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# The AMMA field campaigns: Multiscale and multidisciplinary observations in the West African region

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**ABSTRACT:** AMMA – the African Monsoon Multidisciplinary Analysis – is the biggest programme of research into environment and climate ever attempted in Africa. AMMA has involved a comprehensive field experiment bringing together ocean, land and atmospheric measurements, on time-scales ranging from hourly and daily variability up to the changes in seasonal activity over a number of years. Many of the publications in this special issue make use of subsets of the AMMA measurements, collected from a diverse set of sensors.

As a general introduction to the special issue, this paper provides a comprehensive overview of the AMMA observational programme, and summarises the scientific strategy which has defined the field deployment. The relationship between the existing observational monitoring networks of the region and the new sensors deployed for AMMA, and for the future, is described. Making use of regional and sub-regional maps, the main groups of sensors are described in terms of their deployment periods and their spatial co-ordination. The key linkages between different groups of measurements are also outlined, in terms of the strategy for their combined use and in terms of their interdependence. Some brief summaries of conditions sampled during the three years of the AMMA Extended Observing Period are also given. Copyright © 2009 Royal Meteorological Society and Crown Copyright

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## 1. Introduction

African Monsoon Multidisciplinary Analysis (AMMA) is an international project to improve our knowledge and understanding of the West African monsoon (WAM), as well as the environmental and socio-economic impacts of its variability (Redelsperger *et al.*, 2006). AMMA relies on a field programme which is the largest and most extensive ever attempted in Africa. This field programme is organised in nested time-scales (Figure 1): the long-term monitoring programme (LOP, 2001–2009) is based on existing infrastructure, some of which has been active for many years (including operational networks and specific research projects) and some of which was reinforced thanks to AMMA. In 2005, a widespread intensification and co-ordination of these networks was set up for the duration of the so-called Enhanced Observing Period (EOP, 2005–2007), which also saw the implementation of specific land-based and sea-based instruments. At the core of the EOP, a one-year series of Special Observing Periods (SOPs) was organized in 2006, during which intensive measurements from the surface (continent-based and ocean-based) and from the air (research aircraft and balloons) took place.

The scientific diversity of measurements embraces oceanic, hydrological and atmospheric studies, in physical, chemical and socio-economic disciplines, from the global scale to the 'local' scale of specific instrument

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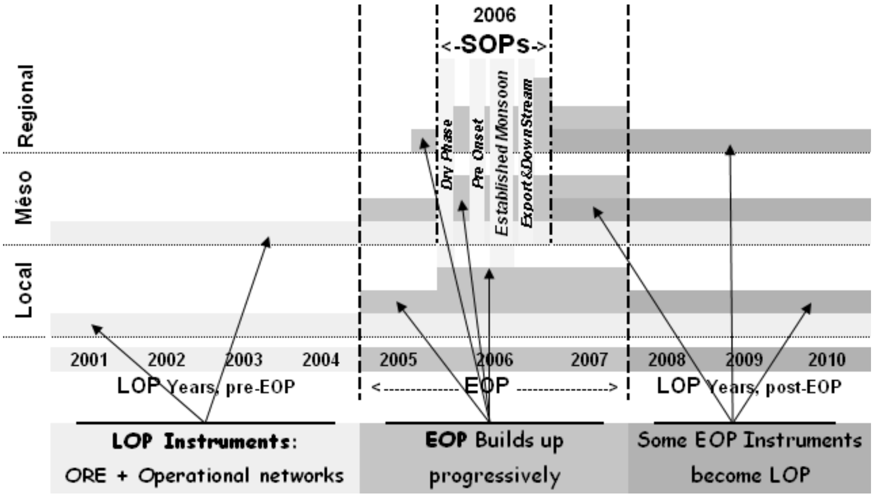

Figure 1. Space–time schematic of the AMMA observation programme. 'ORE' refers to 'Observatoires de Recherche en Environnement', a French programme supporting long-term observations both in France and in a few tropical areas. This figure is available in colour online at www.interscience.wiley.com/journal/qj

sites. Several hundred scientists, working in a tough environment, were, and are still, involved in the AMMA field programme, which represents one of the most complex scientific deployments ever attempted. In spite of the difficulties, this programme has been very successful and has generated a multidisciplinary observational database which will have a long legacy. As a general introduction to this special issue, this paper aims to provide a concise summary of the field programme and its scientific rationale, so that observations described in the following papers may be interpreted in terms of their quality, their wider context, and their interdependencies. The overview includes a description of the scientific rationale (section 2) and linkages (section 3) of the whole set of observations. Most of the papers of the special issue deal with studies of atmospheric dynamics based on the SOP measurements; in order to place the SOPs into the context of the EOP years, section 4 provides a survey of the EOP monitoring systems in which the SOPs were embedded and makes an overview of the climatic and environmental conditions that prevailed during the EOP. A detailed analysis of the meteorological conditions during the SOP year is given in Janicot *et al.* (2008). Section 5 presents in more detail the set-up of the SOPs, whose observations are heavily used in the papers of this special issue.

## 2. Background

The climate and environment of West Africa are matters of international concern. Decadal and interannual variability in the regional climate are now well-known (e.g. Hulme *et al.*, 2001; Le Barbé *et al.*, 2002). Long-term shortfalls in rainfall have had a severe impact on the water cycle (Lebel and Ali, 2009), which is in turn related to vegetation and water resources. On a local and regional scale, variability in the seasonal climate is linked to food security problems for the local populations, as well as the prevalence of diseases such as meningitis and malaria. The overall impact on the economic growth of the region is very significant (see e.g. Davidson *et al.*, 2003; ECOWAS-SWAC, 2006).

Superimposed on this decadal signal, marked interannual variations are another key characteristic of the WAM and its associated rainfall regime. These variations are closely linked to changes in the zonal and meridional winds that are established in association with the meridional heating contrasts and associated thermally-direct circulations (the mean monsoon-season winds are shown schematically in Figure 2). The African easterly jet is located in the region of strong low-level potential temperature gradients between the Sahara and the Guinea Coast (see profiles of potential temperature, $\theta$, in Figure 2) consistent with thermal wind balance, which reverses with height around the jet level (Cook, 1999; Thorncroft and Blackburn, 1999; Parker *et al.*, 2005a). At low levels, southwesterlies from the Atlantic provide most of the moisture for the WAM while polewards of this, northeasterlies advect relatively drier Saharan air into the rainy region. The low-level winds are part of a lower-tropospheric thermally-direct meridional circulation (Thorncroft and Blackburn, 1999; Trenberth *et al.*, 2000; Zhang *et al.*, 2006) whose dry, southerly return-flow at around 600–700 hPa (Figure 2) is also related to the African easterly jet through the Coriolis acceleration. There is a strong continental-scale diurnal cycle in the meridional circulation (Parker *et al.*, 2005b), which makes a significant contribution to the continental moisture transport (Lothon *et al.*, 2008).

