as isoprene, mono- and sesquiterpenes, as well as a range of oxygenated organic compounds like alcohols, aldehydes and ketones, many of which have yet to be observed in the atmosphere. There is a large variation in emissions depending on the vegetation species. The tropical forest canopy is the main source of isoprene (Zimmerman et al., 1988, Guenther et al., 1995). The organic compounds emitted by tropical vegetation, in particular isoprene, are very rapidly oxidized leading to the formation of oxidation products which can lead to the production of biogenic sub-micron carbonaceous aerosols (Cachier et al., 1995). The global isoprene emission (420 MT[C]/year) amounts to approximately one third of the total emissions of VOCs. Higher atmospheric carbon dioxide and temperatures are expected to increase isoprene emissions.

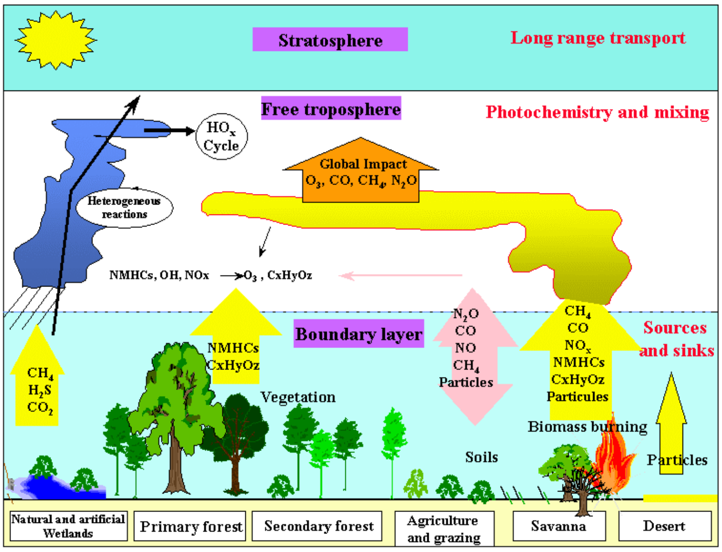


Figure 2.6.1 Overview of major chemical species in the WAM region, their fate and impact.

Nitrogen oxides (NO_x) play a major role in the chemistry of the troposphere with the catalytic conversion cycle of nitrogen monoxide (NO) into nitrogen dioxide (NO_2), which through subsequent reactions constitutes the photochemical source of tropospheric ozone. Tropical soils constitute an important source of NO (Yienger and Levy 1995 ; Delmas et al., 1997) and forest soils are one of the main sources of atmospheric nitrogen protoxide (N_2O), estimated at approximately 2MT of nitrogen a year. Higher temperatures and rainfall are likely to increase soil NO_X emissions, while it has been shown that the conversion of forests into agricultural systems tends to disturb the recycling of the nutrient elements and to increase the N_2O emissions (Keller et al., 1994). West Africa is one of the most electrically active regions of the world and the production of NO by lightning in convective clouds is an important source of NO_X in the troposphere (see Fig. 2.2.5(d)). Large uncertainties surround the estimates of the magnitude and spatial/temporal distribution of this source (Tie et al., 2002).

The combustion of biomass due to the human activities is certainly one of the most ancient sources of anthropogenic pollution to the atmosphere. Combustion of organic matter produces primarily water vapor and carbon dioxide, under ideal conditions of complete combustion. However, the oxygen supply is never sufficient, consequently combustion is incomplete and pyrolysis of vegetable matter lead to the formation of reduced compounds like CO, CH_4, VOC, NO, NH_3, H_2S, SO_x and aerosols. Several field campaigns have already taken place to examine biomass burning emissions in South America, southern/central Africa. The results of experiments such as GTE/ABLE 2A and 2B, DECAFE-EXPRESSO STARE-SAFARI 92, SAFARI 2000, provide the necessary data to further develop parameterizations of these emissions required to improve chemical models. In addition to significant biomass burning during the dry season over West Africa, it is clear that there are also important emissions from the large urban areas which exist in this region. These emissions still need to be quantified.

2.6.2 Tropical atmosphere chemistry and oxidant cycle

Trace constituents emitted by the biosphere through natural or combustive processes and/or from fossils fuel emissions are the main source of photo-oxidants in the atmosphere. Their degradation by various photochemical reactions can lead to the production of ozone and also the hydroxyl radical and other oxidants. The tropical troposphere is responsible for ~70% of the total oxidation of long-lived gases such as CH_4, CO, HCFCs and CH_3Br. West Africa, as noted previously, is an important source of many trace gas emissions and therefore there is a need to quantify the impact that this region is having on the global oxidizing capacity and tropospheric ozone levels: The tropics are very active in terms of photochemistry due to:

- The presence of major sources and sinks of trace constituents
- Maximum availability of sunlight and water vapour, which results in enhanced potential for photochemical production of ozone and other oxidants
- Deep convective processes leading to the rapid transport of trace constituents from the boundary layer into the free troposphere and even, into the stratosphere, from where they can be transported far away thus affecting the chemical composition of the atmosphere at both regional and global scales.

Deep convection facilitates the vertical exchanges between the boundary layer and the upper troposphere. It has been shown, for example, that a convective cloud has an impact on the upper tropospheric CO and NO_x concentrations, the increase of which induces a post-convective ozone formation in the middle and upper troposphere (Pickering et al., 1996). This phenomenon occurs in the whole of the equatorial zone where the atmospheric circulation is organized in cells driven by convection over the continental areas (Walker cells, see Jacob et al., 1996). The lifetime of

NO_x also strongly increases with altitude thus increasing significantly the potential photochemical activity of these compounds (Ehalt et al., 1992). This is partly because NO_x within the boundary layer is subject to dry deposition. It has also been shown more recently that concentrations of various oxidants and their reservoirs (e.g. peroxides, ketones) are enhanced in regions of convective uplift (Jaegle et al., 2000 and 2001; Mari et al., 2002). The tropical upper troposphere is photochemically more active than previously thought (Prather and Jacob, 1997), due to the existence of HO_X radicals which result from the fast convective transport of these precursors. Understanding the chemistry of HO_X in the upper troposphere is crucial as HO_X are the main atmospheric constituents which oxidize the reduced gaseous compounds including CO, CH_4, NMHCs, SO_2, DMS, NO_X ($NO + NO_2$) and other hydrogenated and halogenated compounds into forms more liable to deposition processes. HO_X and the products of these oxidation reactions are also responsible for the majority of in-situ photochemical ozone production and destruction. In the vicinity of the tropopause, ozone is a particularly active greenhouse effect gas and it strongly influences photochemistry as it is a source of HO_x in the presence of UV radiation and water vapor. Therefore, the determination of the contribution of emissions over West Africa to the HO_X and ozone budgets over this region and beyond is thus a key objective of AMMA.

Moreover, West Africa is of particular interest for the study of tropospheric chemistry as it is a unique superimposition of contributions from different African sources that will enter the ITCZ convection: monsoon moist air passing over the South Atlantic ocean and the tropical rain forest (biogenic emissions), Harmattan dry air flowing over arid areas, and polluted air from growing human activities (see Fig. 2.6.2).

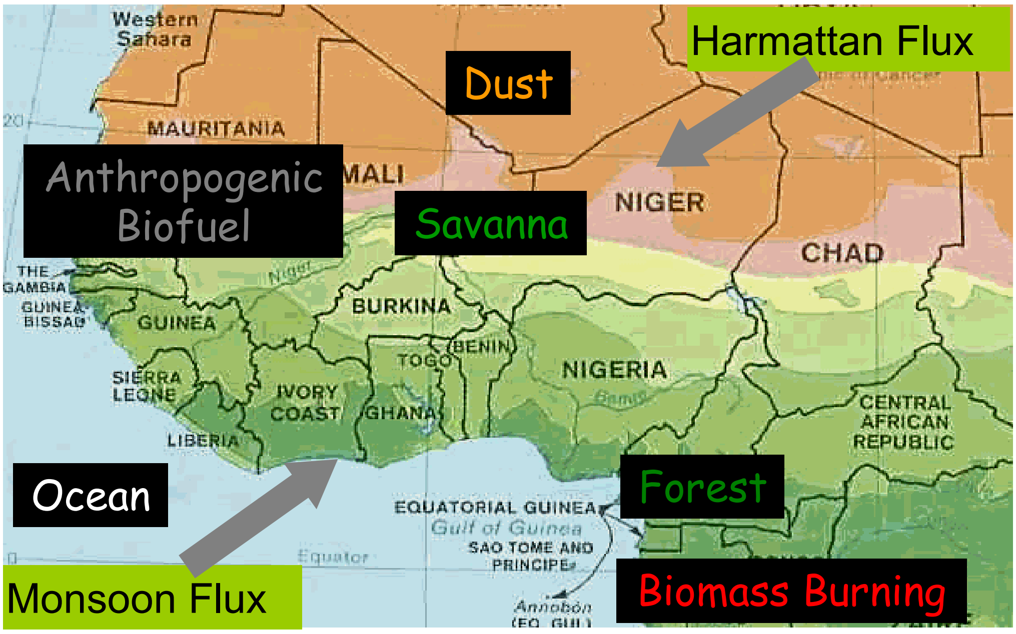


Figure 2.6.2 Schematic indicating location of different African sources of chemical species.

Chemical transformations are carried out either via homogeneous and/or heterogeneous processes. Heterogeneous loss processes by aqueous uptake in rain drops, aerosols or ice particles are likely to be particularly active in the tropics because of the cloud related to convective activity. Moreover, some of the oxidation products such as H_2SO_4, HNO_3 and the organic derivatives play a part in the composition, nucleation and growth of the aerosol particles. In turn, the aerosols can affect the chemical and physical properties of the cloud particles and thus their radiative properties. The variable and often high concentrations of dust over the savanna region further complicate the picture. The details of these processes clearly require further investigation.

2.7 Scientific Basis for Impact Studies

The variability of the West African Monsoon impacts on almost every component of the regional socio-economy: water resources, food security (rainfed agriculture with very little irrigation thus direct dependency on rainfall), health (availability of clean water for washing and drinking, creation of mosquito breeding sites), and energy (rivers/dams for hydropower). A healthy monsoon dynamics, producing rainfall regularly distributed in space and time, is a key requirement for replenishment of the water resources and good crop yields. In some instances the very survival of the populations depends on the abundance of the rainy season and entire villages may have to be abandoned for some time when the drought is too severe. In order to make a proper use of the resources for sustainable development in Africa, adaptative strategies and early warning systems must be founded on a strong body of knowledge. Reciprocally the advances in knowledge expected from an integrated project on the WAM should benefit research communities serving climate sensitive sectors.

Climate information which serves the needs of sectoral decision makers may differ from that routinely produced by the meteorological and climate community and much of the work of AMMA will only enter the realm of decision-makers after it has been used to successfully improve our capacity to monitor and predict the region’s climate at a range of spatial scales. However, within the programme there are ample opportunities to engage with user community interested in assessing the impact of climate on specific societal outcomes.

In order to address specific sectoral needs effort is required to identify the climate sensitive components (specific variables, located in space and time) of complex systems and to use this information to obtain, modify or create appropriate climate/environmental databases which can be used for analysis. Initially six “cardinal” variables can be identified as the most commonly requested: maximum and minimum temperature, precipitation, incident solar radiation, relative humidity, and wind speed. Nevertheless, this list is far from exhaustive. Other climate or climate/environment-related variables of importance in West Africa include aerosols, vegetation indices, soil moisture indices etc and remote sensing products combined with station data, as appropriate, may provide the most useful climate/environment data sources for many studies.

The climate science community is rich in analytical methodologies for climate data. These methodologies are often designed for data rich analysis and may or may not be appropriate for the analysis of relationships of climate to particular sectoral data in West Africa where observations may be limited, have frequent missing values and broad confindence limits with different sectors tending to favour particular methodologies according to their perceived needs. A thorough understanding of the substantive problem – whether it is malaria transmission, disaster occurrence, agricultural yield/food security or water supply – is essential to understanding the data issues and choosing the appropriate methodologies. Time series analysis is essential for many impact studies and limit the type of climate/environment data that can be used to those which have been collected systematically over the time period for which yield, disease incidence, water flow etc data are available.

It has to be recognized that in West Africa, as elsewhere on the continent, enormous data constraints exist in virtually every field (climate, health, agriculture, water) and many of the basic studies linking spatial and temporal variations in climate to societal outcomes are yet to be undertaken although new efforts to measure the impact of interventions designed to achieve the specific development goals mean that data gathering, archiving and analysis are increasing considered as essential to Africa's development agenda. A major contribution of the AMMA project to the region's capacity to apply new climate science to the development problems will be in problem specific data rescue, archiving, synthesising, dissemination and use in policy orientated impact analysis.

In order to allow the AMMA research to be used and ultimately translated into changes in policy and practice by decision-makers working in various sectors and at various scales it is essential that the needs of sectoral decision makers are incorporated into the research design from the earliest opportunity. A typical illustration of this general statement is related to the scale at which climate variability is characterized and predicted. Whether considering agriculture, health or local water resources, small scale variability may be as important as – or even more important than – large scale variability. Optimal climatic observation networks, data and model integration, education and training are but some tools that need to be connected to the fundamental research carried out in AMMA.

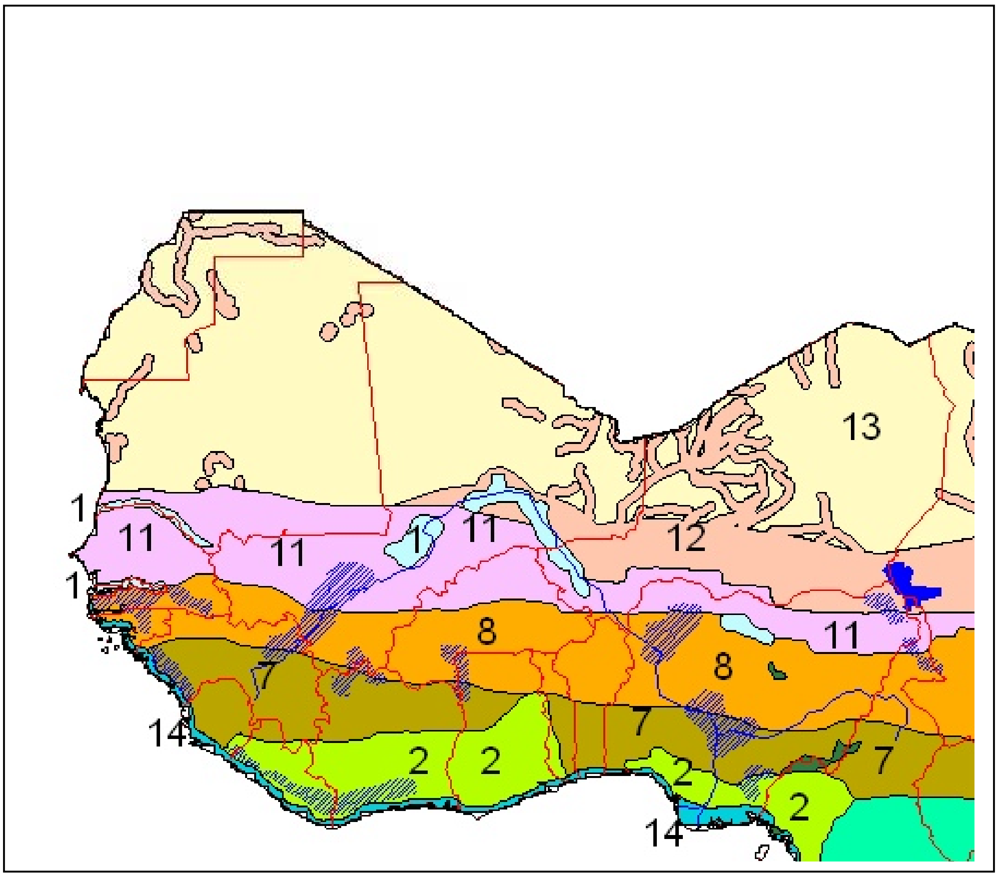


Figure 2.7.1. Farming systems in West Africa:1, irrigated; 2, tree crop; 7, root crop; 8, cereal-root crop mixed; 11, agro-pastoral millet/sorghum; 12, pastoral; 13, sparse (arid); 14, coastal artisanal fishing. From FAO (2001).

2.7.1 Crops and food security

The year-to-year variability of rainfall is a significant constraint to the sustainability of rainfed farming systems in West Africa where irrigation plays a very small role in agricultural production (see figure 2.7.1). Climatic extremes, such as drought and flooding, have a direct and often persistent impact on farmers' assets and livelihoods. Perhaps more important, the uncertainty associated with climate variability is a disincentive to sustainable resource management, and to the intensification and adoption of innovation that are necessary for secure livelihoods and long-term rural prosperity. The distribution of farming systems across West Africa is largely determined by rainfall and hydrology. There are three critical phases in crop development which could benefit from improved observed climate information and climate prediction. Rain onset is the first critical stage. It determines the success of plant varieties with a short or a long vegetation cycle and the best moment for sowing. There is a difficult compromise to find between an early sowing date allowing the crop to fully develop – provided no major dry spell happens – and a latter date that will minimize the risk of a dry spell but reduces the length of the growing period and the likely yield. After sowing, a close monitoring of possible dry spells is necessary. In case of an anticipated lost of production it has to be envisaged to substitute current varieties for those that are low yielding but drought resistant. Finally, yield prediction based on observed and forecasted climate information is important as early as two months in advance, in order to initiate food security responses and prevent severe suffering in drought stricken areas.

To transform climate prediction into a prediction useful at the scale of the peasant, applied research should be especially directed towards the development of water balance models at the small scale (plot, small catchment), taking into account the large spatial variability of the rainfall input. Another important point to consider is vulgarisation towards pastoralists, farmers, fishermen. Ideally they could make use of seasonal prediction at each of the critical stages mentioned above. Developing communication networks and training programs to make use of the information is thus essential.

A last point to mention is the data availability. Detailed yield data upon which to develop predictive models are hard to come by and in the last 20 years there has been a steady decline in the climate data collection process in the region. In the CILSS countries, rainfall data seem to be still collected regularly at the regional level, but the number of stations whose data are reaching AGHRYMET tend to decrease. Temperature and humidity data are most often not transmitted from the national to the regional level. These data are essential for the monitoring/prediction process, because they help detect possible prediction errors of the model and thus correct them in near real time. Actions in this area have thus to be promoted.

2.7.2 Water Resources

The continental water cycle is affected by climate variability at all scales. At the seasonal and intraseasonal scales the impact of this variability is mostly important for food and health applications. It may also be significant for water resources in the Sahel, where temporary pools provide easily accessible water for the cattle during and immediately after the rainy season. In case of low seasonal rainfall these pools dry out rapidly and the cattle water must be found from other resources (long distance surface water in the perennial rivers or difficult to access ground water). There are a considerable number of such temporary pools. Using a combination of high resolution Digital Terrain Models (DTM), Spot images and hydrological modeling, a climatological inventory and survey of the pools is possible. Real time data – mostly rainfall – would permit to run hydrological models predicting how the pools are filled. Data from the SPOT VEGETATION sensor may also be valuable in determining changes in environmental factors associated with disease transmission.