The large-scale dynamical factors controlling the WAM are the Azores anticyclone over the Atlantic Ocean, the Libyan anticyclone over the continent and the intertropical convergence zone (ITCZ). In boreal winter the ITCZ is located around 5°S on the tropical Atlantic and the continent is dry; the ITCZ reaches its northernmost position in August between 10°N and 12°N before retreating to the south. It is worth noting that while the ITCZ keeps a relatively stable position at the surface from year to year, the position of the African easterly jet displays

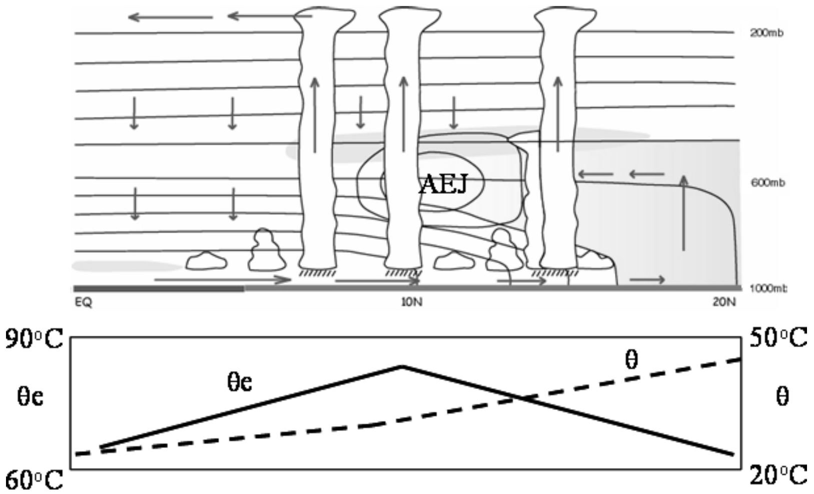

Figure 2. Schematic of the atmospheric circulation in the West African monsoon system during the boreal summer. Closed solid lines represent the isotachs of the African Easterly Jet (AEJ), which lies around 600 hPa. The red arrows show the thermally direct meridional monsoon circulation, and are typical of the time-mean winds in the peak monsoon season. This circulation will also be observed on many individual days, but there is strong variability over the diurnal cycle, and around mesoscale convective systems. The typical corresponding meridional variations in atmospheric boundary layer potential temperature ($\theta$) and moist static energy equivalent potential temperature ($\theta_e$) are given in the panel below. North of 10°N, $\theta_e$ starts to decrease while $\theta$ continues to increase, due to the drying of the boundary layer north of the core of the ITCZ. Grey stippled shading represents peak rainfall and yellow shading indicates the location of the Saharan Air Layer (SAL). North of the AEJ, convective systems are highly intermittent, commonly with several days' interval between the occurrences of organised systems. (After the AMMA International Science Plan, 2005, adapted from Parker *et al.*, 2005). This figure is available in colour online at www.interscience.wiley.com/journal/qj

much more intraseasonal and interannual variability. One important surface feature controlling this variability is the thermal heat-low located at the latitude of the tropic, with a maximum intensity usually between 5°W and 0°, but displaying significant fluctuations at various intraseasonal time-scales: variability in the heat-low seems to contribute to variability in the low-level monsoon moisture fluxes (Parker *et al.*, 2005b). On the continental scale, the heat-low drives a strong diurnal cycle in the monsoon circulation (Parker *et al.*, 2005b), which makes a significant contribution to the continental moisture transport (Lothon *et al.*, 2008). On the other hand, smaller-scale structures are also pivotal for rainfall production. First, the African easterly waves developing in the African easterly jet (e.g. Hall *et al.*, 2006; Kiladis *et al.*, 2006) play an important role in the development of large, organised mesoscale convective systems (MCSs), responsible for most of rainfall over the region. Secondly, the way in which the MCSs interact with the surface and the large-scale environment, including the jets and monsoon-layer winds (e.g. Redelsperger *et al.*, 2002), but also dust-laden harmattan winds, is a determinant for the effective production of rainfall.

One fundamental goal of AMMA in terms of process understanding was to document the various atmospheric structures described above at the appropriate scale in order to better understand their interactions (on the scaling hierarchy, see Fig. 1 in Redelsperger *et al.*, 2006 and a more detailed discussion in AMMA-ISSC, 2005). This was especially the goal of the SOP year, 2006.

While a comprehensive observation of the atmosphere over a large range of scales is necessarily limited in time due to the cost and logistics involved, there are other key factors that control the interannual variability of the WAM, and which deserve to be monitored over several years in order to document contrasting situations and possible year-to-year memory effects. The brief description above shows that the WAM dynamics is basically a response to the contrast in temperature and humidity (1) between the continent and the tropical Atlantic, and (2) within the continent from south to north. The variations of the surface conditions of the oceanic and continental domains, and their two-way coupling with the WAM dynamics, were thus another fundamental subject of study for AMMA. Some specific factors were identified as essential to monitor. The position and intensity of the Saharan heat-low together with the cold tongue developing in the waters of the Gulf of Guinea in June are key to the monsoon onset. The aerosol loading is a controlling factor of the radiative budget, and has an ancillary impact on the surface conditions (erosion and vegetation growth). In turn, the aerosol loading during the dry season is associated with dust transport from the desert areas and biomass-burning products originating further south, while during the wet season the aerosols are dominated by desert dust, and strongly affected by convective systems. The storage of water by the soil layer and the water absorption and transpiration by the vegetation control the gradients of moist static energy; it is thought that the relatively slow ground water processes might consequently induce memory effects from one rainy season to the next. Therefore, besides the atmospheric processes (that were the object of a work package and associated observation programme spanning the SOPs and the EOP), the oceanic processes, the land surface processes, and the aerosol and chemical processes were each the focus of a specific work package with an observation strategy articulated around the EOP.

Beyond the process studies listed above, the core of AMMA is the integrative science dealing with (1) the overall monsoon dynamics, (2) the water cycle at regional scale, and (3) the surface–atmosphere feedbacks. This integrative science requires attention to a wide range of scales and thus heavily relies on the observations made over several years during the EOP and the LOP.

## 3. Strategy of the observational programme

### 3.1. Four interacting spatial scales

Operational networks over West Africa are sampling some important elements of the WAM system, namely the atmospheric circulation (through the synoptic and upper-air networks) and the classical surface parameters (standard meteorological variables, and daily rainfall and riverflow for the large hydrological systems). While part of the overall AMMA scientific strategy is to incorporate these operational observations in a single database, the AMMA field programme has had to take account of the fact that they are neither covering uniformly, nor with a sufficient density, the four main scales characterizing the WAM.

*The global scale* is the scale at which the WAM interacts with the rest of the globe, primarily on intraseasonal-to-decadal time-scales.

Monsoon processes and interactions between the atmosphere, land and tropical Atlantic Ocean are studied at *the regional scale,* for time-scales ranging from the diurnal up to seasonal and interannual (Figure 3).

*The mesoscale* is the scale of the typical rain-producing weather systems in the WAM. Coupling between hydrology and the atmosphere at this scale is pivotal on a daily to seasonal range of time-scales (Figure 4).

Two mesoscale sites (the Niamey/southwest Niger meso-site in the north and the Ouémé meso-site in the south) contain heavily instrumented super-sites on which some key aerosol emission and hydrological processes are studied at *the sub-meso scale* (Figure 4(b)).

The AMMA field programme aimed at providing accurate data to document all the components of the WAM for these four interacting spatial scales. As for any large-scale field experiment, a balance has had to be reached between the demands of a very large and diverse community of scientists and the feasibility of meeting these demands, in terms of logistics, financial and human resources, in a very challenging working environment. Beyond the central requirement of providing adequate datasets for the AMMA science, it was recognised that the observations must address the needs of numerical weather prediction systems, from which analyses are generated and used by the whole science and 'applications' community. Furthermore, this process has needed to be integrated with long-term international strategy for monitoring in the sub-region, including the new generation of satellites recently launched or in the planning – most notably A-Train, Envisat, MSG, IASI, SMOS, Megha-Tropiques, VENUS[†] – that will provide enhanced spatial and spectral resolution and require some validation over the Tropics.

### 3.2. Nested time-scales

The three main periods of observation introduced in section 1 had the following goals:

- *LOP (2001 – 2009)* is concerned with observations of two types: (1) the operational observations covering the regional scale and (2) additional observations on the mesoscale and local sites. The objective is to document and analyse the interannual variability of some components of the WAM which have characteristic long time-scales (sea-surface temperature and salinity, ground water balance, vegetation dynamics, anthropogenic forcing). The LOP set-up is made of 26 LOP instruments. Since many instruments are in fact the combination of several sensors[‡], either co-located or covering a local or meso-site, the LOP set-up is in fact made of a few hundred sensors covering the whole spectrum of scales identified in the previous section. The achievements of the LOP will not be developed here, the reader being referred to Bourlès *et al.* (2008) and to Lebel *et al.* (2009) for details on the LOP deployment and some of its scientific results.
- *Enhanced Observing Period (2005 – 2007)* is designed to provide a detailed documentation of the annual cycle of the surface and atmospheric parameters from convective scales of a few kilometres up to regional scales. The regional coverage is obtained through various actions including a restoration and upgrade of the operational networks, and the installation of specific new instruments deployed in networks. Added to this continental deployment are oceanic measurements carried out by a research vessel during two annual cruises. Altogether, this represents 46 additional instruments, with an emphasis on the regional and the mesoscale. Some insights into the environmental and climatic conditions that prevailed during these three EOP years are given in section 4 below.
- *Special Observing Periods (2006)* focused on specific processes and weather systems at various key stages of the annual cycle of the WAM, with intensified observations occurring over the following periods: (1) the dry season (SOP0; 10 January–20 February), (2) Monsoon onset (SOP1; 15 May–30 June), (3) Peak monsoon (SOP2; 1 July–30 August) and (4) Late monsoon, defined here as the period when the downstream impact of the WAM on the formation of cyclones over the tropical Atlantic is at its peak (SOP3; 15 August–30 September). A set of 47 additional

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[†] See list of acronyms in Appendix B.

[‡] An AMMA instrument is defined as a sensor or set of sensors allowing for a coherent spatio-temporal sampling of a geophysical variable or of a set of interrelated variables with respect to the study of a given process.

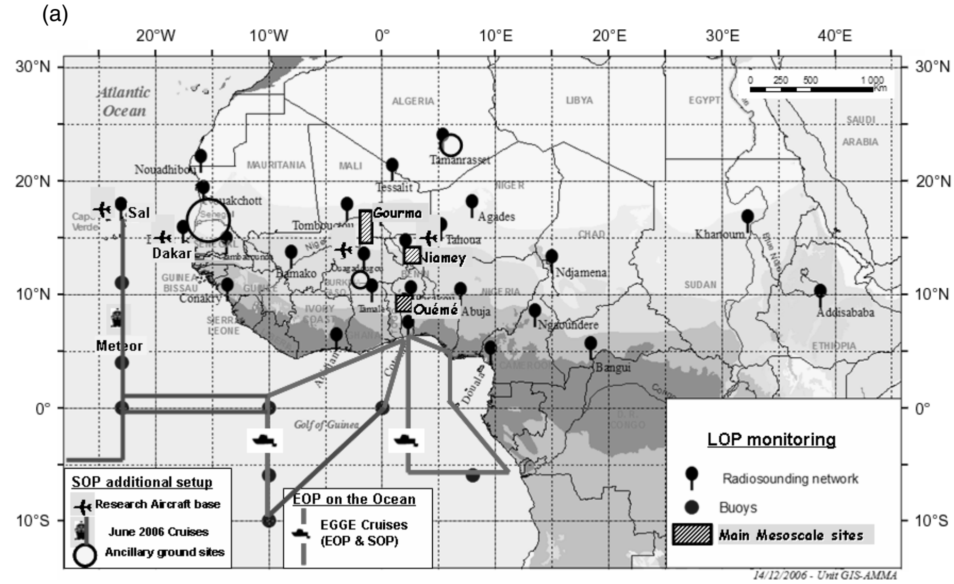


Figure 3. Regional scale monitoring of the whole AMMA domain. The long-term (LOP, 2001–2009) monitoring includes the radiosonde network in the atmosphere, the PIRATA buoys over the ocean, and the mesoscale sites of the AMMA-CATCH observing system over the continent in which dense hydrometeorological networks document the variability of the water cycle (see Figure 4(b) below). Additional measurements during the EOP (2005–2007) included the EGEE cruise in the Gulf of Guinea and observations on the continent that are shown in Figure 3(b). During the SOPs, aircraft and balloons in the atmosphere, *Meteor* and *Ron Brown* (located westward of the map limits) cruises in the ocean and three ancillary ground sites (Dakar, Tamanrasset and Dano) were activated. Regional-scale monitoring of the AMMA continental domain. The long-term (LOP, 2001–2009) monitoring is based on the three AMMA-CATCH mesoscale sites (Gourma, Niamey, Ouémé), the PHOTON-AERONET network and the IDAF network. Additional measurements during the EOP (2005–2007) included three stations of the GPS network, the dust aerosol transect, and enhancement of the flux and soil moisture measurements on the mesoscale sites (see Figure 4(b) for a zoom on the Ouémé meso-site). During the SOPs, aircraft (Figure 3(a)), balloons and three additional GPS as well as intensified radio-sounding were used for documenting the atmosphere. A zoom on the intensification of measurements carried out during the EOP and the SOP over the southern quadrilateral delimited (blue dashed contour) and the Ouémé meso-site is shown in Figure 4(a) and (b) respectively. The two large shaded rectangles indicate the area covered by the scientific flights of the aircraft based in Niamey in SOP1 and SOP2 (see details in Table AI). During SOP3, the aircraft were based in Dakar and Sal and made flights around the Dakar area and remote excursions into the tropical Atlantic. This figure is available in colour online at www.interscience.wiley.com/journal/qj