At a larger time scale and in an environment of more perennial rivers, deficits accumulated during consecutive years of drought have a significant effect on the river regimes and on the aquifer levels, even though this effect may vary from place to place and as a function of the spatial scale considered as mentioned in section 2.3. One outcome of the research undertaken to better understand the impact of the monsoon variability on the hydrological cycle will thus be to use the resulting models in order to obtain a better vision on how the various water resources compartments are affected by rainfall fluctuations at various scales.

Another major issue is related to water budget errors discussed in section 2.3. Errors in establishing a water budget have direct consequences for reservoir designing, early drought warning and flood forecasting. Improved modeling capacities and a more efficient use of the available data could be used to build a better expertise in the area of water resources management.

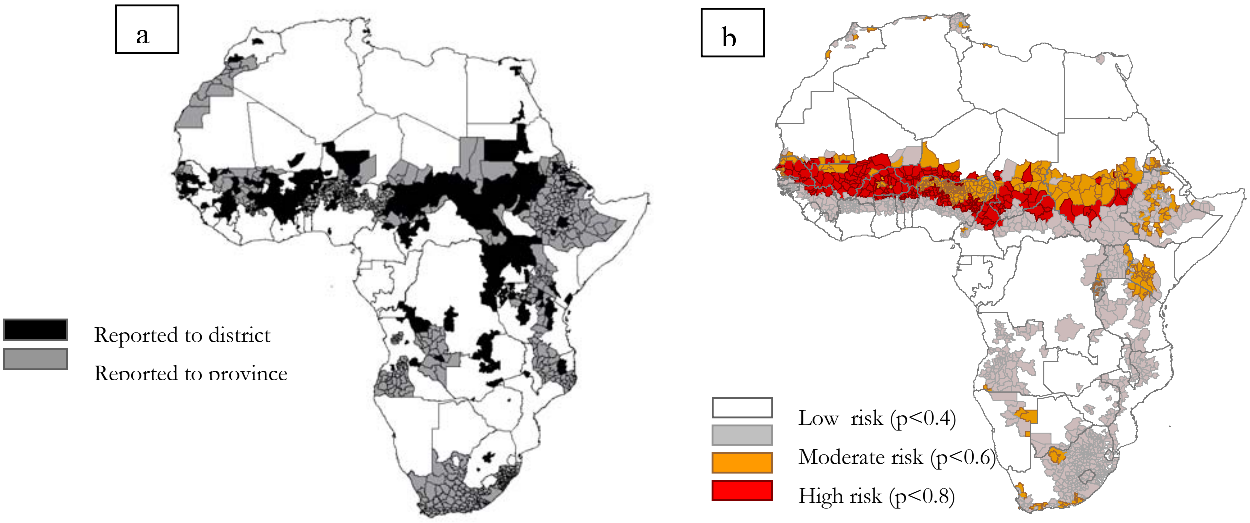
2.7.3 Health

Apart from direct effects, such as heat stress, climate impacts indirectly on health in a number of important ways: for example a) through its role in determining agricultural output and consequently food security which directly effects nutritional status; b) through its role in the economy via agricultural exports, hydrological power etc. which affects the ability of individuals to maintain nutritional status, prevent infection (e.g. through the purchase of mosquito nets) and when necessary obtain health care; c) through its role in determining seasonal and inter-annual demographic processes and d) through its impact on the spatial,seasonal and year-to year variability of climate related infectious disease – most commonly, but not always, transmitted by vectors (see Fig. 2.7.2 for a non-vector climate-sensitive disease).

A better knowledge of macro and micro climatic factors directly associated with transmission dynamics, their spatial and temporal distribution and their interannual variability may improve our capacity to predict and prevent the effects of a number of climate-sensitive infectious diseases in West Africa. Pools appearing during the rainy seasons provide breeding sites for mosquito, cyclops and snail vectors of parasitic and viral diseases (such as malaria, schistosomiasis, Guinea worm, lymphatic filariasis and rift valley fever). Local variation in climate, soils and topography and socio-economic factors are important in determining their contribution to local disease incidence. The survey mentioned in the water resources section can help in determining the pools that are the most favorable to the development of these various vectors of infection. A multidisciplinary approach is thus required in this area. Clarifying the relationship of climatic and hydrological data, (including that obtained from remote sensing instruments) to disease transmission dynamics to vector microhabitats may provide insights into the most effective means by which to use such information in disease control.

Epidemics of meningococcal meningitis regularly devastate large areas of the Sahel with 10s of thousands of cases and many thousands of deaths (see Fig. 2.7.2) These epidemics erupt in climatically sensitive areas and almost invariably occur in the dry season and end when the rainy season arrives. Both dust intensity in the dry season and the timing of rainy season onset of the rains has been suggested as important factor in the epidemic incidence levels. Monitoring and prediction of both dust aerosols and rain may therefore be useful in instigating timely reactive vaccination programs where increases in transmission are predicted - or in the case where early onset is predicted may result in local changes in the vaccination strategy.

Figure 2.7.2 a) spatial distribution of meningitis epidemics, b) model of epidemic risk based on landcover and seasonal absolute humidity



3. THE AMMA PROGRAMME

3.1 Introduction

African Monsoon Multidisciplinary Analysis (AMMA) is an international project to improve our knowledge and understanding of the West African monsoon (WAM) and its variability with an emphasis on daily-to-interannual timescales. AMMA is motivated by an interest in fundamental scientific issues and by the societal need for improved prediction of the WAM and its impacts on West African nations. The international AMMA project has three overarching objectives:

(1) To improve our understanding of the WAM and its influence on the physical, chemical and biological environment regionally and globally.
(2) To provide the underpinning science that relates climate variability to issues of health, water resources, food security and demography for West African nations and defining relevant monitoring and prediction strategies.
(3) To ensure that the multidisciplinary research is effectively integrated with prediction and decision making activity.

AMMA will address these objectives through the international coordination of ongoing activities, basic research and a multi-year field campaign over West Africa and the tropical Atlantic. AMMA will develop close partnerships between those involved in basic research of the WAM, in particular operational forecasting centers and decision makers, and it will establish blended training and education activities for African technical institutions and schools.

At the heart of the AMMA programme is a multi-scale analysis of the coupled atmosphere-land-ocean West African monsoon system supported by substantial enhancements to the current sustained observing system and special observations concerned with key processes (see 3.3.2). Additional observations and analysis will take place that take advantage of this including those concerned with atmospheric chemistry and downstream tropical cyclogenesis.

The science background for AMMA was presented in section 2 along traditional subject lines (e.g. atmosphere, land, ocean etc). Here we build on this and provide the key scientific issues and questions that will be addressed by the AMMA programme (section 3.2). Also, in order to promote integrative science, these are presented according to their appropriate spatial scale. The scientific strategy and implementation strategy of AMMA is described in section 3.3 and includes a brief summary of the planned field program. A more detailed “Implementation Plan” that describes the field observations and planning is in development and will be available in a separate document during 2005. In section 3.4 we describe the linkages with prediction of weather and climate and their impacts and in section 3.5 we describe briefly how the international AMMA programme will be coordinated and implemented.

3.2 Variability of the West African Monsoon: A Multiscale Approach

To address the multiple scales that characterize the WAM the program is structured around 4 interacting spatial scales (see Fig. 3.1): ***(i) Global scale.*** This is the scale at which the WAM interacts with the rest of the globe; emphasis is given to improving our understanding of the role of global SST patterns on WAM variability; seasonal-to-decadal variability are the main time scales of interest ***(ii) Regional scale.*** This is the scale at which we consider monsoon processes and scale interactions; emphasis is given to improving our understanding of the interactions between the atmosphere, land and tropical Atlantic ocean (especially the Gulf of Guinea). It is important to study the role of surface feedbacks on variability of the WAM at this scale including the key roles of vegetation and soil moisture over the continent and SSTs in the Gulf of Guinea. The annual cycle and seasonal-to-interannual variability are the main time scales of interest. AEWs are also studied at this scale. ***(iii) Mesoscale.*** This is the scale of the typical rain-producing weather systems in the WAM. It is central for studying the variability of rainfields at the seasonal scale and the coupling between hydrology and the atmosphere at the catchment scale. It is important to study the interactions of the mesoscale weather systems with synoptic scales (e.g. AEWs). ***(iv) Local scale or sub-meso scale.*** From an atmospheric point of view, this is the convective rain scale; it is central to the hydrology of the Sahel and of small watersheds to the south; it is the main scale of interest for agriculture.

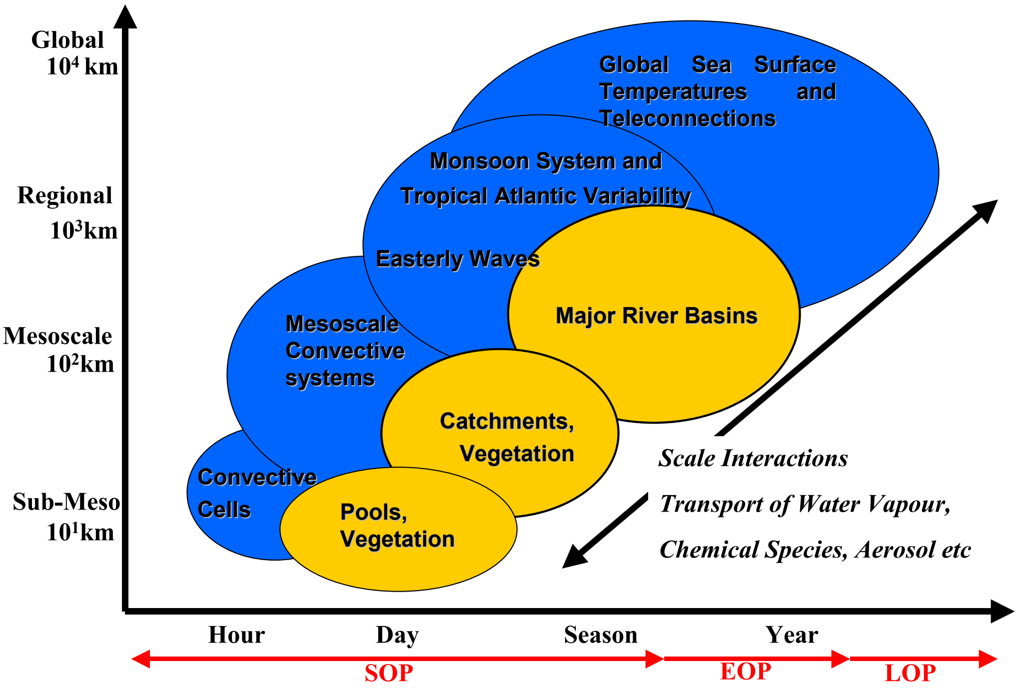


Figure 3.1 Simplified schematic of key phenomena together with their associated space and time scales. The arrow is included to highlight the importance of scale interactions and transport processes in the WAM.

AMMA emphasizes the importance of improved understanding of how these scales interact and combine to characterize the WAM and its variability, including how these interactions impact sources and transport of water vapour, aerosol and key chemical species (e.g. key greenhouse gases, ozone and aerosol precursors) in the West African region and globally. The key science issues and motivating questions are now discussed at each scale.

3.2.1 Global scale

At the global scale AMMA is concerned with how the WAM interacts with other regions of the globe including the rest of the African continent in order to better understand the processes that determine climate variability and predictability on seasonal-to-decadal time-scales. Interactions with international projects concerned with these regions will be ensured. This includes especially the CLIVAR monsoon panels (VACS, VAMOS, AAM), the CLIVAR-Atlantic panel, GEWEX including CEOP, and PIRATA and also IGAC which is concerned with improved understanding of chemical composition and the impact on climate. While the emphasis is on large spatial and long temporal scales it is important to consider how processes operating on these scales can influence the variability and predictability of smaller space and timescales important for applications (discussed in 3.4.2).

(a) Variability and Predictability of the WAM

Optimism for improved climate prediction on seasonal-to-decadal timescales is based on the fact that slowly varying surface conditions (e.g. sea surface temperatures, soil moisture, vegetation) can significantly influence climate. If these surface conditions can be predicted it may be possible to predict the climate associated with those conditions. At the global scale particular emphasis is given to the role of sea surface temperatures (SSTs) but interactions between the WAM and the other monsoon systems including the rest of the African continent will also be considered. The role of land processes in determining variability and predictability of the WAM will be dealt with at the regional scale in the next section. AMMA will promote research in the following areas:

- ***Teleconnections:*** Research efforts will be directed towards unraveling the mechanisms through which global sea surface temperatures (SSTs) and their variability influence the WAM on seasonal-to-decadal timescales. Previous research has highlighted the importance for the WAM of SSTs in the tropical Atlantic, Pacific and Indian Oceans but our understanding of the mechanisms that operate to communicate these SSTs to the West African continent is incomplete. The focus of this research will be on improving our understanding of how large-scale circulations interact with convection, radiation and other physical processes, including how they transport water vapor and impact SSTs themselves. Global reanalyses, satellite-based measurements along with coupled and uncoupled GCM simulations are the main tools for this work. Major efforts will be devoted to evaluate available analyses and simulations through comparisons with available in situ and satellite data.

- ***Intraseasonal Variability:*** West African rainfall can vary significantly on intraseasonal timescales. We know very little about such variability, its causes and predictability and its relationship with the WAM and associated regional circulations. Several mechanisms may influence the nature of intraseasonal variability and require investigation. The role of the MJO and other equatorial waves along with intra-continental teleconnections will be explored.

- ***Predictability:*** It is important to assess the extent to which the key modes of variability for the WAM are predictable. Predictability will be investigated through analysis of a hierarchy of GCM simulations including hindcasts with prescribed surface conditions and predictions with coupled atmosphere-land-ocean GCMs. It is important that we highlight the predictable aspects of the WAM and to exploit these where appropriate.

Key Questions:

- What are the key SST anomaly patterns that influence the WAM on seasonal-to-decadal timescales and to what extent are they predictable?
- What mechanisms operate to communicate these SST anomaly patterns to the West African region and how are these teleconnections influenced by other regional circulations in the tropics including other monsoon regions and the rest of the African continent?
- What mechanisms determine the observed intraseasonal variability over West Africa? What are the relative roles of intra-continental teleconnections and equatorial waves?

(b) Impacts of the WAM on the global scale

It is important to improve our understanding of the relationship between seasonal-to-decadal variability of the WAM and the rest of the world. Two of the most important areas of investigation include the WAM's impact on Atlantic tropical cyclone variability and West Africa's role as the most important source of the world's mineral dust aerosol. This region is also very important for the global oxidizing capacity being a potential source of HO_x and ozone in the global troposphere.

- ***Variability and Predictability of Atlantic Tropical Cyclone Activity:*** Two main avenues require exploring: (i) the role of WAM heating anomalies and associated teleconnections that impact the environment where tropical cyclones develop (e.g. through impacting vertical shear, humidity, aerosol or SSTs) and (ii) the variability of the weather systems (e.g. African easterly waves and MCSs) that trigger many of the tropical cyclones (e.g. through changes in frequency, intensity, location or structure). This analysis must be achieved through a combination of modeling and diagnostic studies that make use of in situ and remotely sensed data.

- ***Aerosol Variability:*** It is important to improve our knowledge on the aerosol physical, chemical and radiative properties. Depending on the location and on the season, the aerosol component results from a mixing of dust coming from the desert, biomass burning aerosols from fire activities or sulfates coming from urban and industrial regions in North Africa or Europe. The direct radiative effect of aerosols can go from a warming effect to a cooling effect depending on the surface albedo and aerosol absorption, which is related to the type. The modification of the aerosol properties along their transport has also an impact on the cloud properties.

- ***Atmospheric Chemistry:*** Due to the existence of major sources of key greenhouse gases, ozone and aerosol precursors over West Africa it is likely that this region is making a significant contribution to the global oxidizing capacity, tropospheric ozone budget and aerosol production (e.g. secondary organic aerosols). Once emitted these trace constituents and their degradation products can be rapidly uplifted in the free troposphere by deep convection and then transported over large distances (several 1000 kms) away from source regions. Therefore, the potential impact of emissions over West Africa may be to perturb oxidant levels and global climate on a global scale.

Key Questions:

- How does seasonal-to-decadal variability of the WAM impact Atlantic tropical cyclone variability and to what extent is this predictable? What are the relative roles of the large-scale impacts of WAM and the weather systems?
- How do the chemical, physical and radiative properties of African aerosols change during long-range transport?
- What is the impact of aerosol on weather and climate including the direct and indirect radiative effects?
- What is the extent of long-range transport of oxidants and aerosols downwind from West Africa and their impact on the global oxidizing capacity (lifetime of GHGs) and global radiative forcing?

3.2.2 Regional Scale

At the regional scale AMMA is concerned with providing an improved description and understanding of regional scale processes that influence West African rainfall, its associated regional circulations and how they interact with the evolving surface conditions over the land and the ocean. The role of deep convective systems in determining the chemical composition of the free troposphere and possibly the tropical tropopause layer (TTL) will also be explored.

(a) Monsoon Dynamics and Scale Interactions

- ***Annual Cycle:*** Mechanisms that control monsoon onset, intensity and meridional migration including the "jump" need to be investigated through diagnostic and modeling studies. Emphasis will be given to analysis of the annually varying surface conditions, the associated low-level θ and θe gradients and associated regional circulations. The annual cycle and associated processes offer an important testbed for GCMs used in the AMMA program.

- ***Diurnal Cycle:*** The role of diurnal circulations on the continental water budget and precipitation will be investigated. Analysis of the processes that determine the coherent diurnal cycle will be examined including how the diurnal circulations interact with MCSs and AEWs. A detailed examination is required of the relationship between convection and the diurnal evolution of the boundary layer and low-level flow.

- ***African Easterly Waves and interactions with convection:*** A major objective of AMMA is to improve our knowledge and understanding of AEWs and their interactions with MCSs and convection. Composite studies indicate that moist convection is preferentially located in the northerlies ahead of the jet-level trough of the AEW in the rainy zone and in the southerlies behind the jet-level trough polewards of the AEJ. We cannot describe with confidence the processes that explain these observed phase relationships. The relative roles of adiabatic ascent expected in this baroclinic environment, meridional advection of temperature and humidity and surface processes are unknown and require investigation through analysis of observations and modeling. Previous projects of convective-synoptic interaction have generally made little progress in understanding the mechanisms of interaction. Simply associating convective features with a particular phase of a passing large-scale wave does not indicate necessarily how the interaction is occurring. To study this the airflow in and through the MCSs need to be mapped on both the convective and mesoscale at the same time that AEWs are clearly distinguished on the synoptic scale (see below).

- ***Mesoscale Convective Systems and their interactions with the Environment:*** Analysis of the interactions between the MCSs and the environment will be investigated at the regional scale and the mesoscale (see 3.2.3). At the regional scale, analyses of the environmental conditions (atmosphere and surface) will be combined with satellite data to study MCSs over the whole West African region and at seasonal-to-interannual timescales. New satellite data (TRMM and MSG) allow for detailed studies of the life cycle of the mesoscale convective systems, both over the Sahel where they provide 90% of the annual rainfall and over the Sudano-Guinean region, where their characteristics are much less well known. Linking with mesoscale measurements, a better understanding of the environmental control of the MCSs will be sought, including the scale interactions with the AEJ, TEJ and AEWs.

- ***Tropical cyclone intensity change:*** Tropical cyclones often develop from mesoscale convective systems embedded within AEWs that developed over West Africa. We lack a good understanding of the processes that organize these systems into tropical cyclones and modulate their intensity once they enter the oceanic environment. It is well-known that the amplification of vorticity at the surface is vital in marking the onset of tropical cyclogenesis. Proposed mechanisms for vorticity generation include stretching in association with deep convection and diabatic heating within an existing low- and/or mid-level circulation, the merger of multiple mid-level vortices, axisymmetrization of vorticity associated with convective flare-ups from a parent vortex, wave accumulation (Webster, personal comm.) or a combination of these. Observations of wind and temperature fields at high temporal and spatial resolutions, over land as well as over the water, are needed to be able to document the structural changes that occur to tropical weather systems when they experience convective outbreaks and to address which of the processes listed above is important for amplifying low-level vorticity. Satellite imagery of the dust associated with the SAL suggests that mesoscale systems are less likely to evolve into tropical cyclones when the SAL becomes intertwined with the mesoscale circulations. This compelling working hypothesis has powerful implications for hurricane forecasting for the Caribbean, western tropical Atlantic and southeastern US and will be explored.

- ***Impacts of land Processes on Variability and Predictability of the WAM:*** The extent to which internal dynamics of atmospheric and hydrologic processes within the WAM increase or limit predictability of the WAM will be investigated. Improved monitoring of the land surface conditions is required for studying the connections between gradients of soil moisture and vegetation and WAM dynamics. Such observations are required for evaluating the parametrisation of surface schemes in climate models.

Key Questions:

- What mechanisms determine the nature of the annual cycle of the WAM including especially rainfall onset, intensity and meridional migration including the “jump”?
- What are the relevant physical processes that determine the coherent diurnal cycle of the heat low circulation and its impact on the continental water budget? How are AEWs and MCSs and their interactions influenced by the diurnal cycle?
- What are the relative roles of AEW dynamics (e.g., PV advection, adiabatic ascent, synoptic advection of temperature and humidity) and surface processes on the development of convection and MCSs in AEWs?
- How do MCSs feedback and interact with the synoptic environment?
- What is the role of the East Atlantic environment on tropical cyclone intensity change including the impacts of the dry air, vertical wind shear, east-west variations in zonal wind and dust aerosol?
- On what space and timescales do land surface feedbacks impact predictability of the WAM?

(b) Land Processes and Hydrology

The continental water cycle has dramatically changed over the past 30 years. Due to the lack of a consistent regional observing system and of cross-scales studies, a general understanding of this cycle and of its component is still missing. To address this issue, a multi-scale approach is proposed that ranges from convective rainfall scale to the regional scale. The water cycle is in close interaction with the land surface conditions and AMMA will provide to study this interaction.

- ***Rainfall:*** Rainfall is seen here as the input to the continental water cycle. Its spatio-temporal variability has a central influence on the partitioning of the water input between the various components of the water balance. Emphasis will be to provide a coherent analysis of rain data provided by operational ground networks, in conjunction with satellite imagery (MSG, TRMM). The scaling properties of the rainfields will be analyzed in order to provide some guidance for validation of rainfall output from atmospheric models. These scaling properties will also be used to study how input errors propagate into hydrological models. This action will be closely linked to rainfall data analysis carried out on the mesoscale data sets (see below).

- ***Large river systems:*** Outflow of the large West African river systems significantly diminished over the last three decades. This is due both to a modification of the rainfall regime and to changing surface conditions. Thus, quantifying the respective influences of climate change and of land surface changes in the modifications of the hydrology of the large river systems remains an open field of investigation. It requires the development of appropriate modeling strategies taking into account the spatio-temporal structure of the rainfields.

- ***Vegetation and soil moisture:*** An improved description of the multi-year variations of land conditions and analysis of their meteorological and hydrological impacts is needed to address the role of surface conditions on WAM variability and predictability. Vegetation and surface humidity maps will be made for West Africa by blending various historical satellite and in situ data with available aerial photographs. For the current period, the potential of new satellite sensors will be analyzed to determine optimal strategies of surface condition monitoring over West Africa using a combination of ground data, satellite information and models. This methodological research is needed if one is to investigate how the land surfaces impact on the WAM dynamics.

Key Questions:

- What are the atmospheric and surface factors that determine the spatial pattern of rainfall deficits or excess over West Africa
- What are the respective contributions of the degradation of vegetation and of the rainfall deficit in the modification of the outflow of large West African rivers during the last 30 years ?
- To what extent do land and regional ocean surface processes determine the variability and predictability of the WAM?
- What is the variability of aerosol emissions over West Africa due to wind erosion and biomass burning activity? To what degree is the variability of dust and biomass burning emissions related to human activity?
- How do the annual cycle and seasonal variability of vegetation and soil moisture at regional scale modify the nitrogen and organic emissions ?

(c) Ocean Processes

Thirty percent of water vapor in the Monsoon flux is estimated to come from the Gulf of Guinea. For this reason, it is necessary to improve our knowledge of Gulf of Guinea oceanic circulation its variability and the oceanic processes responsible for SST variability, which are not well known. Also, SST variability in the tropical Atlantic has a strong influence on variability of WAM. Coupled models are poor at simulating these SSTs.

- ***Sea Surface Temperatures:*** Particular emphasis will be given to improving our understanding of the role of SSTs in the Gulf of Guinea and off the west coast of Senegal on intraseasonal-to-interannual variability of the WAM. The Gulf of Guinea is an area where strong SST fronts may influence the meridional gradients in low-level θ and θe. These fronts are observed mostly due to the presence of the equatorial or coastal upwelling, linked to the cold tongue that develops in boreal summer, and coastal upwellings. Even less is known of the effects of the Senegal upwelling on the WAM. The mechanisms through which SST anomalies in the Gulf of Guinea and off Senegal arise, how they are communicated to the boundary layer and subsequently impact the WAM need to be investigated using a combination of diagnostic and modeling studies. SST's, along with winds and air humidity, and their spatial variability also play a key role in the surface heat budget, through latent, sensible heat and evaporation which are the main terms which determine the evolution of the oceanic and atmospheric mixed layers. The precision of this heat budget will be evaluated with the help of in situ measurements and compared to satellite or model heat flux estimates.

- ***Ocean Processes:*** Variations in the oceanic circulations in the Gulf of Guinea will be documented using available in situ and satellite data at intraseasonal, seasonal and interannual timescales. The corresponding variation of heat, salt and momentum budgets in this oceanic basin and the role of heat transports by oceanic currents, in analyzing particularly the impact of the barrier layer on the oceanic heat budget on SST. In situ observations of SSTs should be made to evaluate satellite derived SSTs and SST climatologies. A hierarchy of large scale and small scale models including assimilation of altimetry and in-situ data need to be run, compared and evaluated in order to estimate the role of surface exchange compared to upper layer oceanic processes.

Key Questions:

- What key processes act to determine the observed SST variability in the Gulf of Guinea? What are the respective roles of surface fluxes, advection and mixing in the evolution of the SST's? What effect does the salinity have on the buoyancy fluxes? What are the relative roles of runoff, evaporation, barrier layers in determining the oceanic circulation in this region?
- To what extent are the tropical Atlantic SSTs coupled to the WAM and how does this impact the predictability of the SSTs? What is the role of SST heterogeneities (cold tongue, equatorial and coastal upwellings, tropical instability waves) on the atmospheric heat and momentum transports? Do they act on the coastal rainfalls and how do they modulate (increase or decrease) air-sea exchanges? To what extent are the atmosphere and the ocean mixed layer coupled in the Guinea Basin?
- Which part of oceanic water and heat is transported from the Guinea Gulf toward the WAM? Which part is directly provided by the surface fluxes and which part transit from other Atlantic regions toward the continent?

(d) Water budget analysis in the coupled Ocean - Land - Atmosphere system

At the regional scale the coupling aspects of the Ocean – Land – Atmosphere systems play a major role in shaping the spatial patterns of rainfall deficits or exceedances. The various components of the water budget that control these patterns are not directly measurable and are consequently evaluated through an array of modeling and/or balance calculation methods. It is important to evaluate the accuracy of such calculations/estimates in order to obtain an idea of the errors involved in attempting to compute a regional 3D water budget.

- ***Atmospheric Water Vapour:*** A first action will be to try to improve our knowledge of the sources and sinks of moisture over the region. A consistent sounding network and the deployment of a transect of flux measurement stations will be established to provide the data needed for a better documentation of the atmospheric water budget. Their assimilation together with new satellite sounder data (e.g. AIRS and IASI) into models will allow an in depth investigation of the recycling of atmospheric moisture and of its contribution to rainfall over the Sahel. Improvement of our knowledge and understanding of water vapour transport and its variability will be sought.

- ***Rainfall:*** The patterns of rainfall variability will be characterized, depending on the time scale considered, in order to assess the errors involved in estimating the input to the hydrological systems. These patterns may vary depending on the phase of the monsoon and the region considered. Different modifications of the atmospheric circulation have different effects on rainfall pattern and this must be studied in order to gain a better understanding of how climate variability impact on the rainfall regime. This in turn is crucial for representing how the surface hydrology is affected by the climate fluctuations.

- ***Continental Water Budget:*** A proper evaluation of the continental water budget at the regional scale requires an assessment of the amount of water returning to the ocean through river outflows. To that end not only the large river systems will have to be considered (as mentioned above in section (b)), since only 60 % of the continent drains into the ocean through the three largest river systems of the region (Sénégal, Volta and Niger). It will thus be necessary to evaluate the contribution of smaller river systems draining directly into the ocean and to characterize the variability of this contribution, depending on the atmospheric forcing and changes of the land cover. Strategies for linking hydrological models at the regional and meso scales will be developed.

- ***Surface Fluxes:*** An essential part of this analysis is the surface water and energy budget, needed to understand the evolution of θ and θe gradients crucial for the WAM. The surface budget will be investigated through model assimilation of satellite products and synoptic observations. Evaluation of the budget will be performed using ground measurements in locations representative of the different surface conditions. The role of continental surface and its time variability (e.g. soil moisture, vegetation) in controlling sensible and latent heat fluxes to the atmosphere will be evaluated. This issue is important for the water budget but also for establishing the low-level gradients of θ and θe in the boundary layer (important for the WAM circulation).

Key Questions:

- What are the sources and sinks of water vapour in the region and how does the water vapour distribution impact convection and its variability? How much is transported into the region and how much is recycled?
- What are the key scales of rainfall variability over the region? How do these scales vary on seasonal-to-decadal timescales and to what extent are they predictable?
- What is the variability of surface water and energy budget? How important is this variability to understand the water cycle? How does this variability impact the variability of low-level gradients of dry and wet static energy in the boundary layer?

(e) Atmospheric Chemistry and Aerosol

The chemical and aerosol composition of the regional circulation flows associated with the WAM together with the annual and seasonal evolution of their properties during the meridional progression of the ITCZ need to be determined. The chemistry and aerosols composition in the monsoon and Harmattan flows or the AEJ for example will be characterized. Understanding the chemical and aerosol properties of these regional flows and how they mix in the convective convergence zone are key areas of investigation. Another regional aspect is the determination of the variation of the emissions (gases and aerosols).

Key Questions:

- What is the potential for secondary organic aerosol production over West Africa?
- What is the role of the monsoon circulation and other flow patterns in the transport and processing of the chemistry and aerosols emissions and how do these emissions affect the dynamics of the WAM?
- What are the chemical characteristics of the TTL region over West Africa and its role in transporting trace constituents to the stratosphere?
- What are the meteorological processes in West Africa that result in such a close linking of dust transport to rainfall deficits in the region?

3.2.3 Mesoscale

The mesocale in the atmosphere mainly refers to the mesoscale convective systems which bring most of the rainfall over West Africa. It is also the scale where the coupling between atmospheric and hydrological components can been studied in detail as it corresponds also to the scale of many catchments. This scale is also important as it is the scale where parameterisations of numerical atmospheric models will be carefully evaluated and improved.

(a) Mesoscale Convective Systems

The monsoon circulation cannot be reduced to moisture advection in the boundary layer. Numerous processes occurring over a large range of scales (synoptic, mesoscale and microscale) are involved and MCS play a key role in these interactions. A better understanding of this scale-interaction problem, which is of paramount importance, will be sought and is closely linked to an effort to better represent key physical processes in models used for weather and climate prediction. The sources of heat, moisture and momentum due to MCS need to be determined in a synoptic framework but also at the scale of MCS. In addition, the water budget of MCS needs to be studied over their whole cycle as MCS are key components of the whole hydrological cycle. The nature of the interactions between the convection and the aerosols is not yet understood. Aerosols can affect the chemical and physical properties of cloud particles, their radiative properties and, thus, precipitation mechanisms. These interactions could have implications for hydrological budgets. For example recent studies suggest that mineral dust can suppress precipitation in clouds. Thus increased dust during drought cycles could have the effect of exacerbating drought and propagating drought conditions over larger areas. These processes need to be first understood at the scale of convective systems.

Key Questions:

- What processes determine the various aspects of the life-cycle of MCSs including triggering, growth, propagation, the extent to which they become organised and their decay? What are the relative roles of the synoptic environment and surface conditions? How does the MCS structure determine the pattern of rainfields at the ground ?
- What are the effects of MCSs on the synoptic circulation in terms of heat, moisture and momentum? How does the degree of organization modulate these effects ? How do the differences between stratiform and convective regions evolve between initial, mature and decay stages of MCS? What are the differences between systems north and south of the AEJ?
- What are the feedbacks acting between MCS, the monsoon and Harmattan flow, and the 3D structure of the jets (AEJ, TEJ) ?
- What role do MCSs play in effecting the transport of gases and aerosols from West Africa to global scales? Is the strong and persistent generation of dust aerosol in West Africa linked to the MCS life-cycle? Does dust play a role in modulating the life cycle of MCSs?

(b) Catchments and vegetation

- ***Water Budget:*** The size of the catchments in the West African region range from a few square kilometres to more than 10,000 km² (the upper Ouémé catchment area is 14,200 km²). During the recent dry period it was found that the magnitude of the resulting streamflow deficit varied considerably depending on the scale and the type of surface conditions – increased runoff coefficients having even been observed in places. It is thus crucial to gain some understanding on how scale affects the variability of each term of the water budget over this continuum of scales. This is needed to evaluate how precisely the water balance may be closed depending on i) the size of these catchments, ii) the nature of the rainfall forcing, iii) the type of surface conditions (topography, geology, vegetation).

- ***Land-Surface Feedbacks*:** Sharp rainfall gradients are known to be an important characteristic of the rainfields produced by squall lines and convection in general. This creates gradients in soil moisture and in vegetation growth which can in turn influence the triggering and organisation of subsequent convection. A dense rainfall network at the ground (gauges and radar) and boundary layer measurements are required to better understand such mechanisms.

Key Questions:

- How does the space-time variability of rainfall associated with convective systems impact the variability of the surface water budget ?
- At which time scale and with which degree of accuracy is it possible to estimate the evapotranspiration at the mesoscale?
- To what precision is it possible to close the surface water balance depending on the size of a catchment?
- How is the variability of water budgets and vegetation in catchments linked to dust generation

(c) Land surface Atmosphere Interactions and the Water Budget

The mesoscale is the key scale at which to attempt to close a 3D water budget. It is the lower limit in size from an atmospheric point of view while being an upper limit from an hydrological point of view. A good understanding and documentation of the interactions between the land surface and the atmosphere is necessary in order to determine reference areas for which the 3D water budget will be studied.

Key Questions:

- Is there a significant feedback of the continental surface on the dynamics of the convective system and can this in turn create persistent patterns in rainfields and impacts on vegetation, soil moisture and texture spatial distributions?
- With which accuracy can we determine the various components of the continental water budget and what are the errors involved in closing the 3D water balance?

3.2.4 Local Scale

The rainfall over West Africa is mostly of convective origin and thus occurs at the scale of convective downdrafts, e.g. at the scale of a few kilometers. The strong variability of rainfields at this scale, produces heavy gradients in soil moisture and infiltration that deeply impact agriculture and water resources. It was also shown during the Hapex-Sahel experiment, that local feedbacks from the surface to the atmosphere may thus happen at the convective scale. Water partitioning at the surface also happens at small spatial scales. Thus, water budget studies will include a local scale component, which will complement the mesoscale and regional approaches described above.

(a) Hydrological Cycle

- ***Process studies:*** As part of the water budget monitoring, process studies will be carried out to better understand i) how vegetation, slope, soil moisture determine the partitioning between surface runoff and infiltration and ii) to recommend the minimum measurements required to evaluate this partitioning in an operational mode.

- ***Surface Water Budget***: To complete and to validate the studies carried out at the mesoscale, detailed studies of the water budget are needed at the local scale. It is necessary to evaluate how the surface water budget may be closed at this scale and how this closure is depending on surface conditions and rainfall regimes. Sensitivity studies to the land cover changes and rainfall regime changes (meridional gradients, wet years versus dry years) are also important to evaluate how these factors have affected the hydrological cycle following the long lasting drought.

Key Questions:

- How does vegetation degradation act to enhance or reduce the runoff coefficients and can thus mitigate the impact of rainfall deficit?
- How does the geology contribute to the various components of the water budget and to the partition between fast and delayed responses of the rivers ?
- To what extent can we evaluate the deep infiltration and evaporation terms at the local scale so as to be able to close the water balance of small watersheds ?
- To what extent do small scale hydrological features (e.g., ephemeral streams, dry lakes, etc.) act as dust sources?

(b) Vegetation

- ***Interaction between the water cycle and the dynamics of vegetation:*** The use of water by vegetation is governed by both competitive or facilitation behavior leading to high heterogeneity of the vegetation cover. The result in terms of vegetation structure and function at plot scale determines the vegetation-soil-atmosphere transfers at the regional scale. Local changes in the vegetation cover under climatic and human pressure must lead to changes in regional vegetation function. Plant distribution and specific functions control the water transfers – such as water fluxes in the soil, soil evaporation, transpiration – and most of the phases of the carbon cycle – such as photosynthesis, plant respiration, biomass production and decomposition. Understanding and modeling how the various components of the vegetation cover are distributed and how they function according to water resource availability (climatic and anthropic factors) is thus crucial. This has to be carried out through a joint monitoring of the water budget and of the vegetation pattern, composition, phenology, and physiology.

- ***Eco-Physiology:*** The studies on vegetation at local scale seek to quantify specific physiologial behaviour (sap flows, stomatal resistance, water potential), phenology (leafing, flowering, fruiting), and biomass pattern (distribution of the cover, root depth biomass, and above-ground biomass) of the different components of the vegetation. These parameters need to be analysed in relation to the spatial- and temporal distribution of water resources (rainfall, soil water availability). Specific biomass related parameters (cover density, height, LAI) also need to be collected in order to scale up the vegetation functions.

- ***Source of Chemistry Species:*** The emissions of gaseous and particulate organic compounds from soil and vegetation play a major role in the photochemistry of the atmosphere over West Africa. Emissions can vary over a wide range depending on the vegetation species and the response of vegetation and soil to monsoon rainfall and evaporation. It is important to understand how vegetation in the WAM region responds to the monsoon cycle so that the emission rates can be incorporated into photochemical models.