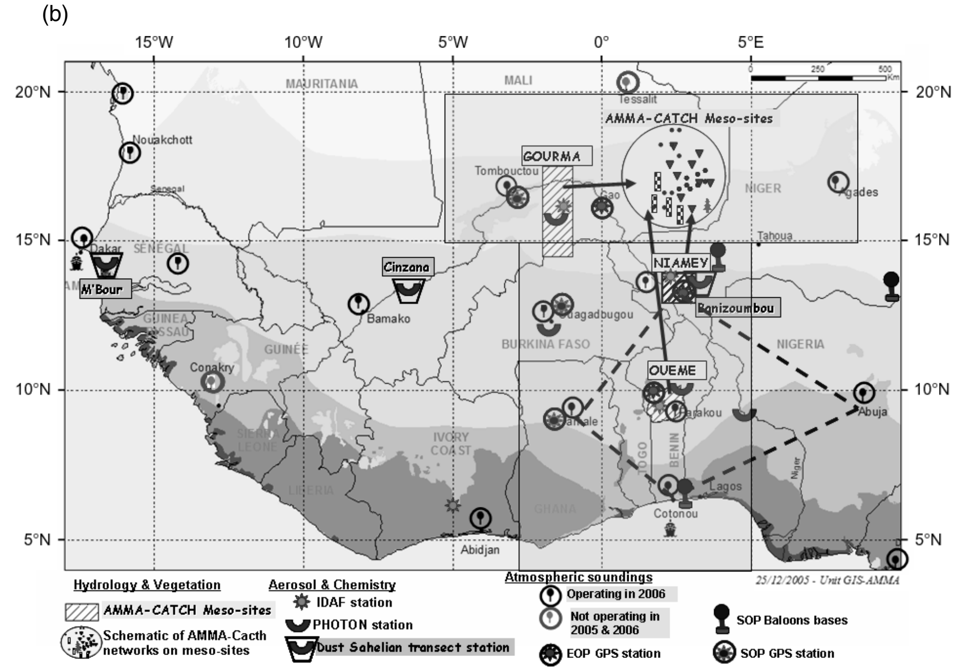


Figure 3. (*Continued*)

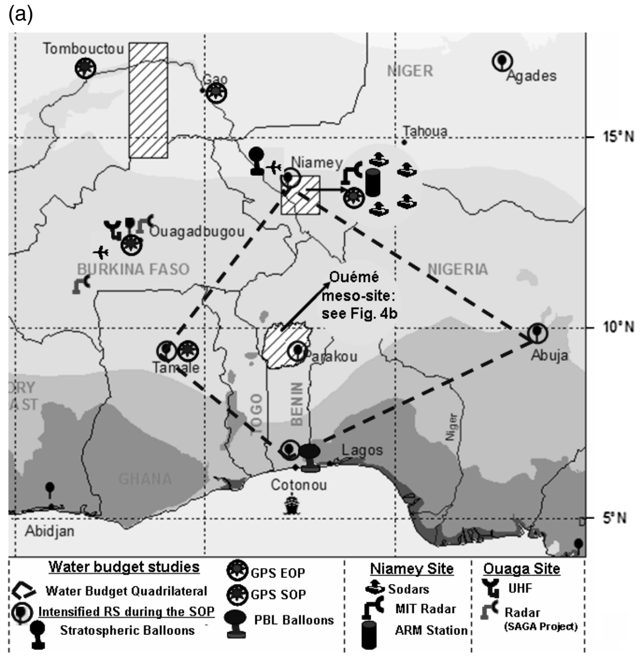


Figure 4. Mesoscale monitoring of the central AMMA continental domain: focus on SOP 3-D water budget studies. The AMMA-SCOUT stratospheric balloons launched from Niamey were equipped alternatively for studying water vapour injection into the stratosphere and for atmospheric chemistry flights. Mesoscale monitoring of the Ouémé site (LOP/EOP, top) and the Donga super-site (LOP/EOP/SOP, bottom). This figure is available in colour online at www.interscience.wiley.com/journal/qj

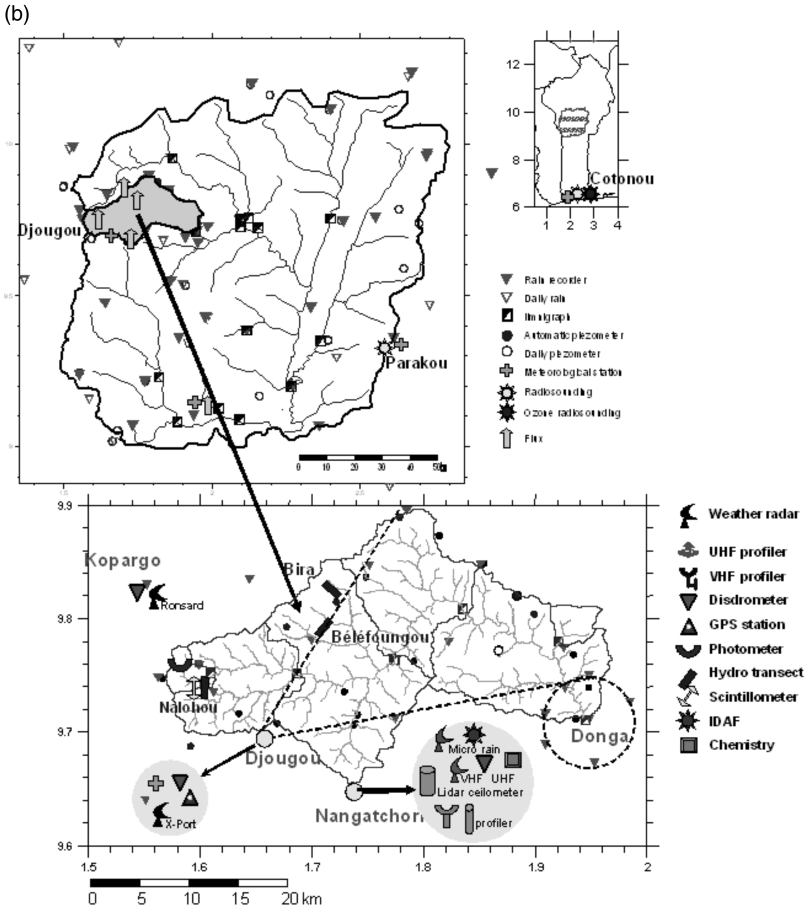


Figure 4. (*Continued*)

instruments was specifically deployed for the SOP (Figures 3 and 4); adding up the LOP, EOP and SOP instruments, several hundreds of sensors were deployed over the land and ocean at the peak of the experiment in 2006. This number does not include the instruments deployed onboard the six aircraft that participated to the various SOPs and for which details are given below in sections 5.