Key Questions:

- How do specific plant functional strategies and variations in water resources, through controlling vegetation cover maintenance and soil water flux regulation, interact?
- Does the variation in the distribution of the same cover density at local scale change functional processes monitored at regional scale?
- What are the contributions of the different components (annual, deciduous, evergreen) of the vegetation to the biomass and fluxes (water, C) when upscaling from the local scale to the mesoscale?
- What are the contributions of the different components of the vegetation to natural emissions of chemistry species and how do they change with season and rainfall?

(c) Microphysics and Lightning

Analysis is required to explain the ubiquitous ice particles aloft in the West African continental MCSs, their lightning, and their tendency to have a lower proportion of stratiform precipitation. Observing and explaining these cloud microphysical characteristics of the West African MCSs will lead to a better understanding of continental tropical MCSs in general. Better understanding of the microphysics will require more precise understanding of the dynamics of the MCS, which will lead to better definition of the vertical distribution of latent heat release in the MCSs, and hence a clearer picture of how the MCSs may interact with synoptic scale circulations. Convection over central tropical Africa, specifically the Congo, produces the largest lightning flash rates of any region on earth, associated with intense, isolated convective cells. Significant flash rates occur in the West African region in association with organized convection in the form of squall lines and MCSs. The substantial flash rates raise important scientific questions that need to be explored. Whether these flash rates are more related to buoyancy and updraft dynamics (lightning-CAPE mechanism as mentioned in the previous section), or to the microphysics associated with enhanced aerosol concentrations, (or a combination of these processes) can be addressed in AMMA

Key Questions:

- What are relevant microphysical processes leading to heavy convective rainfall in the convective elements of the MCSs?
- What are the relative contributions of instability, aerosol concentration and type, and cloud base height in determining lightning flash rates?
- What are the dynamical (including the pre-storm environment) and microphysical controls on MCS organization and intensity, and convective and stratiform rain proportions?

(d) Atmospheric Chemistry and aerosols

Deep convective systems provide a mechanism for the rapid transport of trace constituents out of the boundary layer into the free troposphere. The role which entrainment and detrainment play in this process will determine the fraction of boundary layer air which reaches the upper troposphere or the TTL. It is important to know this fraction because photochemical production of ozone and other oxidants tends to be more efficient at higher altitudes and also many constituents have longer lifetimes and can then be transported over long distances between continents. Deep convection is also an important source of lightning NO_x, a key ozone precursor as well as being a sink for trace constituents through washout processes and loss on aerosol/ice surfaces. The role of deep convection in determining the chemical composition of the free troposphere and the TTL will be addressed based on modeling of the convective processes at cloud scale combined with simultaneous aircraft measurements in the boundary layer and the free troposphere.

Key Questions:

- What is the role of deep convective processes (transport, deposition, heterogeneous chemistry) in the budgets of major oxidants HOx and tropospheric ozone in the free troposphere over West Africa?
- What is the magnitude of NOx production by lightning in convective clouds over West Africa?

(e) Downscaling issues

Spatially aggregated estimates of some key geophysical variables are obtained through remote sensing or as outputs of models, while direct measurements are most often obtained as point values. At the same time, some models include an explicit representation of processes, requiring fine scale values of some key parameters or variables. There is thus a two-way scaling issue depending on whether aggregation from point measurements or disaggregation from large scale models or remote sensing data is sought. One point to have in mind in the case of downscaling from remote sensing observations is that the available data are not of same nature than the required data (i.e., brightness temperatures versus a geophysical value).

Key Questions:

- Is it possible to identify scaling properties in the field of variables that display the strongest spatial variability (i.e. convective structures, rainfall, soil moisture, …) ?
- How can these scaling structures, when they exist, be used in disaggregation or aggregation algorithms?
- To what extent can a field available at a given resolution be used at a higher spatial resolution, either directly or through disaggregation techniques ?
- How can the errors inherent to coarse resolution fields produced by large scale models or remote sensing be taken into account when used as inputs to higher resolution models (either directly or through disaggregation techniques) ?

(f) Climate impacts and decision making

The local scale is the relevant scale for considering climate impacts.

Key Questions:

- What are the climatic and environmental determinants of specific measurable outcomes of interest to public health, food security, and water resource management in West Africa?
- Which of these can be routinely monitored and/or predicted and how can their spatial, temporal scale and relevance to the problem be improved with new knowledge?
- How can climate information be made available to decision makers such that they can use the information to change policy and practice in order to improve resource allocation and outcomes in climate sensitive sectors.

3.3 Scientific Strategy

3.3.1 Integrative Science

Key objectives and planned research activities for each scale have been formulated for AMMA. While it is convenient and appropriate to describe the research plans in terms of these different spatial scales, it is essential for an improved understanding to study the scale and process interactions. The implementation of AMMA is designed in this spirit. The AMMA project integrates the scales at which the geophysical and human processes interact. Also the various disciplines involved in the study of the West African Monsoon need to be integrated to achieve the three overarching aims. This approach has guided the structuring of the scientific objectives.

From the geophysical perspective, the fundamental science underpinning the AMMA project can be viewed as the various disciplines coming together within broader integrative science topics: i) the interactions between the WAM and global climate from a physical as well as a chemical perspective, ii) the water cycle of the WAM from the regional to the local scale and iii) the coupled atmosphere-land-ocean system and its multiple scales. To feed these integrative topics with sound disciplinary knowledge of the processes and their scale dependence detailed studies of the processes are needed: i) atmospheric processes with a focus on the convective processes which are key to the rainfall production, ii) oceanic processes as they contribute and depend on the WAM, iii) biophysical processes over the continent from the regional to the local scale and iv) aerosol and chemical processes in the atmosphere.

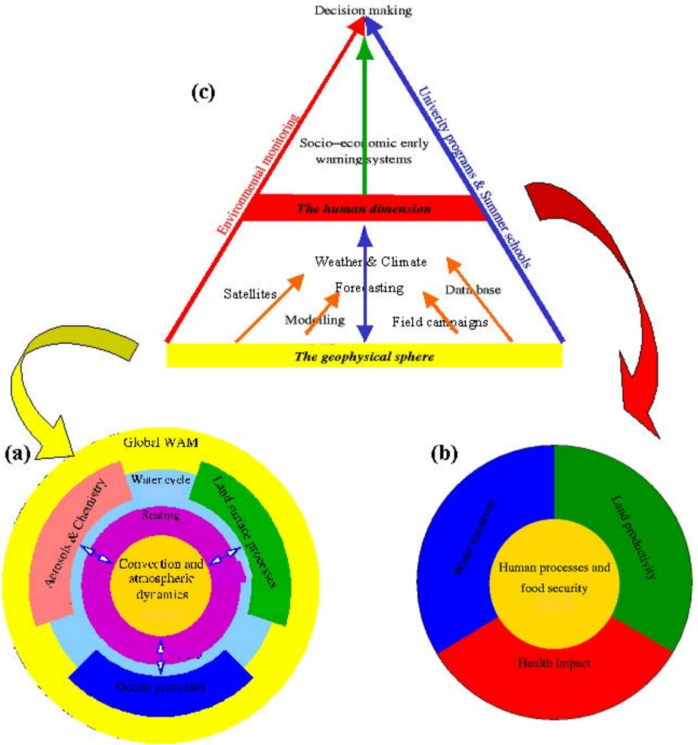


Figure 3.2 Implementation of AMMA: Integrative science for (a) the geophysical dimension, (b) the human dimension and (c) integration of this knowledge through various tools for the exploitation of impact studies

To study the human dimension of the variability and possible trends in the West African Monsoon AMMA aims to address the direct impact of the environmental conditions on three limiting conditions for the African societies: i) Land productivity, ii) water resources and iii) health impacts. This activity will be coordinated to achieve a better understanding of how weather and climate variability impact food security and human processes in the region.

To achieve the AMMA objectives and to master the challenge of providing a multi-scale and multi-disciplinary analysis of the WAM, an integrated set of tools and methods will be adapted to the problem of the West African Monsoon:

- ***Field Programme:*** Enhancements to the current sustained observing system are planned to address the overarching aims raised in section 3.1 and the science questions raised in section 3.2. The extra in-situ observations in the multi-year AMMA field programme have been planned according to scale to facilitate integration of disciplines. Extra in-situ observations are planned at local-to-regional scales within the core AMMA region that encompasses West Africa and the tropical eastern Atlantic (Fig. 3.3). To achieve the complete multi-scale analysis required, these observations will be integrated with satellite and modelling activities.

- ***Satellites:*** Satellite-derived geophysical parameters and their uncertainties will be produced at different scales and gathered in a unique database allowing multiscale as well as multidisciplinary analysis of the WAM and its variability. The unique set of integrated in situ observations provided during the AMMA field programme will be used to validate satellite products at local-to-regional scales. This is important for extending the analysis of the WAM beyond the location of in-situ observations and through increasing the value of multi-year observations in the region, key for studies of climate and its variability. It will also provide the framework to build a reliable monitoring strategy combining satellite and in situ atmosphere/land/ocean networks, to make up for the low density of routine observations in and offshore Africa.

- ***Models:*** As in the case of satellites, models offer an ideal tool for integrating the in-situ observations made during the AMMA field programme. Through data assimilation efforts regional analyses of the WAM can be provided that extend the analysis of the WAM in space and time. The in situ observations also provide us with an opportunity to evaluate the quality of the current analysis products and data assimilation approaches and the value of the in-situ observations. Integrating this effort with the satellite activity is crucial for defining and building a sustained observing system for monitoring and predicting the WAM and its variability. In addition to this, the in situ observations will be combined with a hierarchy of modelling approaches at local-to-global scale to investigate key process operating in the WAM and to assess the extent to which these processes are adequately represented in models used for weather and climate prediction.

- ***Database:*** An essential part of the AMMA programme is the establishment of the AMMA database. All data will be collected and distributed from a central database, that will be achieved with the needs of both the geophysical and human dimension communities in mind. Indeed, the database is a key aspect for transferring knowledge and relevant geophysical data from the geophysical community in AMMA to the activities in the human dimension.

AMMA will strive to use the above tools and activities to collect and consolidate knowledge, integrate the knowledge and materialize the predictive skill gained with this knowledge. Each of these tools and their role in AMMA will now be described in more detail.

3.3.2 Field Programme

The AMMA field programme will provide enhancements to the current sustained observing system in West Africa and builds on the CATCH hydrological experiment that has been ongoing successfully in the region since 1997. The CATCH observational "window", indicated in Fig. 3.3 by solid lines, includes 3 mesosites that sample contrasting environments across the marked north-south gradient in surface conditions. This "climate transect" is at the heart of the AMMA field programme. Extra in situ observations will be made at the mesosites and along the climate transect within the broad CATCH window to address science issues at local-to-regional scales. In addition, AMMA will provide enhancements to the regional observing system over West Africa and in the Gulf of Guinea to support this analysis at regional scales and to extend the climate transect into the Atlantic, key for understanding the coupled WAM system.

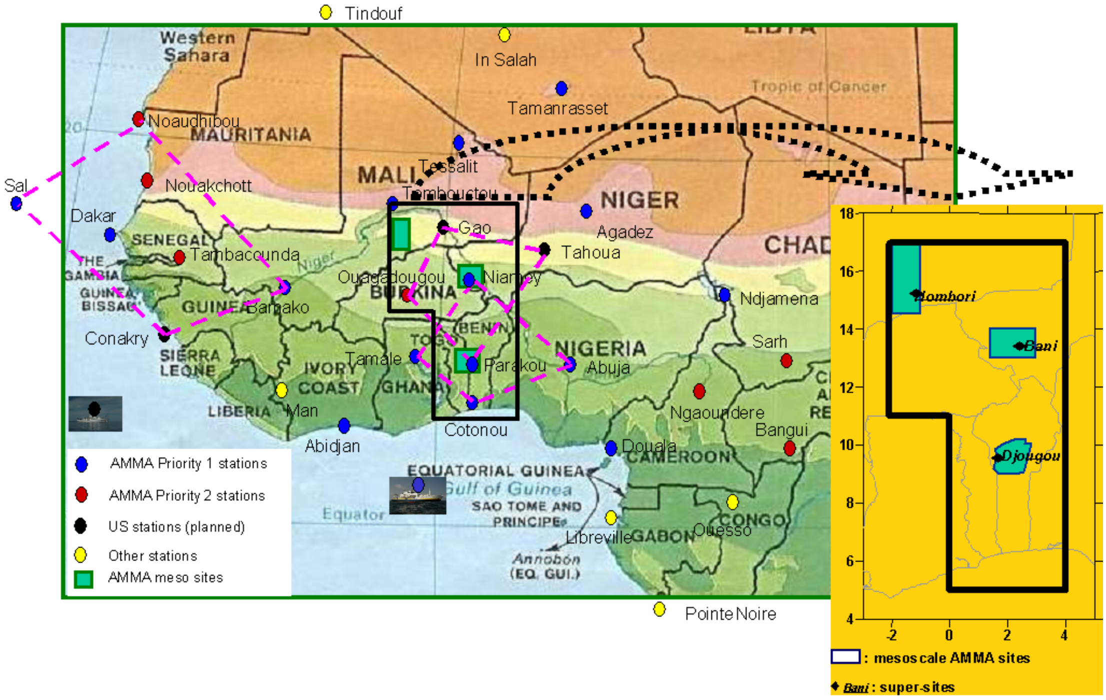


Figure 3.3 Field implementation of AMMA observations based on nested networks. Circles indicated the atmospheric sounding network activated during the SOP.

AMMA is planned to be a multi-year project and consists of 3 nested observing periods :

- **The Long term Observing Period (LOP)** is concerned with observations of two types: (i) historical observations to study interannual-to-decadal variability of the WAM (including currently unarchived observations) and (ii) additional long term observations (2002-2010+) to document and analyse the interannual variability of the WAM.

- **The Enhanced Observing Period (EOP)** is designed to serve as a link between the LOP and the SOP (below). Its main objective is to document over the climatic transect the annual cycle of the surface conditions and atmosphere and to study the surface memory effects at the seasonal scale. The EOP will be 2-3 year duration (2005-2007).

- **The Special Observing Period (SOP)** will focus on detailed observations of key processes during the winter of 2006: (i) SOP-0, Dry Season (Jan-Feb 2006) and at key stages of the rainy season during the summer of 2006: (i) SOP-1, Monsoon onset (15 May-30 June), (iii) SOP-2, Peak monsoon (1 July – 14 August) and (iv) SOP-3, Late monsoon (15 August-15 September).

The enhancement of observations during these periods will provide a unique opportunity to determine future operational monitoring necessary to improve weather and climate forecasts in the West African region. More than this, a high priority for AMMA is to establish this operational network of observations.

A brief summary of the different observing periods, their main objectives and strategy is now described. More detailed information regarding the different field phases is available in the AMMA Implementation Plan.

(a) Long term Observing Period (LOP)

The main objective of the LOP is to provide observations needed to support the analysis of the WAM on seasonal-to-interannual timescales. Multi-year observations of the atmosphere, land and ocean are required to document the coupled WAM system and its variability. While practical considerations have led to a particular focus on seasonal-to-interannual timescales, efforts will be made to provide observations of the coupled WAM system on multi-decadal timescales to support assessments of the nature and causes of long-term trends and regional climate change.

Central to the LOP observing strategy is the CATCH hydrology project. CATCH has established enhanced observations in the "CATCH-window" depicted in Fig. 3.4 to support the long-term monitoring of the surface component of the continental water cycle. It includes 3 mesosites with enhanced observations of rainfall, hydrology, surface and subsurface conditions. The Oueme catchment, in the Sudan, experiences frequent rain events during the summer and has lush vegetation. The Niamey region, in the Sahel, experiences more intense but fewer rain events during the summer and is semi-arid. The Mali site, in the northern Sahel is also semi-arid and is even drier on average than Niamey. These contrasts are linked to the strong meridional gradients in surface conditions that characterize this region and the associated monsoon dynamics that influence the poleward extent of the WAM rainfall.

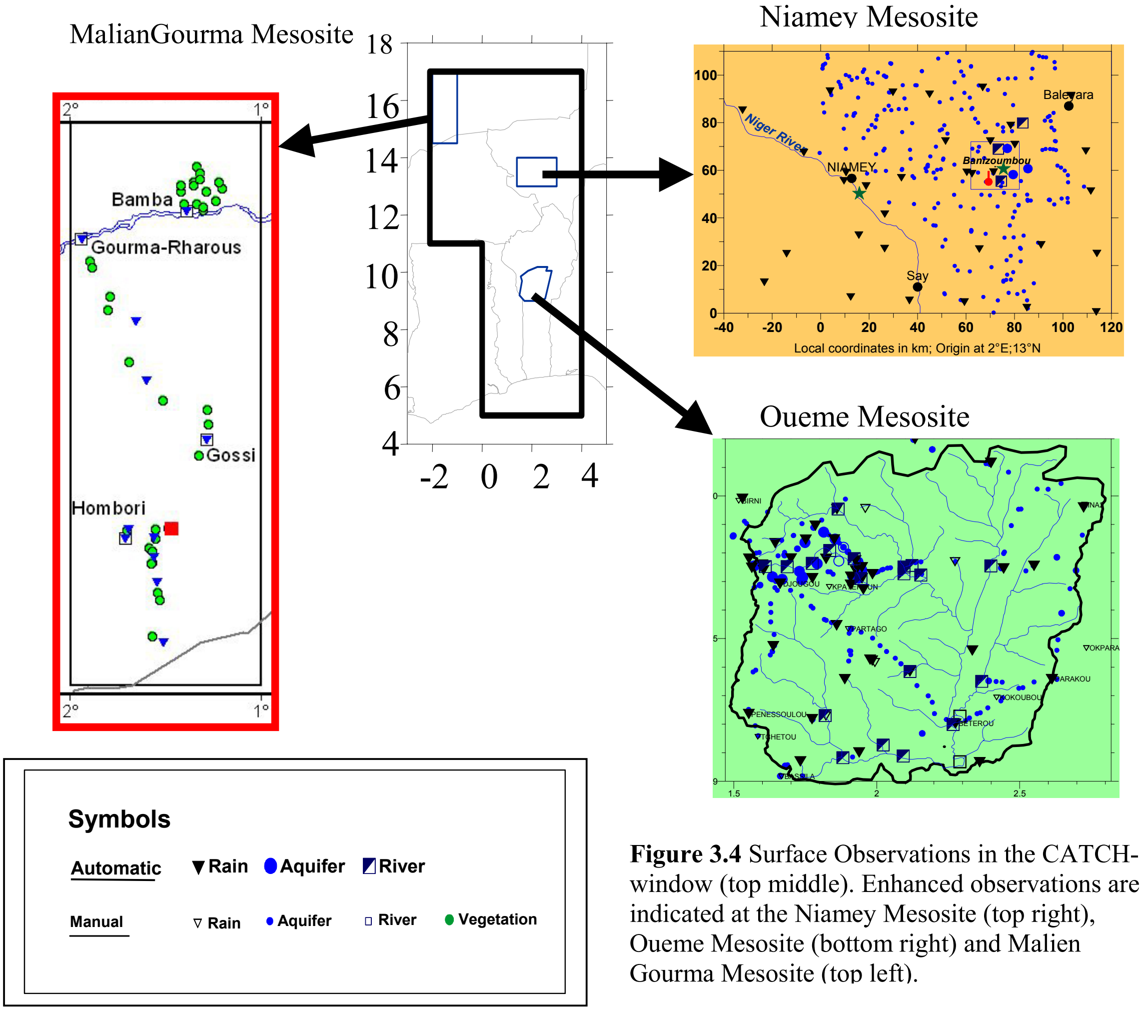


Figure 3.4 Surface Observations in the CATCH-window (top middle). Enhanced observations are indicated at the Niamey Mesosite (top right), Oueme Mesosite (bottom right) and Malien Gourma Mesosite (top left).

In addition to data from the mesosites, AMMA will ensure that data from current operational networks (e.g. radiosoundings, surface observations, satellite products) collected during the LOP are made available to the scientific community involved in the project. In parallel to the operational networks, there are several pre-existing long term observing systems already operating in the WAM region. Table 3.1, lists the systems that are most relevant to AMMA. Although these observing systems are relevant to the AMMA programme, at present most are not adequately coordinated with studies concerned with the WAM. A major part of the LOP-strategy is to entrain these observing systems into the AMMA programme and include the relevant observations in the AMMA database.

Through the LOP AMMA will ensure that the intensive activities are directed towards systematic improvements in monitoring and prediction over the coming decades. We will develop and upgrade two important land-based atmospheric monitoring systems (for the upper air and surface fluxes), and over the LOP we will transfer responsibility for these networks to the local African agencies. In addition, ocean monitoring systems surrounding West Africa that have been shown to improve both weather and climate forecasts will continue to provide data to these groups. These networks of observations are of enormous value both to global prediction systems and to local forecasting systems, based in Africa.

Table 3.1 Long-term monitoring projects in the WAM Region

Project Name	Starting Date	Parameters	Spatial scale	International Network
PHOTONS	1993	Aerosols	Sahelian transect of 5 stations	AERONET
CATCH	1997	Continental Water Cycle	3 mesoscale areas included in a sub-regional window.	GEWEX-CSA
IDAF	1994	Atmospheric chemistry	5 stations distributed over the region.	IGAC
IMPETUS	1999	Hydrology, Vegetation	Ouémé catchment in Benin.	GLOWA
GLOWA-VOLTA	1999	Hydrology, water resources	Volta catchment	GLOWA
GLOBALSAV	1984	Vegetation	Lamto in Ivory Coast	
African Lightning Network	2004	Location and polarity of cloud-to-ground lightning	Bulk of continent and adjacent waters	GEWEX
CORIOLIS	2003	Oceanic T/S profiles	Tropical Atlantic	ARGO
SSS	1992	Sea surface T/S	Tropical Atlantic	SOOP
ARGO	1998	Temperature and Salinity, profiles to 1000-2000m	Global (3x3 array)	International ARGO Science Team
Global Drifter Program	1979	Sea Surface Temperature, sea level pressure, surface winds on some drifters	Global (5x5 array)	WMO/IOC Data Buoy Cooperation Program
Low density XBT	~1970	Temperature profiles to 450m	Transect from S. Africa to NY and Transect from Mediterranean to S. Africa	WMO/IOC Ship of Opportunity Implementation Panel
PIRATA Array	~1998	Surface met. Observations, subsurface temperature profiles	Tropical Atlantic	PIRATA & TIP

(b) Enhanced Observing Period (EOP)

The main objective of the EOP is to provide and coordinate observations that support analysis of the seasonal-to-interannual variability of the coupled atmosphere-land-ocean WAM system building on the LOP-observing system. The EOP is defined to highlight those multi-year observations that are important but not sustainable for more than a few years. In particular the EOP aims to document over the climate transect the annual cycle of the surface conditions and atmosphere and to study the surface memory effects at the seasonal scale. The EOP will last for 3 years and shall be centered on the SOP in 2006.

The overall observing strategy for the EOP is to enhance the observations of the atmosphere, land and ocean along the ‘climate transect’ that includes the CATCH hydrology project. The CATCH observations provide observations to support analysis of the continental water cycle over the mesosites. However, additional observations of the atmosphere are required to support the analysis of the WAM, for integrated water cycle studies and analysis of the rain-producing weather systems. Enhancements to observations of the atmosphere will be made during the EOP through provision of: (i) extra radiosoundings in the West African region including along the climate transect (Fig. 3.3), (ii) new surface flux measurements along the climate transect (Fig. 3.4) sampling various conditions (Desert, Laterite, Grassland, Open Forest, Culture, ...) and (iii) ground-based remotely sensed observations (e.g. radars, profilers). In addition to these atmospheric observations there will be enhanced hydrological (underground water fluxes, soil moisture), vegetation, aerosol & trace gas monitoring. During the EOP, ocean observations will also be made in the Gulf of Guinea to extend the climate transect into the ocean needed for a complete analysis of the coupled WAM system. The enhancements to the observing system during the EOP will support the analysis of the WAM from local to regional scales.

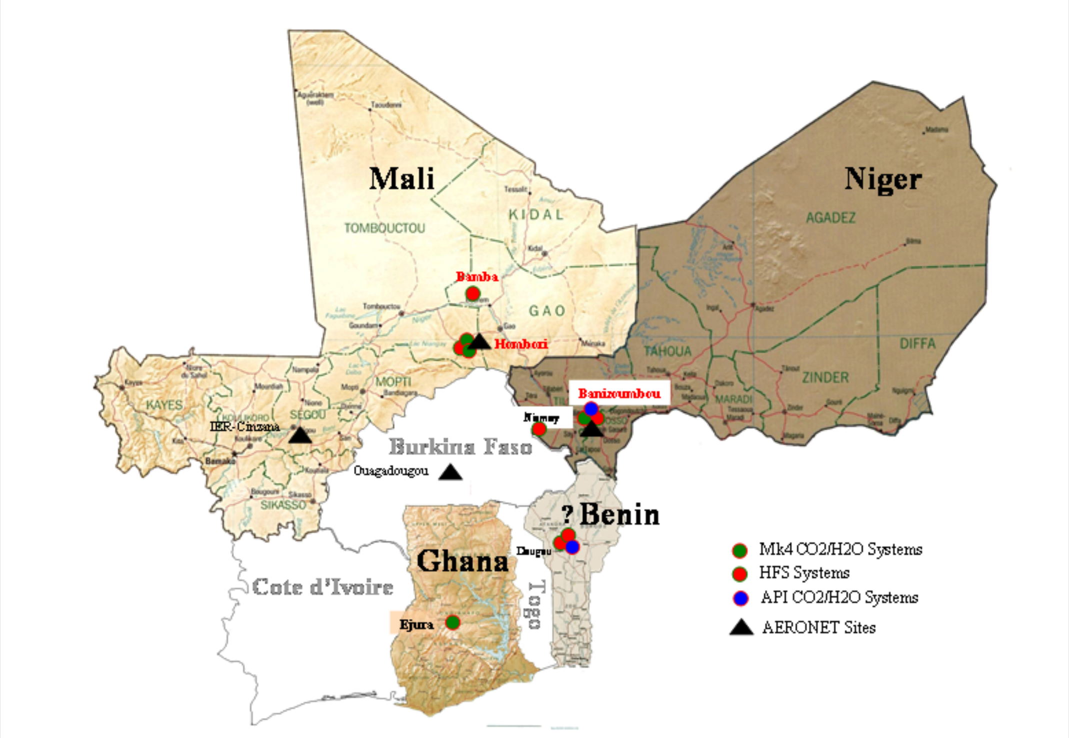


Figure 3.4 AMMA surface flux network activated during EOP.

(c) Special Observing Period (SOP)

Embedded within the multi-year framework provided by the LOP/EOP is the Special Observing Period (SOP). Detailed studies of key processes, impractical to study in a multi-year framework, will be carried out within the SOP. The special measurements proposed during the SOP, combined with those established through the LOP/EOP will provide the international community with an invaluable set of observations to investigate the multiple-scale interactions and processes that determine the nature of the WAM and its variability.

Observations of key processes will be made during the winter of 2006: (i) SOP-0, Dry Season (Jan-Feb 2006) and at key stages of the rainy season during the summer of 2006: (i) SOP-1, Monsoon onset (15 May-30 June), (iii) SOP-2, Peak monsoon (1 July – 14 August) and (iv) SOP-3, Late monsoon (15 August-15 September). This naming convention has aided international discussions and planning but it should be recognized that process studies will take place across more than one sub-period. Here we briefly describe the overarching objectives and observing strategies for SOP-0, SOP-1, SOP-2 and SOP-3.

- ***SOP-0: Dry Season***

  The SOP-0 measurements will concentrate on in-situ and remote sensing measurements of aerosols and their effects on solar and terrestrial radiation. During the dry season, anthropogenic biomass burning occurs on a wide scale across the region. In addition windblown mineral dust events frequently result in a complex and poorly understood mixing of mineral and biomass burning particles. These particles play an important role in determining the surface and top of the atmosphere radiation budgets with subsequent effects on dynamical evolution. Additionally aerosols have detrimental impacts on human health via their effects upon the respiratory system. Because the biomass burning particles are essentially of anthropogenic origin, they may exert a significant but poorly quantified radiative forcing of climate and may therefore play a role in climate change.

  Special observations are required to validate (i) satellite retrievals of intrinsic aerosol properties that have recently been developed over land surfaces (ii) aerosol modules that have been developed for inclusion in climate and numerical weather prediction models (iii) surface based retrievals of aerosol properties such as those from the CIMELS sunphotometer sites. In addition, concurrent aircraft, surface based and satellite observations of the radiation budget will allow synergistic assessment of radiation in the atmospheric column to be assessed. Three aircraft will be deployed in the operating area during the SOP-0 period together with surface observing instrumentation sites including lidar measurements, the ARM Mobile Facility and enhanced radiosonde launches.

- ***SOP-1: Monsoon Onset***

  The focus of SOP-1 is on providing the necessary observations required to support analysis and understanding of the seasonal evolution of the low-level thermodynamic contrasts along the climate transect (including the Gulf of Guinea), their relationship with regional circulations (e.g. jets and direct circulations) and atmospheric and continental water budgets (at local to regional scale). Surface energy budgets over land and ocean are required to support this analysis including how these are impacted by evolution of the land surface (vegetation, soil moisture) and the ocean (mixed layer).

  Special observations are required to support this analysis in addition to those provided by the EOP: (i) atmospheric boundary layer thermodynamic variables and winds over land and ocean will be made by in aircraft and boundary layer drifting balloons observations (in addition to radiosoundings and surface flux measurements provided by the EOP) (ii) high resolution observations of the ocean mixed layer and atmospheric boundary layer will be made from two ships cruising in the Gulf of Guinea and (iii) additional moored buoys and drifters will be deployed to provide extra ocean surface observations extending the coverage provided by the ships.

In parallel with the evaluation of the energy budgets, concentrations and fluxes of trace gases and aerosols at the surface (including emission and deposition) and in the atmosphere will be made, and compared with the results before and after the arrival of the monsoon flow.

- ***SOP-2: Peak Monsoon***

The seasonally evolving surface conditions, low-level thermodynamic contrasts and associated regional circulations will continue to be observed during SOP-2. In addition to this, SOP-2 has key objectives concerned with supporting the multi-scale analysis of the WAM. A major objective of SOP-2 is to provide the observations needed to support mass, momentum and water budgets at the mesoscale (~100km). The SOP-2 is also the key period to focus on the multiple scale interactions between the surface conditions, synoptic environment and propagating MCSs including the role played by microphysics on convection and how this is impacted by aerosol. The role of the MCSs and monsoon on aerosol and trace gas mobilisation and transport will be specifically investigated.

The overall AMMA observing strategy over the continent during SOP-2 will consist of an enhancement of the surface and atmospheric observations along the climate transect. This will be supported by observations from at least 4 aircraft, driftsondes (with dropsondes) and remotely sensed data from Doppler and microwave radars, sodars and satellites. Through such enhancements the CATCH hydrology experiment will be developed into a 3D multi-scale observing system to support the analysis of the seasonal evolution of the coupled WAM system, the diurnal cycle, AEWS, embedded convective and mesoscale precipitation systems and water, heat and momentum budgets. Aerosol and radiative characteristics of clouds will be made using aircrafts.

- ***SOP-3: Late Monsoon***

The seasonally evolving surface conditions, low-level thermodynamic contrasts and associated regional circulations will continue to be observed during SOP-3 as the monsoon retreats equatorwards, although greater emphasis in SOP-3 will be given to the eastern tropical Atlantic just downstream of West Africa. The SOP-3 is also focused on how the WAM impacts the downstream tropical Atlantic both through providing the “seedlings” for tropical cyclones and through the export of trace gases and aerosols and their subsequent contribution to the global oxidising capacity and radiative forcing on a global scale.

The nature of the synoptic and mesoscale systems downstream of the continent will be observed through a combination of research aircraft operating out of West Africa and the Caribbean and dropsondes from the driftsonde system. This strategy will allow an unprecedented opportunity to study the evolution of developing and non-developing tropical disturbances from their origin over the continent to the Atlantic and potentially as far as the Caribbean and will contribute to improved understanding of how the WAM interacts with the Atlantic.

3.3.3 Satellites

Satellite data represent a way to access at a comprehensive dataset over west African continent from daily to interannual scales. Nevertheless, geophysical products determined from various satellite sensors need to be carefully validated with field measurements. In this respect, satellite measurements are complementary as they enable us to spatialize field measurements at larger scales. Satellites will thus contribute to various objectives of the project both for process analysis and for large scale -long term studies : some series of satellites (Meteosat, NASA) have been flown for more than 20 years, ensuring a good quality monitoring of some of the West African atmosphere and surface characteristics. Moreover, several recent missions, and several projects will strongly improve and complement this survey. In fact, the setup of a multi-scale observing system over the AMMA region will provide a unique opportunity for numerous satellite validations over continental tropical areas. Numerous parameters can be derived from satellite observations, and considerable work has been done in the last decades to improve the retrieval methods and most of the products are already available. However, all products have not the same quality, and few have been calibrated/validated over tropical continental areas. The calibration/validation of the satellite algorithms over the relevant areas and time periods will allow to define an unique database optimized for the West African region. The comparison of satellite data will allow to better estimate the uncertainties in function of the time space scales and of the method used and to choice which datasets satisfy the AMMA purposes and to identify the datasets that should be improved. The existing and developmental satellite climatology of key parameters (e.g. cloud classification) will be compared and tested. A methodology will be agreed and used to generate synthetic data.

The main objective of the satellite activity in AMMA is to provide for all AMMA scientific topics, data sets of the relevant parameters at the different scales derived from satellite measurements. These data sets will include the corresponding errors estimates, in order to be able to quantify the quality of the further thematic analyses (for example water & energy budgets), and to allow proper assimilation in models. Special care will be given to the formatting in order to facilitate the use in process studies, model validation, model assimilation. The structure of the AMMA satellite database will follow a scale logic (rather than a discipline one) in part to avoid discipline barriers.

Figure 3.5 shows the study domains corresponding to nested domains with different resolutions necessary to allow optimal use and archive of data. The global scale with coarse resolution is needed for climate studies (e.g. role of SST anomalies on the WAM) whereas the main interest of Atlantic-Africa domain (in red) will be to study the export of species (aerosols and chemical) and the role of land-ocean contrasts of moist and static energy and associated regional circulations on the WAM. The regional domain of West Africa is the central domain of AMMA where the best resolution will be kept in regard to the archiving possibilities. Three mesoscale domains are also considered. They correspond to the three mesosites of ground field experiment.

The temporal resolution of each product will first be chosen in regard to the satellite sensor resolution, then following the considered spatial scale and the variability of the geophysical parameter. For large scale domain, temporal resolution can vary from few hours to month. For small scale domain, the higher resolution allowed by the sensor sampling will be kept.

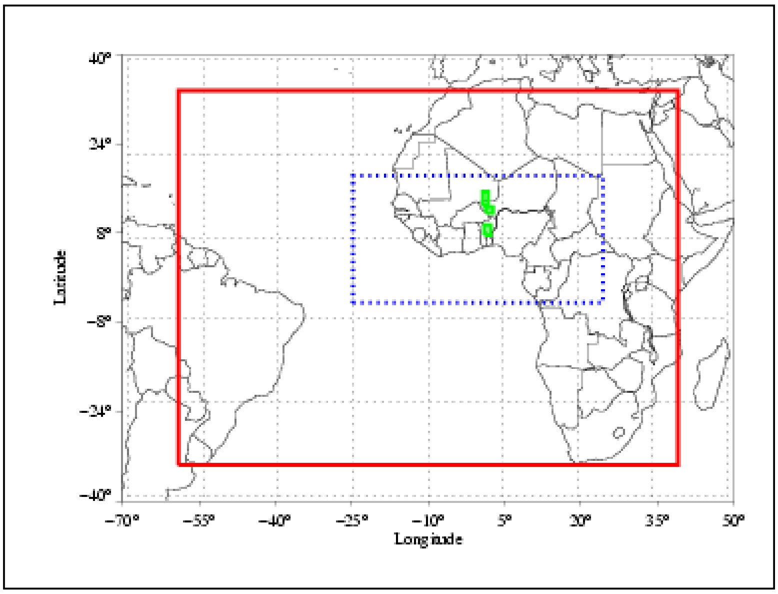


Figure 3.5 Localization and resolution of domains where geophysical products will be retrieved from satellite measurements

Region	Domain	Resolution
Global	180° W / 180° E 90° S / 90° N	2.5°, 1.0°
Atlantic – Africa	60° W / 40° E 35° S / 35 °N	0.50 °, 0.25 °, 0.10°
West Africa	25° W / 25° E 5° S / 20 °N	0.1°, 0.05°, 0.01°
Mesoscale Zones:		
Upper Ouémé Basin (Bénin)	1.30° E / 2.48° E 8.54° N / 10.12°	1 km, 100 m, 1 m, ...
Niamey mesosite & Kori basin (Niger)	1.6° E / 3.0° E 13° N / 14.15° N	
Gourma Area (Mali)	1° W / 2° W 14.3° N / 17.0° N	

The first selected variables relevant to satellite restitution are the following :

- Precipitation
- Cloud cover analysis and cloud motion winds
- Mesoscale Cloud Systems tracking and statistics
- Water vapour
- Radiative fluxes
- Land surface properties
- Sea surface properties and fluxes
- Aerosol and atmospheric chemical components

A list of specific parameters and satellite sensor in regard is given on table 3.2. That corresponds to products which are either operationally available, or to be developed within the next years for AMMA. This preliminary list will be completed using other sensors & longer time periods.