### 3.3. Set-up and co-ordination

One challenge of AMMA was to ensure an efficient co-ordination of the deployment of all the LOP/EOP/SOP instruments, both in terms of scientific strategy and in terms of logistics. To maintain a coherent strategy and to efficiently co-ordinate the deployment, 11 task teams (TTs) devoted to the co-ordination of an ensemble of instruments were set up.

Each TT covers a given domain in terms of space- and time-scales, as summarised in Table I. It is not always easy to define precise boundaries between scales or between processes that interact (it is precisely the goal of AMMA to study these interactions) and there were thus some overlaps between TTs, especially when it came to include EOP measurements (TT1 to TT6) into the SOP strategy (TT7 to TT9). Therefore, the overall coherency of the observation strategy and deployment was maintained by an International Coordination and Implementation Group, working in close co-ordination with the International Scientific Steering Committee. Details on the strategy and *modus operandi* of each TT may be found in the International Implementation Plan (AMMA-ICIG, 2006). Another key component of AMMA is the emphasis on the training of young African scientists, through various formal academic or ad hoc (summer schools) programmes, and through direct engagement in the field operations.

The intensive operations of the SOP year and the specific actions required for scheduling and co-ordinating the aircraft operations were planned by the AMMA Operation Centre. Details on this particular component of AMMA are given in section 5.

## 4. Documentation of the 2005–2007 years by the EOP monitoring

### 4.1. Aerosols

West Africa is the world's largest source of biomass-burning aerosols and mineral dust, and satellite sensors consistently indicate that West African aerosol plumes are the most widespread, persistent and dense found on Earth (e.g. Husar *et al.*, 1997). This has an important impact on the living conditions of the West African population as well as a larger global impact: the effects of dust and carbonaceous aerosols on climate change via their direct and indirect effects and complex potential feedback mechanisms lead to major uncertainties in radiative forcing, feedback and climate modelling scenarios (IPCC, 2007). Adding to the long-term AERONET-PHOTONS monitoring set-up (Holben *et al.*, 2001), a strong aerosol observation programme was thus built within AMMA, including an EOP ground deployment, a dedicated SOP (SOP0, Haywood *et al.*, 2008) and a specific programme within SOP1 and 2 (see section 5.3 below). The AMMA aerosol programme is thus multiscale, reflecting the fact that the seasonal cycle of dust and smoke is directly linked to the WAM meteorological processes.

While the long-term monitoring programme aims at documenting how climatic parameters control the aerosol emissions, the EOP focused on studying the mineral dust content and its transport toward the North Atlantic Ocean. This transport can take place at different altitudes within the Saharan air layer (Carlson and Prospero, 1972), but also within the surface layer (e.g. Chiapello *et al.*, 1995; Formenti *et al.*, 2001). The altitude of the dust transport layer significantly modulates its radiative effect and also induces different deposition patterns, thus impacting the regional dust budget. Therefore there is an important interaction between dust and dynamics, with the aerosol loadings modifying the thermodynamics and winds in the monsoon system, while the winds in turn lift and redistribute dust. This interaction has demanded the integration of aerosol measurements with upper-air data and model analyses (see section 4.3 and Tompkins *et al.*, 2005).

The specific EOP set-up is a *Sahelian Dust Transect* made of three stations (Figure 3) located in M'Bour (Senegal, 16.96°W, 14.39°N), Cinzana (Mali, 5.93°W, 13.27°N) and Banizoumbou (Niger, 2.66°E, 13.52°N). Each of these sites is equipped with a Tapered Element Oscillating Microbalance with a PM10 (particulate matter smaller than 10 μm diameter) inlet, measuring the concentration at ground level, an automated collector monitoring wet and dry deposition, a passive collector for total deposition, a sunphotometer from the AERONET-PHOTONS network, and a meteorological station providing the classical parameters (wind speed and direction, relative humidity and temperature). The vertical profile of aerosol was measured at some periods in 2006 with a micro-lidar operating at 532 nm. Each station allows for precise local-scale measurements while the ensemble of three stations provides a regional view of the distribution of coarse aerosol over West Africa.

To select the PM10 concentrations that are mainly caused by mineral dust, we excluded from the computation of the monthly mean the measurements obtained for wind sectors originating from areas including other aerosol sources (i.e. in M'Bour oceanic wind sectors to avoid sea salts and wind sectors from urban areas to avoid pollution aerosols). The monthly mean dust concentrations measured at the three stations from 2006 to 2008 are plotted in Figure 5. A maximum in winter and spring and a minimum during the wet season are the two features shared by the three stations. This seasonal cycle is consistent with the average seasonal cycle of the aerosol optical thickness observed in Banizoumbou (2002–2004), Agoufou (Mali) (2005–2006) and Ouagadougou (Burkina Faso) (1996–2003) by the sunphotometer of the AERONET-PHOTONS network

(Ogunjobi *et al.*, 2008). However, a strong year-to-year variability is superimposed on this seasonal cycle. The standard deviation of the monthly concentration averaged over the three years tends to increase as the concentration increases. In addition, an eastward gradient is observed with monthly mean in the dry season in the range of 300–400 μg.m$^{-3}$ at Banizoumbou, 200–300 μg.m$^{-3}$ at Cinzana and 100–200 μg.m$^{-3}$ at M'Bour. For comparison, the monthly mean concentration measured in the Cape Verde Islands from

**Table I**a. Topic and scale of interest of the LOP/EOP AMMA task teams. Dark grey is for main scale of interest, light grey is for other scale of interest. Some EOP instruments of TT2a remained active post-EOP (2008, 2009), thus having some LOP bearing. Also, it should be kept in mind that all EOP instruments contribute to the SOP campaigns. (see for instance TT2a and TT2b) but are not SOP-specific.

| Task team | Observation Period | | Spatial Scale | |
|---|---|---|---|---|
| | | Regional | Meso | Sub-Meso (Local) |
| **TT1**<br>Upper air Obs.<br>(RS, GPS, UHF&VHFProfilers) | LOP | | | |
| | EOP | West Africa | | |
| | SOP | West Africa | Southern quadrilateral | |
| **TT2a**<br>Surface flux Obs.<br>(Flux stations, scintillometers) | LOP | | | |
| | EOP | Climatic transect* | 3 meso-sites | ▨ |
| | SOP | | | |
| **TT2b**<br>Aerosol & Radiation | LOP | West Africa | | ▨ |
| | EOP | West Africa | | ▨ |
| | SOP | | | |
| **TT3**<br>Land Surface Obs on the Mali meso-site. | LOP | | Gourma (Northern Sahel) | Agoufou local site |
| | EOP | | | |
| | SOP | | | |
| **TT4**<br>Land Surface Obs on the Niger meso-site. | LOP | | Niamey meso site and Kori de Dantandou | Banizoumbou |
| | EOP | | | |
| | SOP | | | |
| **TT5**<br>Land Surface Obs on the Bénin meso-site. | LOP | | Upper Ouémé Catchment | Donga and Ara catchments |
| | EOP | | | |
| | SOP | | | |
| **TT6**<br>Oceanic Observations<br>(Ships, Buoys, coastal obs.) | LOP | | | |
| | EOP | Guinea Gulf | | |
| | SOP | All Trop. Atlantic | ▨ | |