Table 3.2 Provisional list of geophysical products retrieved from satellite measurements

Sensors	*Product*	*Horizontal Resolution*	*Time Resolution*	*Area*	*Time Window*	*Availability*
POLDER MODIS AVHRR	FAPAR, LAI, NDVI	1 km x 1 km and 16 km x 16 km	10-days Month	West Africa	1998-2000 Since mars 2000 Since 1981	
SPOT-4	Land Use Map	100 m x 100 m	2 scenes	Donga Watershed	18/02/2000 and 04/11/2000	Validated Product
SAR (ERS) + SPOT + LANDSAT	Land Use Map, LAI	100 m x 100 m	Month	Oueme Watershed, Niamey square degree, Gourma area (Mali)	1992-2000	Research product (end 2005)
VEGETATION	Inter-annual variability of land use	1 km x 1 km	10-days	West Africa	1998-2000	Research product (end 2005)
MOPITT/TERRA	CO integrated content & profile	22 km x 22 km vertical : 3 km	1-day	Global	03/2000 To 05/2001	
SEAWIFS + POLDER	Sea surface color	4 km x 4 km	1-day	Global	Since 09/1997	
MSG	Over Ocean : SW/LW surface fluxes, SST, surface wind	3 km x 3 km	30 minutes	West Africa	2004-2005	SAF Ocean
TRMM sensors	Surface rainfall, and hydrometeor concentration / type profile	16 km x 9 km and 4 km x 4 km	1-day	Global	since 11/1997	Standard product. Validated, but of poor quality over land
TMI SSM/I	SST, surface wind, WV content, cloud liquid water content	0,25° x 0,25°	1-day	Global	1987-2004	Operational
SSM/I + TOVS + radiosondes	Precipitable water 3 layers (surf.-700, 700-500 et 500-300) (NVAP)	1° x 1°	1-day	Global	1988 - 1997	
MSG-TRMM	Surface Rainfall	3 km x 3 km	30 minutes	West Africa	2004-2005	Research product (end 2005)
METEOSAT	Free Tropospheric Humidity (FTH)	30 km x 30 km	3-hours	60° S / 60° N 60° W / 60° E	1983 - 2004	Research product (end 2005)
ERBE, ScaRaB CERES, Meteosat	LW, SW and Net fluxes	2,5° x 2,5°	Month	Global	1984-2004	
MSG	Over land : Albedo, SW/LW surface fluxes, Surface temperature	3 km x 3 km	30 minutes	West Africa	2004-2005	SAF Land
MODIS POLDER METEOSAT TOMS	Aerosol optical thickness & size distribution	10 km x 10 km 18 km x 18 km 30 km x 30 km 1° x 1°	1-Day Month	Global	Since 2000 11/1996 – 06/1997 1997-2000	

3.3.4 Modelling Studies in AMMA

(a) Introduction

AMMA aims to provide an improved understanding of the variability of the WAM and its impacts on daily-to-interannual timescales. Research carried out in AMMA will serve as the basis for improving models and designing an efficient sustained observing system necessary for future research and prediction at these timescales. A range of modeling activities will take place within the international AMMA program to support these aims:

- Data Assimilation and Reanalysis
- Modeling of Weather
- Modeling of Climate
- Coupled Modeling of the Earth System (Aerosol and Chemistry, Hydrology and Vegetation)
- Modelling of Impacts

The AMMA project will link strongly with prediction activity at two key timescales: (a) 1-5 day and (b) seasonal-to-interannual. The datasets obtained in AMMA will provide a unique opportunity to assess the ability of models to predict the WAM and its impacts at these timescales and to evaluate and improve key parameterizations.

(b) Data Assimilation and Reanalysis

A major deliverable of the AMMA program will be the provision of improved analyses of the WAM and the tropical Atlantic. Observations of the atmosphere, land, ocean and aerosol will be used to create reanalyses of the WAM and the tropical Atlantic to support the science objectives highlighted in section 3. While separate reanalysis efforts will take place for the individual components of the WAM system, the AMMA observations will offer an opportunity for coupled reanalysis efforts of the atmosphere, land and ocean. The enhanced observations and data assimilation systems will enable us to carry out a host of observing system simulation experiments (OSSEs) that will support research on the utility and efficiency of the observing system, allowing recommendations to be made for future sustained observing networks.

Data assimilation and reanalysis efforts will focus on the following areas:

- ***Atmosphere :*** Efforts will be made to have as much of the atmospheric data on the GTS in real time although this will not be achieved for all data. It is inevitable therefore that special atmospheric reanalyses will be necessary to take advantage of all data. These will include high-resolution regional reanalysis efforts that will take advantage of the enhanced observations over the West African continent. It is particularly important to assess the benefits of the enhanced West African soundings available during AMMA through focused OSSEs.

- ***Land surface conditions:*** Initialization of land surface conditions in models used for weather and climate prediction is extremely important. New methods (LDAS for Global Land Data Assimilation Scheme) have been recently developed based on high-resolution land data assimilation schemes using relevant remotely sensed and in-situ observations. North American (NLDAS), European (ELDAS) and Global (GLDAS) LDAS systems have been developed. Similar efforts are proposed over the West African region to provide an African LDAS (ALDAS). Such reanalyses will take advantage of the enhanced surface observations in the CATCH region.

- ***Ocean conditions:*** A number of reanalyses are now becoming available under the auspices of CLIVAR and GODAE. A purpose of these reanalyses is to allow examination of the ocean circulation taking best advantage of the limited observational network in analogy to, and perhaps in conjunction with atmospheric reanalyses. The analyses include those produced by the National Centers for Environmental Prediction, Global Ocean Data Assimilation System, the European Center for Medium Range Weather Forecasts, GFDL, the UMD Simple Ocean Data Assimilation, ECCO, and MERCATOR. Methods range from 3Dvar and OI to an effort involving a full 4Dvar. Most concentrate on the past few years and are motivated by the needs of operational forecasting. Early comparisons among analyses suggested substantial disagreement in the Atlantic in contrast to the Pacific (Chepurin and Carton, 1999) and these differences persist. The cause of these differences is still unclear, but may be due to the importance of salinity (which is badly undersampled), and is made much worse by the generally limited observational network. The observations proposed in AMMA provide an opportunity to investigate and assess data assimilation efforts in the tropical Atlantic.

- ***Aerosol:*** Gases and aerosols in West Africa and over the Atlantic represent a complicated superposition of contributions from different African source regions (oceanic, biomass burning, urban pollution, and desert). Chemistry and aerosols models have to take into account this variety and to evaluate and improve the representation of their sources in all models. Data from satellite missions dedicated to gases and aerosols (including the CALIPSO aerosol lidar) will be available. Several groups are currently developing 3D or 4D variational assimilation schemes to assimilate chemistry fields using these satellite data (e.g. MOPITT).

(c) Modelling of Climate

The extra in-situ observations over the land and ocean made during the multi-year field programme combined with routine observations and satellite observations will be used to investigate the nature of the WAM, its variability and causes. Emphasis will be given to using models to better understand key processes for the coupled WAM system including the annual cycle, diurnal cycle, scale interactions and surface feedbacks. A variety of modeling activities will be promoted to support this analysis. Specific modeling strategies will be developed and coordinated by a modeling working group. In general we expect that this will include:

- AMIP-type (multi-year) and PROVOST-type (seasonal prediction) experiments will be carried out using GCMs with observed SSTs to explore variability and predictability issues of the WAM.
- Coupled GCMs will be used to investigate coupled atmosphere-land-ocean processes and to assess their ability to predict the WAM variability.
- Specific modeling experiments will be setup to investigate the role of land surface processes in determining the nature of the WAM and its variability.

AMMA strongly encourages the ongoing research on decadal prediction. AMMA's observational contribution to this activity will come from the LOP in particular through the development of the historical archive of surface conditions and the promotion of new sustained observations for future monitoring. Modelling activity will use these surface observations to assess the role played by land surface conditions on decadal variability last century.

AMMA recognizes the need for assessments and predictions of climate change in the West African region. AMMA can contribute to this modeling activity through providing an evaluation of dynamical models used for climate change prediction in the WAM region at daily-to-decadal timescales. This will allow some assessment of our ability to model the regional climate on longer timescales. This information will be communicated to the IPCC in order to analyze the model uncertainties in the different scenarios of future climate change, especially due to the biases in the ocean-atmosphere coupled models, the lack of dynamic vegetation, and the various insufficiencies in the parametrization of atmospheric processes. Presently the scenarios for the Sahel region are ambiguous (Hulme et al. 2001) whereas since the 2001 IPCC report, some modeling studies suggest that the global warming would induce a wetter regime in the Sahel and southern Sahara (Brooks 2004, Hoerling et al, 2005).

AMMA recognizes the need for assessments and predictions of climate change in the West African region. AMMA can contribute to this modeling activity through providing an evaluation of dynamical models used for climate change prediction in the WAM region at daily-to-decadal timescales. This will allow some assessment of our ability to model the regional climate on longer timescales. This information will be communicated to the IPCC.

(d) Modelling of Weather Systems

The extra in-situ observations made during the SOPs combined with routine observations and satellite observations will be used to investigate the nature of the weather systems and associated physical processes. Key weather systems that will be considered include mesoscale convective systems (MCSs), African easterly waves (AEWs) and tropical cyclones (TCs). It is understood that throughout this analysis there will be a requirement to investigate how model parametrisations handle unresolved scales. Rather than focus on individual parametrisations AMMA will promote a philosophy that considers all relevant parametrisations in the context of the weather systems of interest. A variety of modeling approaches will be used to support this analysis:

- Atmospheric GCMs and RGCMs will be the major tools for providing analyses and forecasts of the various cases that will be investigated. They will be particularly useful for investigating the synoptic systems including the AEWs, jets and monsoon flow and associated physical processes. They will be used to help understand the synoptic evolution in the CATCH region that will support the work with CRMs below.
- Cloud resolving models (CRMs) will be used for studying convection and in particular the MCSs observed during the SOPs. This work will be combined with column model studies and investigation and assessment of parametrisations.
- Idealised models will continue to be used to help interpret the observations and more sophisticated models above. This will include adiabatic models, balanced models and models of intermediate complexity that include simplified physics.

(e) Coupled Modeling of the Earth System

AMMA offers a great opportunity to improve our understanding of the coupled dynamics of the Earth-system operating in the WAM region. AMMA will focus on the following key areas of study:

Hydrology and Vegetation

Various SVAT (Soil Vegetation Atmosphere Transfer) have been developed for use in GCMs, RGCMs, NWP models, coupled atmospheric-hydrological models and large scale hydrological models. SVAT models require a large number of soil and land surface parameters controlling the vertical fluxes at patch, regional and larger scales. To simulate the hydrological cycle (surface runoff, percolation to groundwater and river flow), hydrological models need as an input rainfall and potential evaporation data and provide as an output overland flow, impermeable area runoff, soil moisture storage, groundwater storage, and actual evapo-transpiration.

Both hydrologic and biospheric models face various difficulties: scaling incongruities between atmospheric, hydrological and terrestrial components, advection, mixing and redistribution of mass and energy at sub-grid scales, validation of the models at appropriate space and time scales. Thus there is a crucial need for improved characterization of soil and land surface properties at regional and global scales. This involves aggregation over heterogeneous surface. The modeling of SVAT, water balance, and precipitation-runoff processes at a range of space and time scales are key issues for the integration of land-surface processes in atmospheric models and hydrological processes in large catchments. Within a numerical grid element topography, vegetation characteristics and soil characteristics will exhibit spatial variation. Effective parameters representing the integrated behavior of the processes over the scale of a numerical unit are thus required, following a multi-scale approach similar to the atmospheric models.

Distributed catchment models require specification of the relevant parameters at every spatial unit included in the model. Obviously, this information can rarely be established from traditional point measurements and monitoring networks. Therefore satellite and radar derived spatially distributed data on vegetation characteristics, soil moisture and precipitation will be necessary (see below soil moisture retrieval below).

Aerosols and chemistry

A hierarchy of models is now available to treat the full range of scales and the atmospheric and chemistry processes involved in the WAM. These include GCMs, CTMs, mesoscale models and cloud resolving models (CRM). Coupling between these atmospheric and chemistry models is in a highly developed state. A focus will be brought on the representation of convective vertical transport and scavenging of gases and aerosols in these models. At regional and synoptic scales, transport (e.g. through the African Easterly Jet) needs to be carefully evaluated.

Gases and aerosols in West Africa represent a complicated superposition of contributions from different African source regions (oceanic, combustion, urban pollution and desert). Chemistry and aerosols models have to take into account this variety and to evaluate and to improve the representation of their sources in all models. Data from satellites missions dedicated to gases and aerosols are available and there is a potential for additional missions. Several groups are currently developing 3D or 4D variational assimilation schemes to assimilate chemistry fields using these satellite data (e.g. MOPITT).

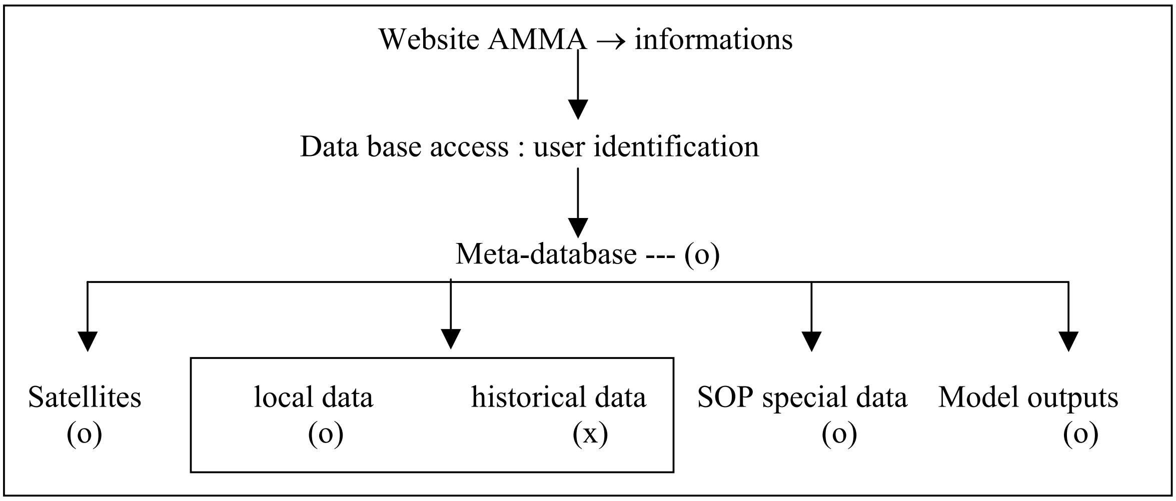
(f) Modelling of Impacts

Modelling of climate impacts on societal outcomes is taking place in various institutions in West Africa as well as in international centres such as IRI or projects such as the PROMISE project. It is important for the AMMA project to interact with these ongoing research activities in order to bring lessons learnt and best practice into AMMA impact studies. It is important to communicate to the community the limitations of current models used to predict weather and climate and to know what variables are required buy these groups. The main way that AMMA can contribute to the modeling of impacts is through providing improved reanalyses during the EOP and LOP periods and by providing improved high-frequency and small scale observations that can be used to evaluate downscaling methodologies. AMMA will also be able to provide an assessment of the ability of current models to predict those aspects of WAM variability important for running the models of impacts.

3.3.5 Database

A database is developed in AMMA-France and in AMMA-EU. A web page will be designed, developed and managed, in order to provide information about the project, data availability and results obtained. It has been proposed that all data, as well as model results, used and acquired in the AMMA project will be stored in a project database that will be specifically developed for AMMA. The data base development will be done in strong relationship with the Regional Database and Software Engineering Unit (RDBSI Unit) of AGRHYMET in Niamey (Niger), who will manage the mirror site of the AMMA data-and meta-database. This database will be developed to facilitate interfacing with the visualisation software (i.e., GIS) used by the partners of the project.

A first step has consisted of defining the global architecture of the data archive and user interface. As these data are managed by two centers (Medias-France and IPSL), an emphasis has been placed on ensuring easy access to data from any connection mode. The overall structure of the data base management is presented in the following scheme:



(o) : data open to all partners, members, collaborators (see data policy section)
(x) : access to some data can be restricted. Access to others given after authorization given by the coordinator/ WP leaders

Metadatabase. A user interface (http://medias.cnrs.fr/amma2/accueil.htm) has been designed and developed allowing selecting data subsets according to various criteria (location, time period, name of parameter, etc.). Through this interface, specific request can be sent to the database, and data subsets corresponding to these requested criteria extracted and imported on the user's computer. Some data will be available through user identification and password. The first information on data (descriptors) have been entered to test the relevance of the specifications (AMMASAT and from first LOP observations). Other data files will be inserted at reception.

Satellite data base (AMMASAT at: http://ammasat.lmd.polytechnique.fr). Only level 2 data are archived, and put into a lat/long grid. Several grid resolutions are available, to optimise the instrument exploitation, but allowing one to superimpose data from various sensors (see section 3.3.3). Products come either from operational centres or from research laboratories, and several algorithms for the same variable are possibly stored, to help cross-validation exercises. Access to some data is already operational. New web tools will be added to help the user to re-interpolate data from one grid to another.

Local data (mainly time series): The design and filling up of the LOP/EOP/SOP time series of local data will be stored (http://medias.cnrs.fr/amma2/accueil.htm). Each partner will provide his data in the AMMA secured ftp site, in formats defined both by the data provider and the database manager, particularly true for the metadata which will be produced using international standard. Then, the data will be compiled in the database, with a standardised nomenclature. It is planned to install, maintain and set up the appropriate structure (e.g. in a PostgreSQL Relational Database Management System) for data archival for the AMMA community at large.

SOP specific database (from aircraft, radars, etc…): the design and development will be performed in 2005 when the SOP plans will be completed and fixed.

The Model data output of the atmospheric, hydrological and ecological models to be used for the AMMA project will be stored.

3.4 Applications

3.4.1 Weather and Climate Prediction

Improving weather and climate forecasts of the West African monsoon is a major long-term goal of the AMMA project. The improved analysis and understanding of the West African monsoon will support evaluations of the global and limited area models used for weather and climate prediction. General analyses of data from the AMMA experiments data assimilation systems will be done to shed light on the potential of the additional data to improve short to medium range weather forecasts produced either by LAM or global models, and climate monitoring and prediction. Initialization of land surface conditions in models used for weather and climate prediction is also extremely important. Impact of new method (ALDAS for Global Land Data Assimilation Scheme) which will be developed in AMMA (see previous section) over the West African region will be thus tested.

(a) Weather Prediction

Useful predictions of weather are required at short- (1-4 days) and medium-range (5-15 days). At short-range the main focus is on the variability of synoptic and mesoscale systems and their associated weather. At medium-range the main focus is on the risk of severe weather (e.g. MCSs, tropical cyclones) and of transitions between wet and dry spells including rainfall onset.

The enhanced observations gathered during the EOP and SOP will provide a unique opportunity for evaluating models and predictions of the weather systems and their associated weather at short and medium range. Data assimilation systems will enable us to carry out a host of observing system simulation experiments (OSSEs) that will support research on the utility and efficiency of the observing system, allowing recommendations to be made for future sustained observing networks, a critical issue for the AMMA region. This work will be performed in a collaborative framework with THORPEX (See section 3.5.2 and section 4). The forecast skill evaluation systems will focus on the prediction of the Inter-Tropical Convergence Zone (ITCZ) characteristics, the atmospheric weather systems, and the surface continental and oceanic conditions, at regional, sub-regional and local scales.

A specific effort will be also put on the running and evaluation of mid to high (about 10 km) resolution real-time short-range forecasting over the AMMA area using an ensemble of limited area models (LAM). Kilometric resolution models will be used also for applications to local scale sub-areas.

(b) Climate Prediction

At climate scales the AMMA program is particularly focused on improving our knowledge and understanding of the processes that determine and influence seasonal-to-interannual variability. Useful predictions at these timescales are needed now by society. Predictions at these timescales are routinely made offering a routine test for our ability to make these predictions and highlight problems with these models. Improving the ability of dynamical models to make predictions at these timescales will improve our confidence in predictions at longer timescales. While the emphasis is on seasonal-to-interannual variability, AMMA also recognizes the importance of continued investigations on decadal variability and climate change.