The climatic transect is a zone centred on 2°E and extending from the Gulf of Guinea (5°N) to the heat-low (20°N)

**Table Ib**. Same as Table la except for specific SOP Task Teams.

| | | | | |
|---|---|---|---|---|
| **TT7** | LOP | | | |
| Aerosol & Radiative impact | EOP | | | |
| (Aircraft+intensive ground obs) | SOP0 | Climatic transect*+Dakar | | |
| **TT8** | LOP | | | |
| Wet Monsoon intensive obs | EOP | | | |
| (Aircraft, Balloons, ships, intensive land obs) | SOP1&2 | Climatic transect*+ Meso sites + Ouagadougou + Dakar | | Enhancement of mesosites |
| **TT9** | LOP | | | |
| Downstream studies | EOP | | | |
| (Aircraft, Balloons, land obs) | SOP3 | Dakar and Ocean to the West | | |
| **TT10** | LOP | | | |
| Accurate radiative budget | EOP | | | |
| (ARM Mobile Facility) | All SOPs | | | Niamey |

1992 to 1995 never exceeded 100 µg.m$^{-3}$ (Chiapello *et al.*, 1995). In this location, due to a low-level transport, the maximum concentration is measured in December, while the surface concentration in summer are five times lower (Chiapello *et al.*, 1995). At the beginning of the wet season (June) a secondary maximum is generally observed at Banizoumbou and at Cinzana but not at M'Bour. This second maximum is due to local dust emission associated with the strong squall lines at the leading edge of mesoscale convective systems; it was also detected on the monthly aerosol optical depth in Banizoumbou, Agoufou and Ouagadougou and attributed to local dust sources (Ogunjobi *et al.*, 2008). The gradient in the dust concentrations from Niger to Senegal can be linked to the precipitation gradient between the three stations that lead to less intense dust emission and more scavenging from east to west.

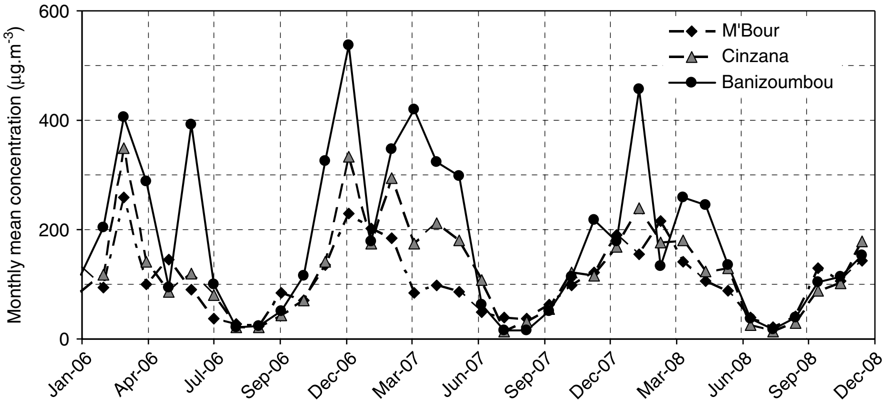


Figure 5. Monthly mean concentrations of PM10 for 'dust' wind sectors in M'Bour (Senegal), Cinzana (Mali) and Banizoumbou (Niger).

The analysis of the whole dataset will allow us to quantify the atmospheric dust content and deposition pattern over western Africa and their variability at various time and spatial scales and to further understand what are the key parameters controlling this variability. Comparisons between the surface concentrations, aerosol optical depth and vertical aerosol profiles are going on to investigate the seasonal variations in the altitude of the dust layers over West Africa. Such comparisons between aerosol optical thickness and surface concentration are also useful to evaluate the relevance of aerosol thickness derived from remote sensing, as a proxy of the human exposure level for health issues. It also allows us to further constrain the regional and global models of the mineral dust cycle that are generally tested against the aerosol optical thickness from AERONET-PHOTONS photometers only.

### 4.2. The ocean

The ocean plays a key role in the WAM dynamics, especially during the onset phase. The EOP oceanic campaigns thus aimed at providing measurements needed for the study of processes determining:

- the seasonal to interannual variability of sea-surface temperature and sea-surface salinity, mixed-layer depth and heat content, in the tropical Atlantic and in the Gulf of Guinea;
- the seasonal evolution of the cold tongue-ITCZ-WAM system.
- the air–sea exchanges in the tropical Atlantic during the monsoon onset of the SOP year, through both the ocean and the atmospheric boundary layers.

The EOP part of the programme was called EGEE, and consisted of two annual cruises; one during the establishment of equatorial upwelling, the cold tongue in sea-surface temperatures and the monsoon onset (June), and one at the end of the equatorial upwelling corresponding to a warming of the sea surface and the retreat to the south of the ITCZ (September). To assess the seasonal and interannual variability of these key oceanic conditions, the same tracklines were repeated with particular attention directed at the 10°W meridional section, which had been occupied several times during previous PIRATA and EQUALANT cruises (Brut *et al.*, 2005), and at the 2°50′E meridional section (Figure 3(a) and Bourras *et al.*, 2009, their fig. 2). In addition to classical acoustic Doppler current profilers and hydrological measurements, 34 surface drifters and 45 Argo profilers (Argo being a global array of temperature/salinity profiling floats) were deployed during the cruises. The five PIRATA ATLAS buoys located in the Gulf of Guinea (Figure 3(a)) were also maintained during the June cruises.

The June 2006 campaign has seen the concomitant deployment of three research vessels (the French *Atalante*, the German *Meteor* and the US *Ronald H. Brown*), equipped with atmospheric, radiosounding and turbulent flux measurement capacities, documenting simultaneously the tropical Atlantic during the monsoon onset.

During each cruise, all measurements made with conductivity–temperature–depth and expendable bathythermograph instruments were sent in quasi-real time to the CORIOLIS Data Center for operational oceanography and assimilation in the MERCATOR model. Thus, from the six EGEE cruises carried out in 2005, 2006 and 2007, a total of 322 conductivity–temperature–depth profiles and 670 expendable bathythermograph (and expendable conductivity–temperature–depth) profiles have been provided for assimilation (the 251 balloon soundings of the SOP cruises were also provided in real time for assimilation in weather prediction models).

An example of significant results obtained during these cruises is provided in Figure 6, illustrating the vertical distribution of the ocean temperature at 10°W (in the west of the Gulf of Guinea), between 10°S and 1°30′N and from the surface down to 300 m depth, in June 2005, June 2006 and June 2007. These sections clearly show the large differences of ocean temperature observed within the upper layer, from one year to the other. In 2005, the surface water was around 22–23°C north of 2°S – a signature of the equatorial upwelling that appears in boreal summer. In 2006, the surface water was significantly warmer (above 25°C) everywhere, while in 2007 it was about 23–24°C north of 4°S. As the ocean temperature strongly affects the energy exchanges at the air–sea interface, these differences have to be considered in relationship with the WAM onset, which occurred in early June in 2005, early July in 2006 and mid June in 2007 (see also Figure 7, showing the variations in the mean Saharan heat-low for these years, and Figure 9, regarding the seasonal cycle of rainfall for the same period).

### 4.3. Monitoring of the atmosphere at the regional scale

The regional-scale atmospheric dynamics are fundamental to the evolution of the monsoon system. In order to understand the processes controlling the monsoon, it is necessary to develop an accurate description of phenomena such as the monsoon layer, with its mean southwesterly flow, African easterly waves, the African easterly jet, the Saharan heat-low and the overturning monsoon circulation, each of which varies on diurnal and longer time-scales. Prior to AMMA the atmospheric monitoring network, and the upper-air network in particular, was in a degraded state, meaning that regional-scale studies of the atmosphere, whether as case-studies or climatologies, were based on extremely sparse data, or in many cases, no *in situ* data at all. Therefore, a central part of the regional atmospheric observational strategy has been to reinforce the monitoring network, and to introduce more intensive monitoring for the EOP period; at the heart of this monitoring is the radiosonde network (see Parker *et al.*, 2008).

The radiosonde network shown in Figure 3(a) represents a widespread refurbishment of the pre-AMMA operational network, but its operational activity during the AMMA periods has also been enhanced in some key

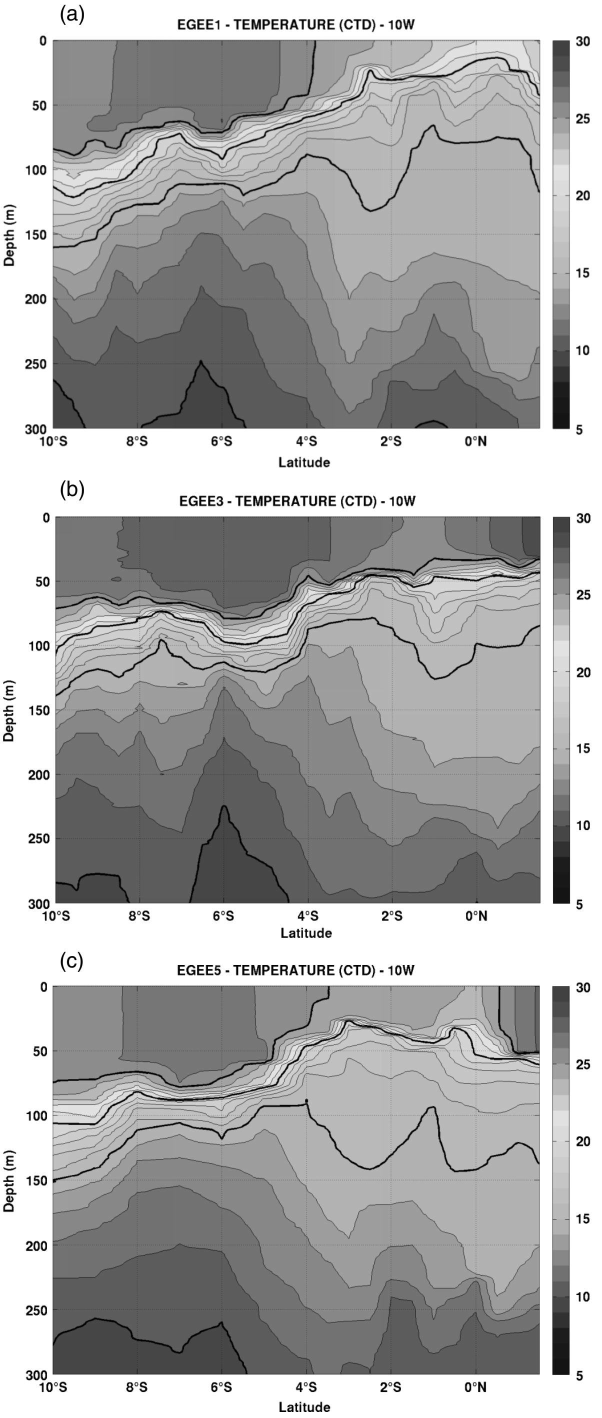


Figure 6. Vertical (0–300 m) sections of oceanic temperature in the Gulf of Guinea, along 10°W and between 10°S and 1°30′N. June 2005 (top), June 2006 (middle), June 2007 (bottom). Courtesy of Frédéric Marin. This figure is available in colour online at www.interscience.wiley.com/journal/qj