Seasonal-to-interannual forecasts of the WAM are made routinely by several operational centres around the world. There is increasing pressure from society to use these forecasts to make predictions of impacts (see below). AMMA will include the necessary research (see previous section) to evaluate the ability of the models to simulate and predict the WAM variability and in particular those aspects of the variability that are relevant to impacts. In doing this it will be possible to assess the usefulness of these forecasts.

Validation of statistical predictive schemes at various ranges from intra-seasonal to seasonal timescales will be also performed at regional scale (regional indices, 5-day to 3-month cumulative rainfall fields, dates of onset and pauses during the meridional progression of the monsoon). Interactions with projects such DEMETER dedicated to seasonal forecasts will be developed. New DEMETER seasonal forecasts with an improved physics and/or an improved land surface initialization will be used in AMMA. The skill of these new subsets of forecasts with an improved physics and/or an improved land surface initialization will be evaluated. Validation with the AMMA datasets will be made after performing downscaling procedures.

AMMA recognizes the need for assessments and predictions of climate change in the West African region. AMMA can contribute to this modeling activity through providing an evaluation of dynamical models used for climate change prediction in the WAM region at daily-to-decadal timescales. This will allow some assessment of our ability to model the regional climate on longer timescales. This information will be communicated to the IPCC. AMMA's observational contribution to this activity will come from the LOP in particular through the development of the historical archive of surface conditions and the promotion of new sustained observations for future monitoring. Modelling activity will use these surface observations to assess the role played by land surface conditions on decadal variability last century.

3.4.2 Impact Prediction and Scenarios

Translating climate scenarios into impact scenarios is one great challenge of climate research for this new century. While climate prediction is obtained at large scale and low resolution, the impact of climate change might greatly vary at lower scale as the result of complex interactions between atmospheric forcing, continental response and human activities. There are known thresholds that considerably smooth out temperature and rainfall changes as long as they are not activated. When these thresholds are overshot, however, then the impact of changes in the atmospheric forcing can become much stronger than atmospheric changes themselves. An example was given in section 2.3 (Fig. 2.3.2) where the rainfall deficit of the 1970-1980's produced, in relative terms, a double discharge deficit of the Niger river. There are three main areas where AMMA will investigate the possibility of producing realistic impact scenarios: water resources, agriculture and health.

This involves three steps. The first is to develop and test reliable downscaling methodologies that will enable to link large scale climate models to impact models; this work is part of the modeling studies mentioned in paragraph (*f)* of section *3.3.4*. A second step consists of testing the impact scenarios produced from GCM simulations of the present climate. Since there are important known biases in these simulations, it is important to study how these biases are propagated through the impact modeling chain. The final step will be to produce impact scenarios from various climate scenarios and to attribute error bars built from the work of step 2. It is easy to anticipate that the degree of precision of the impact scenarios will decrease when going from water resources scenarios to predictions in the health domain. In this latter case the water cycle plays an important role but there are many intervening factors that may amplify or reduce the consequences of modifications in the water cycle. Independently of the degree of accuracy that can be reached in this type of exercise, one objective of promoting such research is to bring together people from different scientific communities that will increasingly need to work together in order to address the issue of predicting the impact of climate change.

3.5 Implementation of AMMA

The international AMMA programme benefits from several national and pan-national projects that are described below in 3.5.1. A description of the international coordination of these projects is also described here in 3.5.2.

3.5.1 National and Pan-National Projects

AMMA-Africa (or AMMANET) brings together scientists from many African nations and coordinates their contribution to AMMA. It is based on proposals made by individual scientists and small teams in universities and operational and research centers. The scientific committee of AMMA-Africa (**CSAM** : Comite de Suivi AMMA-Afrique) reviewed these proposals and initiated collaborations. Compared to the other components of AMMA the emphasis in AMMA-Africa is more on impact studies. The review process produced a science plan for Africa called the PIAF : Plan d'Implementation AMMA Afrique. Efforts are now underway to seek funding in African and elsewhere for the various working packagess of the PIAF. A detailed description of AMMA-Africa is available at: http://www.ird.ne/ammanet/

AMMA-EU is the project funded by the European Union. It has been selected as an Integrated Project under the call entitled "Hot spots in the Earth System". AMMA-EU federates the various national activities in Europe and brings together the geophysical and socio-economical communities working in Africa. The goals set for this project is to improve our capability in weather and climate forecasting and food security management. This will be achieved by advancing our knowledge of the processes active in the monsoon and enhancing the environmental monitoring systems. A corner stone of the project is to ensure that radio-soundings in the region reach the weather forecasting centers and that the network is upgraded.

AMMA-France is the French AMMA contribution which is being funded by all French research organizations involved in environmental sciences. The science plan of AMMA-France follows the one of AMMA-EU but the emphasis has been shifted to correspond better to the strength of the French community. Within AMMA-France more refined strategies have been for instance elaborated for the water cycle studies or the use of land-surface models for producing surface states. The oceanographic observations within AMMA are predominantly contributed by AMMA-France. The scientific steering committee (**CCMA** : Comité Coordination Mousson

Africaine) is charged of coordinating the working packages and preparing the deployment of instruments. More details on the French AMMA project can be found at: http://amma.mediasfrance.org/france/

AMMA-UK is a project funded by NERC and bringing together the British AMMA community. The proposed research concentrates on the following topics within AMMA : i) Land surface and atmosphere interaction, ii) WAM microclimate and applications, iii) Convection and WAM dynamics, iv) Tropospheric composition, v) The tropical tropopause layer. A large instrumental deployment is also planed within AMMA-UK. The project is headed by a Scientific Steering Committee (**SSC**) which will coordinate the scientific and observational work-packages and ensure a smooth execution of the project. The activities of the AMMA-UK project are presented at http://www.env.leeds.ac.uk/research/ias/dynamics/amma/

AMMA-US gathers a number of American scientists. A Scientific Steering Group (**SSG**) has been established for AMMA-US and its first action has been to write a science plan. The US proposal emphasized research on weather, climate and aerosol over West Africa and the downstream tropical Atlantic. Parts of this science plan have been submitted for funding to various American funding agencies and we expect to know the outcome of these proposals during 2005. US-funding for the deployment of the mobile ARM facility in Niamey in 2006 has already been secured. More details on AMMA-US can be obtained at: http://www.joss.ucar.edu/amma/

3.5.2 International Coordination

To achieve the aims of AMMA, substantial international collaboration and coordination are required. AMMA International aims to strengthen the international framework needed to facilitate interactions between researchers working in the different national and pan-national projects and ensure the field campaigns are well coordinated to optimize the scientific impact of the observations. An international structure has been established to oversee and coordinate these efforts. The International Scientific Steering Committee (**ISSC**) consists of leading atmospheric, hydrological and oceanographic scientists and is responsible for the formulation of well defined objectives and of a coherent scientific program for AMMA More details are available at http://amma.mediasfrance.org/ (International web site for AMMA). To ensure linkage with the national and pan-national AMMA projects their leaders are also members of the ISSC.

The ISSC will ensure the scientific integrity and coherency of the scientific objectives of AMMA and the fulfillment of the three overarching aims. The ISSC is under the control of the International Governing Board (**IGB**) to ensure that it fulfills its coordination role for AMMA. Implementation of the multi-year field campaign will be the responsibility of the International Implementation and Coordination Group (**ICIG**). More details are available at http://amma.mediasfrance.org/. The ICIG is under the control of the ISSC to ensure that it meets the scientific needs of the AMMA programme. A permanent Project Office **(PO)** funded by AMMA-France and AMMA-EU assists the ISSC & ICIG.

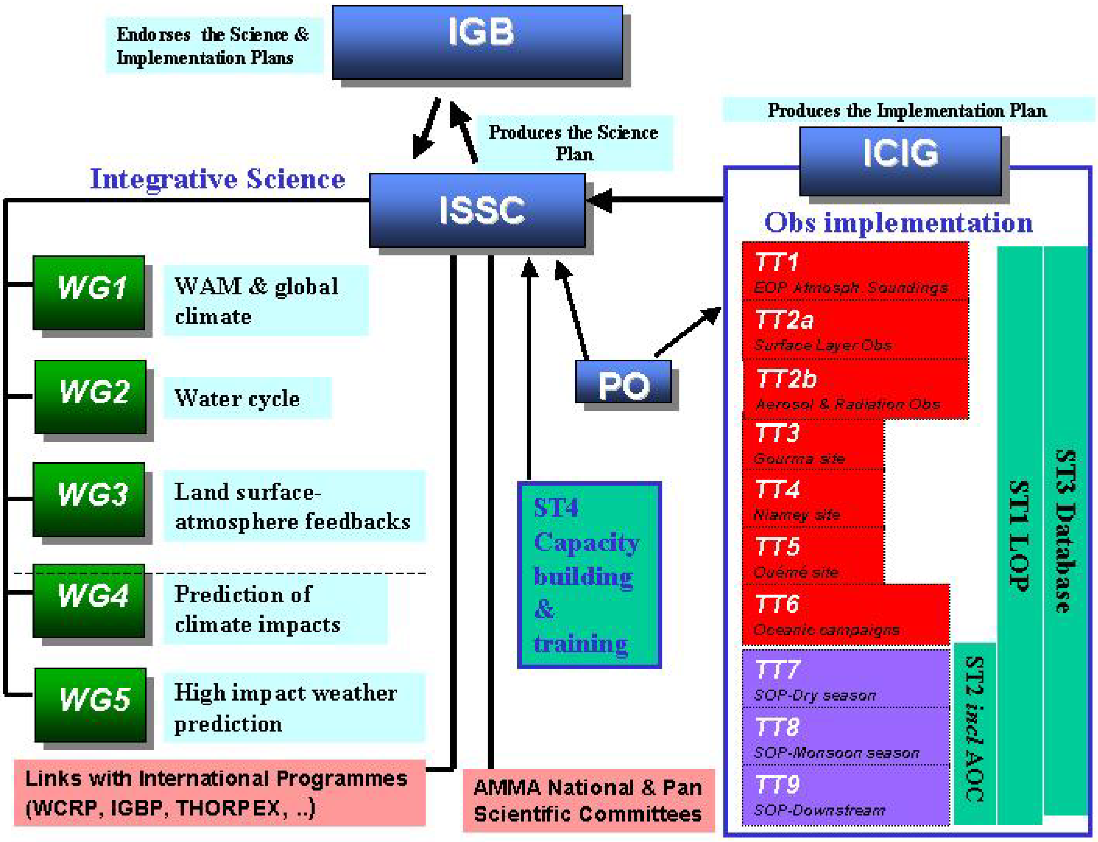


Figure 3.6: International organization of AMMA

For the scientific coordination the work of the ISCC will be structured by 5 working groups **(WG)** (Fig. 3.6) which take up 5 topics central to the aims of AMMA :

- ***WG1: West African Monsoon and Global Climate:*** The 2-way interactions between the West African Monsoon (WAM) and the rest of the globe are important for determining the variability of the WAM and its global impacts. The aim of this working group is to better understand and predict the multi-scale variability of the aspects of global climate linked to the WAM. This WG will be particularly concerned with addressing the science issues raised at the global scale (section 3.2.1).

- ***WG2: Water cycle:*** The efficiency of the processes controlling the advection of atmospheric humidity, its transformation into precipitation, and the destiny of rain water over land, is a crucial aspect of the WAM. The role played by energy transport and exchanges in relation with humidity advection and latent heat release is also central for monsoon dynamics and its variability. Analysis of the water budget will be carried out at *regional-scale (*section 3.2.2(d)), *mesoscale* (3.2.3(c)) and *local scale* (3.2.4(a)).

- ***WG3: Land Surface-Atmosphere feedbacks:*** The West African Monsoon is a coupled system in which the atmosphere is closely linked to land surface properties. This WG is concerned with providing increased knowledge and understanding of the feedbacks between the continental surface and the atmosphere. It will be the task of this WG to bring together the various process studies taking place concerned with the land and atmosphere in order to better understand the coupling between atmosphere and continental surfaces at *regional* (3.2.2) and *mesoscale* (3.2.3). The regional and remote coupling between atmosphere and ocean will be addressed in WG1.

- ***WG4: Prediction of climate impacts:*** A major aim of AMMA is to provide the underpinning science that relates climate variability to issues of health, water resources, food security and demography for West African nations and defining relevant monitoring and prediction strategies. This WG will be concerned with this aim and will be expected to provide strong linkages between the work taking place on impacts and that taking place on observed variability and predictability of the WAM. This WG will benefit from expertise in the impacts community as well as the monsoon community including those concerned with downscaling issues.

- ***WG5: High impact weather prediction and predictability*:** This WG is concerned with improving our knowledge and understanding of high impact weather in different regions: (i) over the West African continent (e.g. intense rainfall events, onset and duration of dry/wet spells), (ii) the downstream tropical Atlantic (e.g. tropical cyclone intensity change and genesis) and (iii) the extratropics (e.g. extratropical transition events, large-scale tropical-extratropical interactions). In addition to addressing key science issues related to the nature and predictability of these high impact weather events, additional operational activities will be promoted including (i) Assessing the impact of additional observations (especially radio-soundings over West Africa) in analysis/forecasting systems for the three regions; (ii) development of targeted observing strategies and (iii) tailoring of forecast products for users.

The implementation of the AMMA field program, coordinated by the ICIG, is organized in three embedded periods (Fig. 3.7) LOP (2001-2010), EOP (2005-2007), SOP (2006). A detailed implementation plan will be available during the first semester of 2005. The implementation of AMMA involves the following steps: i) initial setup of the long term monitoring program; ii) definition of a detailed strategy for the EOP and the SOP iii) deployment of the EOP and SOP instruments; iv) data base, training and capacity building actions.

The implementation of the field programme is carried out through the establishment of task teams (TT) and support teams (ST) (Fig 3.6, 3.7). The TTs responsiblities are: i) to design an observational strategy for a given subset of scales/variables of interest, as identified to be needed to reach the scientific objectives of the present International Science Plan; ii) to monitor and have final responsibility for deployment of relevant instrumentation. The TTs are composed of the PIs of the instruments planned to be deployed in the framework of the space/time scale covered by the TT. They consequently managed all the strategic, technical and operational issues related to these instruments. The ST responsibilities are: i) to act in support of TTs; ii) to look in more detail into operational matters and funding issues related to these "cross-cutting" actions; iii) to propose a scheme of operations to be agreed upon by TT leaders and to be submitted to the ISSC to verify that these schemes satisfy the needs of AMMA. ST4 has the responsibility to help to mobilize human, logistic and funding resources to favour the involvement of Africans in AMMA. This will express in term of technical and university training and capacity building for research and field observations. ST4 will favour collaboration between African teams as much as possible. More information regarding international activities and coordination can be found at **http://amma.mediasfrance.org/.**

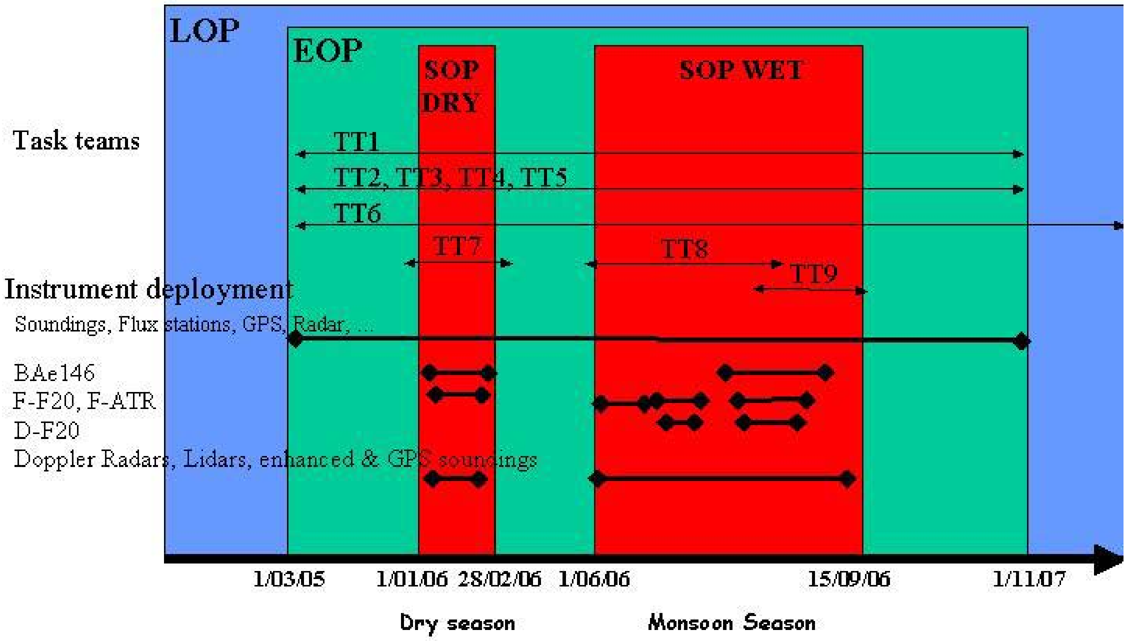


Figure 3.7: Periods of AMMA and implementation.

4. INTERNATIONAL AND PROGRAMMATIC LINKAGES

4.1 Introduction

Awareness of the potentially dramatic consequences of future climate fluctuations in tropical Africa has considerably grown over the past few years, both in Africa and abroad. The need for developing multidisciplinary studies on atmosphere dynamics and related water and chemical cycles is well recognised by an array of African institutions and international programmes. As noted in the CLIVAR Africa Task Team report (ICPO, 2000), West Africa can be identified as a pilot region for a multi-scale and multi-disciplinary experiment due to both a unique scientific context and the vulnerability of people living in the region to climate fluctuations.

It is also recognised that building links between a large number of institutions with different cultural, scientific and economic backgrounds is not an easy task. Regional African institutions and international programs initiated under the umbrella of WMO, UNDP, UNEP - and others - have a key role to play in the construction and establishment of a strong multidisciplinary research program on the WAM. The key international programmes that AMMA has strong linkages with are now briefly described. It should be emphasized that we describe only those linkages that are active now and that we can expect future linkages to be developed as the AMMA programme develops. In particular we would expect stronger linkages with additional international programmes not included here including WMO's World Weather Watch (WWW) and the Earth Systems Science Project (a collaboration between DIVERSITAS, IGBP, IDHP and WCRP) and in particular their Integrated regional Study (IRS) initiative.

We start this section though with a summary of role of African institutions and programmes in AMMA.

4.2 African Institutions

Active participation of African partners from national and regional centres in West Africa is crucially important for the success of AMMA. Recognising this, in November 2001 an open call to African scientists and institutions was made to initiate a discussion on the principal issues and questions that should be addressed in the AMMA programme. This initiative led to the creation of AMMANET in February 2002. AMMANET is a network of African scientists from different countries and disciplines and from NMHSs, universities and regional centres, such as AGRHYMET (Regional Center on Agriculture, Hydrology and Meteorology) and ACMAD (African Center for Meteorology Applied to Development). AMMANET provides a framework where African scientists have the opportunity:

- To develop and consolidate links between research institutions and NMHSs in the aim to improve products for end-users.
- To get help to reply to the different calls for proposals in order to finance their own applied research projects.
- To exchange information, data and tools (software, methods, etc).
- To federate the initiatives and the individual suggestions for more efficiency.
- To organize in collaboration with NMHSs workshops, seminars and public rallies on the importance of hydro-meteorological data and information.

This approach to implementing a scientific project is original and new in Africa and may be a model for future regional initiatives in Africa. The African NMHSs are probably for the first time implicated at very high level in the definition and the implementation of a scientific program.

Our AMMA focal points in the different West African countries are mainly from NMHSs. Some of these contacts are members of the AMMA-Africa Scientific Committee (CSAM: Comite de Suivi AMMA-Afrique) and all NMHSs of the region are partners in the different scientific research projects in the African Involvement Plan in AMMA (PIAF). Operational NMHSs are expected to play a key role in these applied research projects both in terms of implementation of improved early warning methods and dissemination of information to end-users.

4.3 World Climate Research Programme

AMMA has received official endorsement from WCRP due mainly to the strong contributions AMMA will make to the international CLIVAR and GEWEX programmes described below.

4.3.1 CLIVAR

CLIVAR is an international research programme addressing many issues of natural climate variability and anthropogenic climate change. CLIVAR seeks to better understand and predict our climate in order to take precautions and to reduce impacts of climate variability and change on our planet. The programme structure consists of mostly regional oriented principal research areas (PRAs) coordinated by panels within a global framework. The two key regional CLIVAR panels that AMMA interacts with are Variability of the African Climate System (VACS) and CLIVAR-Atlantic panel. In addition to the regional panels there are also three modelling panels concerned with seasonal to interannual prediction, coupled modelling and ocean model development. Recognizing the strong emphasis of AMMA on seasonal to interannual variability and predictability it is particularly important for AMMA to interact with the Working Group on Seasonal to Interannual Prediction (WGSIP). The two regional panels concerned with Africa and the Atlantic are now briefly described.

> **Variability of the African Climate System (VACS):** The VACS panel is concerned with implementation of CLIVAR in the African region. A major goal of the panel is to recommend and facilitate a sustained observing system that will support research and prediction of the African climate system and its impacts. VACS recognizes that this must be achieved through international collaboration between scientists doing basic research and prediction along with focused field programmes aimed at improving our understanding of the African climate system. The prospect of improving our fundamental understanding of African rainfall systems, with the goal of improving our ability to predict climate variability is a strong motivating factor for VACS. From a larger-scale perspective, VACS also recognizes the importance of understanding the role of Africa within the global climate. The CLIVAR-Africa Implementation Plan (ICPO, 2000), that developed from the CLIVAR Africa report (ICPO, 1999), recognizes the strong need to promote basic research of the African climate system including more evaluation of models used for climate prediction. More information about the panel and its activities can be found at http://www.clivar.org/organization/africa/vacs.hm. AMMA will make a major contribution to the VACS research programme and is represented on the VACS panel. AMMA's progress and achievements will be reported to this panel and through this panel to the CLIVAR SSG where feedback can be provided.
>
> **CLIVAR-Atlantic:** A major aim of the CLIVAR-Atlantic panel is to oversee the implementation of observations in the Atlantic sector, in order to meet the objectives of the CLIVAR Science and Implementation Plans particularly with respect to the PRAs:

North Atlantic Oscillation, Tropical Atlantic Variability and Atlantic Thermohaline Circulation. More information about the panel and its activities can be found at http://www.clivar.org/organization/atlantic/index.htm. The Atlantic observations provided through the AMMA programme are coordinated with the CLIVAR-Atlantic activities. In particular it is important for AMMA to continue to interact and work with the CLIVAR-Atlantic promoted Tropical Atlantic Climate Experiment (TACE) concerned with enhanced and long-term observations in the tropical Atlantic (see CLIVAR-Atlantic web pages for more details) and the Atlantic Marine ITCZ (AMI) experiment (US-CLIVAR).

4.3.2 GEWEX

The Global Energy and Water Cycle Experiment **(GEWEX)** is a program initiated by the World Climate Research Programme (WCRP) to observe, understand and model the hydrological cycle and energy fluxes in the atmosphere, at land surface and in the upper oceans. GEWEX is an integrated program of research, observations, and science activities ultimately leading to the prediction of global and regional climate change. The International GEWEX Project Office (IGPO) is the focal point for the planning and implementation of all GEWEX Projects and activities.

The goal of the GEWEX is to reproduce and predict, by means of suitable models, the variations of the global hydrological regime, its impact on atmospheric and surface dynamics, and variations in regional hydrological processes and water resources and their response to changes in the environment, such as the increase in greenhouse gases. GEWEX will provide an order of magnitude improvement in the ability to model global precipitation and evaporation, as well as accurate assessment of the sensitivity of atmospheric radiation and clouds to climate change.

GEWEX is composed of several components designed to address the elements of the scientific focus, the global energy and water cycle.

- **Radiation** - Determine atmospheric and surface radiation fluxes and heating with the precision needed to predict transient climate variations and decadal-to-centennial climate trends.
- **Hydrometeorology** - Demonstrate skill in predicting changes in water resources and soil moisture on time scales up to seasonal and annual as an integral part of the climate system.
- **Modeling and Prediction** - Develop accurate global model formulation of the energy and water budget and demonstrate predictability of their variability and response to climate forcing.

The GEWEX Hydrolometeorological Panel (GHP) coordinates the plans and the focus of scientific issues related to the development and implementation of the Continental-Scale Experiments (CSEs) and has oversight of all GEWEX hydrometeorology and land-surface projects. The principal task of the GHP is to guide these projects in the goal of achieving demonstrable skill in predicting changes in water resources and surface conditions as an integral part of the climate system up to seasonal and annual time scales.

AMMA's objectives are centered around the water and energy cycle and thus make it an important contribution to GHP. Not only does it seek to achieve the same goals as other CSEs but it is furthermore on a continent and in a climate regime in which for the moment no other CSE is active.

During the 17th session of GEWEX Scientific Steering Group (January 2005), AMMA was accepted as a Continental Scale Experiment. This will facilitate and and strengthen the collaboration of AMMA with other CSEs. This new position of AMMA within GEWEX will also ensure that the international modeling community will benefit from the observations which will be taken during the field campaigns through the GEWEX Modeling and Prediction Panel. The CSE status of AMMA also focuses the research activities of the GEWEX Radiation Panel (GRP) around a better exploitation of remote sensing observation over this data poor region.

4.4 International Geosphere Biosphere Programme

The mission of IGBP (International Geosphere- Biosphere Programme) is to deliver scientific knowledge to help human societies develop in harmony with the Earth's environment. The scientific objective is to describe and understand the interactive physical, chemical and biological processes that regulate the total Earth System, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions. As one of four international global environmental change research programmes, IGBP works towards its objective in close collaboration with the International Human Dimensions Programme on Global Environmental Change (IHDP), the WCRP, and DIVERSITAS, an international programme of biodiversity science.

AMMA has been endorsed by two IGBP projects: IGAC and ILEAPS and both are now described briefly here.

4.4.1 IGAC

The International Global Atmospheric Chemistry (IGAC) Project, under joint sponsorship of the Commission on Atmospheric Chemistry and Global Pollution (CACGP) of the International Association of Meteorology and Atmospheric Sciences (IAMAS) and IGBP, aims to develop a fundamental understanding of the processes that determine atmospheric composition; understand the interactions between atmospheric chemical composition and physical, biospheric and climatic processes; and predict the impact of natural and anthropogenic forcings on the atmosphere's chemical composition.

The atmospheric chemistry program in AMMA, especially with the strong focus on aerosols, addresses high-priority issues in IGAC.

4.4.2 iLEAPS

The Integrated Land Ecosystem Atmosphere Process Study (iLEAPS) is a Land-Atmosphere project within IGBP. The goal of iLEAPS is to understand how interacting physical, chemical and biological processes transport and transform energy and matter through the land-atmosphere interface. One of iLEAPS goals is the study of emissions from and deposition to land surfaces including various feedbacks such as aerosol influences on cloud properties and precipitation.

The AMMA atmospheric chemistry studies, especially those over the ocean, will complement those being carried out in iLEAPS; these data, when integrated will facilitate the development of models that can better anticipate the impact of changes in North African ecosystems on processes occurring over the tropical Atlantic.

4.4.3 SOLAS

The Surface Ocean - Lower Atmosphere Study (SOLAS) is an international research initiative whose goal is to achieve quantitative understanding of the key biogeochemical-physical interactions and feedbacks between the ocean and the atmosphere, and how this coupled system affects and is affected by climate and environmental change. SOLAS has been approved and sponsored by the International Geosphere-Biosphere Programme (IGBP), the Scientific Committee on Oceanic Research (SCOR), the Commission on Atmospheric Chemistry and Global Pollution (CACGP) and the World Climate Research Programme (WCRP).

AMMA will contribute to SOLAS by making measurements of various aerosols and gases that are important to air-sea exchange processes. Of primary importance are mineral dust studies because of the great impact that iron in dust is believed to have on biogeochemical processes in the tropical Atlantic.

4.5 Global Climate Observing System

The Global Climate Observing System (GCOS) aims to ensure that the observations and information needed to address climate-related issues are obtained and made available to all potential users. It is co-sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the United Nations Environment Programme (UNEP) and the International Council for Science (ICSU). GCOS is intended to be a long-term, user-driven operational system capable of providing the comprehensive observations required for monitoring the climate system, for detecting and attributing climate change, for assessing the impacts of climate variability and change, and for supporting research toward improved understanding, modelling and prediction of the climate system. It addresses the total climate system including physical, chemical and biological properties, and atmospheric, oceanic, hydrologic, cryospheric and terrestrial processes. AMMA has developed linkages with GCOS, especially with respect to the rawinsonde network.

4.6 THORPEX

THORPEX: Global Atmospheric Research Programme is an international research and development programme responding to the weather related challenges of the 21st century to accelerate improvements in the accuracy of 1-day to 2- week high impact weather forecasts for the benefit of society and the economy. THORPEX research topics include: global-to-regional influences on the evolution and predictability of weather systems: global observing system design and demonstration; targeting and assimilation of observations; societal, economic and environmental benefits of improved forecasts. The programme establishes an organizational framework that addresses weather research and forecast problems whose solutions will be accelerated through international collaboration between academic institutions, operational forecast centres and users of forecast products.

THORPEX contributes to the development of a future global interactive multi-model ensemble forecast system, which would generate numerical probabilistic products, available to all WMO Members including developing countries. The purpose is to provide accurate, timely, specific and definite weather warnings in a form that can be readily used in decision support tools, to improve and demonstrate such tools in order to reduce the impact of natural hazards and to realize societal and economic benefits of improved weather forecasts.

AMMA and THORPEX goals significantly overlap in several key areas that relate to high impact weather. High impact weather in the West African region includes intense rainfall events associated with the passage of mesoscale and synoptic scale weather systems on daily timescales. In addition, at 1-2 week timescales there is a need to better understand and predict the onset and duration of dry/wet spells including the onset of the monsoon rains at the beginning of the season – particularly important for applications. Such medium-range forecasts are new to the West African region and yet potentially have a big impact; e.g. transition from wet-spell to dry-spell, risk of heavy rainfall and flooding etc. Downstream activities concerned with tropical cyclone intensity change, as well as how tropical cyclones undergo extratropical transition will also benefit from joint AMMA-THORPEX interactions. Recognising the overlapping goals and interests, a joint AMMA-THORPEX working group (WG5 in Fig. 3.6) has been established that will report to the AMMA ISSC and an equivalent body in THORPEX.

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APPENDIX : Acronyms used in this document

AAM	Asian-Australian Monsoon (CLIVAR Panel)
ACMAD	African Center in Meteorology Applied to Development
AEJ	African easterly jet
AERONET	Aerosol Robotic NETwork
AEW	African easterly wave
AGHRYMET	Centre Agro-Hydro-Météorologique (CILLS – Niamey)
AIRS	Atmospheric Infrared Sounder
ALDAS	African Land Data Assimilation Scheme
AOD	Aerosol Optical Depth
AMI	Atlantic marine ITCZ
AMIP	Atmospheric Model Intercomparison Project
AMMA	African Monsoon Multidisciplinary Analysis
AMMANET	A network of African scientists contributing to AMMA
AMMASAT	AMMA satellite database
AQUATRAIN	Constellation of satellites AQUA, CloudSat, CALIPSO, PARASOL, AURA, OCO
ARGO	Array for Real-time Geostrophic Oceanography
ARM	Atmospheric Radiation Mission
AVHRR	Advanced Very High Resolution Radiometer
BC	Black Carbon
CACGP	Commission on Atmospheric Chemistry and Global Pollution
CATCH	Couplage de l'Atmosphère Tropical et du Cycle Hydrologique
CCMA	Comité Coordination Mousson Africaine
CCN	Cloud condensation nuclei
CDAS-1	NOAA NCEP-NCAR Climate Data Assimilation System
CEOP	Coordinated Enhanced Observing Period
CERES	Clouds and Earth's Radiant Energy System
CFC	Chloro-Fluoro-Carbons
C-GCM	Coupled General Circulation Model
CILSS	Comité Inter-Etats de Lutte contre la Sécheresse au Sahel
CLIVAR	Climate Variability and Predictability
COPT81	COnvection Profonde Tropicale field experiment (1981)
CORIOLIS	Observational system for operational oceanography in France
CRM	Cloud-resolving model
CRYSTAL FACE	Cirrus Regional Study of Tropical Anvils and Cirrus Layers- Florida Area Cirrus Experiment
CSAM	Comite de Suivi AMMA-Afrique
DEBITS	Déposition of Biogeochemically Important Trace Species
CSE	Continental scale experiment
DECAFE	Dynamique Et Chimie Atmospherique en Foret Equatoriale et Chimie de l'At
DEMETER	Development of a European Multimodel Ensemble system for seasonal to interannual prediction

DTM	Digital Terrain Models
n Dvar	n(1or 3 or 4)-Dimensional variational analyses
ECCO	Estimating the Circulation and Climate of the Ocean
ELDAS	European Land Data Assimilation Scheme
ENSO	El Nino Southern Oscillation
EOP	Enhanced Observing Period
EOS	Earth Observing Satellites
EQUALANT	French campaigns through the equatorial Atlantic
EU	European Union
EUC	Equatorial Under Current
EXPRESSO	Experiment for Regional Sources and Sinks of Oxidants
ERBE	Earth Radiation Budget Experiment
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FOCAL	Français Océan et Climat dans l'Atlantique équatorial
FTH	Free Tropospheric Humidity
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GCM	General Circulation Model
GCOS	Global Climate Observing System
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	Greenhouse Gases
GHP	GEWEX Hydrolometeorological Panel
GIS	Geographic Information System
GLDAS	Global Data Assimilation System
GLOBALSAV	GLOBAL SAVanna project
GLOWA	Global Change in the Hydrological Cycle
GODAE	Global Ocean Data Assimilation Experiment
GOES	Geostationary Operations Environmental Satellite
GPCP	Global Precipitation Climatology Project
GTE/ABLE	Global Tropospheric Experiment/Amazon Boundary Layer Experiment
HAPEX	Hydrological and Atmospherical Pilot Experiment
ICPO	International CLIVAR Project Office
IDAF	IGAC-DEBITS-Africa
IAMAS	International Association of Meteorology and Atmospheric Sciences
IASI	Infrared Atmospheric Sounding Interferometer (on METOP sat)
ICSU	International Council for Science
IGAC	International Global Atmospheric Chemistry
IGB	International Governing Board
IGBP	International Geosphere-Biosphere Programme
IHDP	International Human Dimensions Programme
ILEAPS	Integrated Land Ecosystem – Atmosphere Processes Study
IMPETUS	Integratives Management Projekt für einen Effizienten und Tragfähigen Umgang mit Süsswasser

IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
IPSL	L'Institut Pierre-Simon Laplace
IRI	International Research Institute
ITCZ	Inter Tropical Convergence Zone
JET2000	Aircraft campaign concerned with AEJ in 2000
LAI	Leaf Area Index
LAM	Limited Area Model
LANDSAT	LAND observation satellite
LDAS	Land Data Assimilation Scheme
LOP	Long-term Observing Programme
LW	Long Wave
MDR	Main Development Region
MCS	Mesoscale Convective System
MERCATOR	French operational system to describe the global ocean
MJO	Madden-Julian Oscillation
MLD	Mixed Layer Depth
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPITT	Measurements of Pollution in the Atmosphere
MSG	Meteosat Second Generation
MT	Mega-tonnes
NAO	North Atlantic Oscillation
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NDVI	Normalized Deviation Vegetation Index
NMHS	National Meteorological and Hydrological Services
NVAP	NASA Water Vapor Project
OI	Optimal Interpolation
ORE	Observatoire de Recherche en Environnement
OSSE	Observing System Simulation Experiments
PHOTONS	PHOtométrie pour le Traitement Opérationnel de Normalisation Satellitaire
PIAF	Plan d'Implementation AMMA Afrique
PIRATA	Pilot Research moored Array in the Tropical Atlantic
POLDER	Polarization and Directionality of the Earth's Reflectances
PR	Precipitation Radar
PRA	Principal Research Areas
PROMISE	PRedictability and variability Of Monsoons, and the agricultural and hydrological ImpactS of climatE change
PROVOST	PRediction Of Climate Variations On Seasonal to interannual Timescales
PV	Potential Vorticity
RDBSI	Regional Database and Software Engineering
RGCM	Regional General Circulation Model
SAF	EUMETSAT Satellite Application Facility projects
SAFARI	Southern Africa Fire-Atmosphere Research Initiative

SAL	Saharan Air Layer
SAR(ERS)	Synthetic Aperture Radar on board ERS satellites
ScaRaB	Scanning Radiative Budget instrument
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEQUAL	Seasonal Response to the Equatorial Atlantic
SOLAS	Surface Ocean - Lower Atmosphere Study
SOP	Special Observing Period
SOOP	Ship of Opportunity Program
SPOT	Satellites Probatoire d'Observation de la Terre
SSC	Scientific Steering Commitee
SSG	Scientific Steering Group
SSM/I	Special Sensor Microwave/Imager
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
ST	Support Team
STARE	Southern Tropical Atlantic Regional Experiment
SVAT	Soil Vegetation Atmosphere Transfert models
SW	Short Wave
TACE	Tropical Atlantic Climate Experiment
TC	Tropical Cyclone
TEJ	Tropical Easterly Jet
TERRA	First EOS Satellite
THORPEX	The Observing System Research and Predictability Experiment
TIP	Tropical moored buoy Implementation Panel
TIROS	Television Infrared Observation Satellite Program
TMI	TRMM Microwave sensor
TOMS	Total Ozone Mapping Spectrometer
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Measurement Mission
TT	Task Team
TTL	Tropical Tropopause Layer
UMD	University of Maryland
UNEP	United Nations Environment Programme
UNESCO	United Nations Eductaional Scientific and Cultural Organisation
UV	Ultra-Violet
VACS	Variability of the African Climate System (CLIVAR Panel)
VAMOS	Variability of the American Monsoon Systems (CLIVAR Panel)
VOC	Volatile Organic Compounds
WAM	West African Monsoon
WCRP	World Climate Research Programme
WMO	World Meteorological Organisation
WG	Working Group
WGSIP	Working Group on Seasonal to Interannual Prediction
WP	Work Package
XBT	Expendable Bathythermograph