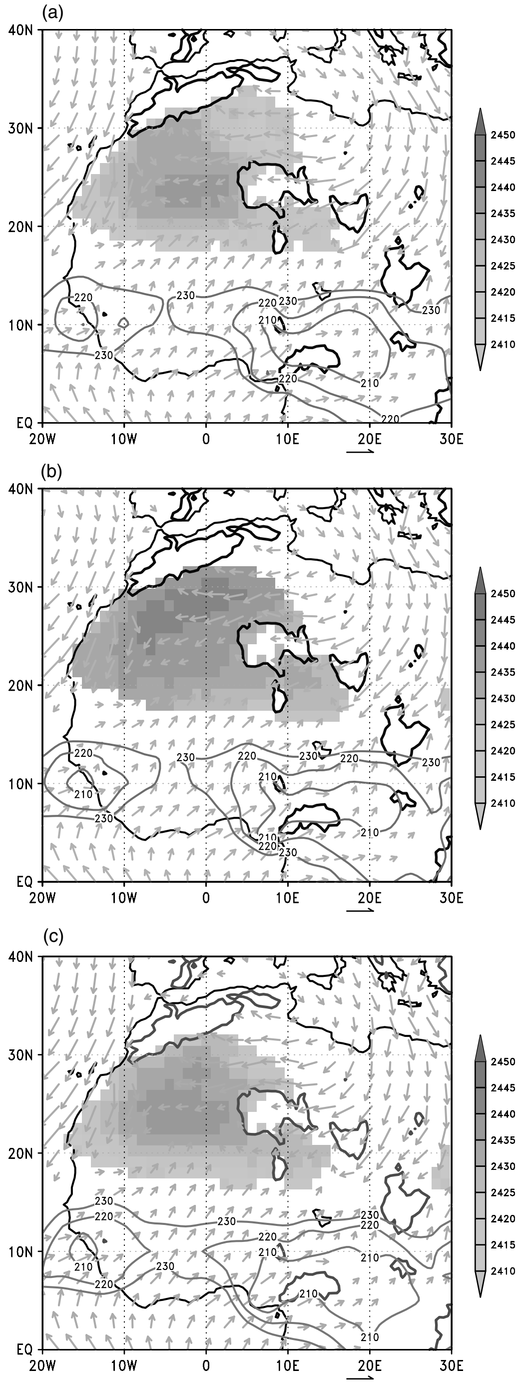


Figure 7. West African heat-low depth (colour, in m) derived from ECMWF operational analyses and averaged over July, August and September in (a) 2005, (b) 2006 and (c) 2007. The heat-low depth is obtained as in Lavaysse *et al.* (2009). Averaged wind vectors at 925 hPa are overlain (arrows). Contours of outgoing long-wave radiation (in W $m^{-2}$) from NOAA Television Infrared Observation Satellite (TIROS) satellites are also overlain. Courtesy of Christophe Lavaysse. This figure is available in colour online at www.interscience.wiley.com/journal/qj

aspects. In particular, a conspicuous gap in the network prior to AMMA lay in the monsoon inflow zone, along the Guinea Coast and to the south of the Sahel, between Dakar and Douala, meaning that effectively there had been no measurements of the monsoon inflow for several years. For this reason, four new stations were installed for AMMA, at Tamale, Parakou, Abuja and Cotonou, while the station at Abidjan was reactivated (see Figure 4(a)).

Similarly, the northern station of Tessalit (Mali) was reactivated for a period of a few weeks, in order to better sample the Saharan heat-low. Therefore, with the soundings made from research vessels, described in section 4.2, a complete upper-air transect from the Atlantic to the Sahara (Figure 2) was achieved. To sample the diurnal cycle of the monsoon, the sounding frequency was increased from 2 to 4 per day at seven key stations from June to September 2006.

Figure 7 illustrates a three-year climatology of the monsoon system over land (as in Lavaysse *et al.*, 2009), which is based on ECMWF analysis data, incorporating the new radiosonde measurements which were stimulated by AMMA. This demonstrates considerable interannual variability in the heat-low and the monsoon circulation, each of which is, for the first time, based on models assimilating consistent *in situ* measurements (including the soundings made over the ocean). Notably, the SOP year of 2006 shows the strongest mean heat-low in these data, possibly linked to the late onset of the monsoon rains (see also section 4.4 and Janicot *et al.*, 2008).

In addition to the radiosondes, three Global Positioning System (GPS, see Bock *et al.*, 2008) stations and one VHF (very high frequency) profiler (Figure 3(b)) were used in the EOP to obtain upper-air observations with a better time sampling frequency. The GPS and VHF data were not assimilated in real time but they are an important contribution for the computation of water and energy budgets, for direct analysis of the atmosphere dynamics and for model evaluation (Bock *et al.*, 2008). The SOP deployment included three additional GPS stations, one UHF (ultra high frequency) profiler located in the Donga super-site and four sodars installed on the Niamey meso-site (Figure 4).

Considerable effort has been needed to generate consistent datasets from the different atmospheric sensors deployed in the AMMA regional network. The diversity of sensors includes six different types of radiosonde: Nuret *et al.* (2008), and Agusti-Panareda *et al.* (2009) have published descriptions of some of the methods needed to deliver calibrated upper-air data from the region, and to generate model reanalyses using these data.

Overall, the regional atmospheric monitoring programme of the EOP and SOP has achieved its aims of delivering a consistent set of atmospheric measurements, on a network which was designed according to the scientific needs of the programme. In particular, for the first time in several decades a regular array of upper-air measurements has been collected in the monsoon inflow region between the Guinea Coast and the Sahel, enhanced in the SOP periods by additional soundings over the ocean and Sahara. The provision of nocturnal upper-air data from a number of additional stations during the EOP and SOP periods has been a step forward in our understanding of the monsoon system and the data needed to monitor it. Evaluation of the model analyses and reanalyses making use of this dataset is an ongoing task.

### 4.4. Rainfall, vegetation and hydrology

#### 4.4.1. *Enhancement of the LOP monitoring programme*

The land surface LOP/EOP programme provides a comprehensive set of data, for water cycle studies across different scales and for hydrological model parametrization. This is certainly the first such programme carried out in West Africa on at least two accounts: (1) joint and coherent monitoring of three sites over several years, covering a range of different surface conditions; and (2) deployment of new sensors never previously used in this region, especially for the monitoring of surface fluxes (latent and sensible heat, carbon dioxide) and soil moisture. While the preliminary results obtained from the process knowledge perspective are published in Lebel *et al.* (2009), a brief account of the rainfall conditions during the EOP years is given below, in association with some comments on their impact on vegetation and hydrology.

#### 4.4.2. *Overall rainfall conditions of the EOP years*

The three time series of Figure 8(a)–(c) illustrate the evolution of the rainfall conditions since the 1950s in three sub-regions of the AMMA domain. After the drought that struck the whole region of West Africa in the 1980s and 1990s, a return to larger rainfall was observed over the Sudanian region (roughly south of 11°N, Figure 8(c)) at the end of the 1980s, while the drought continued over the Sahel. At the end of the 1990s, a recovery was observed over the central and eastern Sahel (Figure 8(b)), while the drought remained unabated in the western part of the region (roughly west to 5°W, Figure 8(a)). The EOP years were in line with the trend observed since the beginning of the 2000 decade. The average rainfall computed over the three EOP years displayed a strong negative anomaly, with respect to the 1950–1990 average, west of 7°W, and a significant negative anomaly (larger than 10%) was also observed over northern Nigeria (Figure 8(d)). In contrast, rainfall significantly exceeded the 1950–1990 average in the northern Sahel, east of 5°W, and increasingly so towards the east. The central part of our region of study recorded rainfall close to the average, but a slight negative anomaly was observed for the three EOP years in the Ouémé region (Figure 8(c)). The average conditions described above hide a strong sub-scale variability; both in time (interannual variability, seasonal cycles) and in space (strong mesoscale gradients), that will be briefly analysed hereafter based on the graphs of Figure 9.

#### 4.4.3. *Seasonal cycle*

The three EOP years displayed significant contrasts to each other, as shown in Figures 9(a) and 10(b):

- In 2005, the rainfall start conformed to the climatology in the two Sahelian meso-sites and over the whole Sahel more generally. Rainfall remained well distributed over the whole season and annual totals were close to the long-term average for 1950–1989; this resulted in an early development of the vegetation and an overall good herbaceous biomass production (Figure 9(c)) and abundant cropping. This is coherent with the normal upwelling conditions observed over the ocean (see Figure 6) and a monsoon onset occurring close to its average date (22 June). The discharge of the Niger river (Figure 9(d)) was significantly larger than in 2004 (a year of

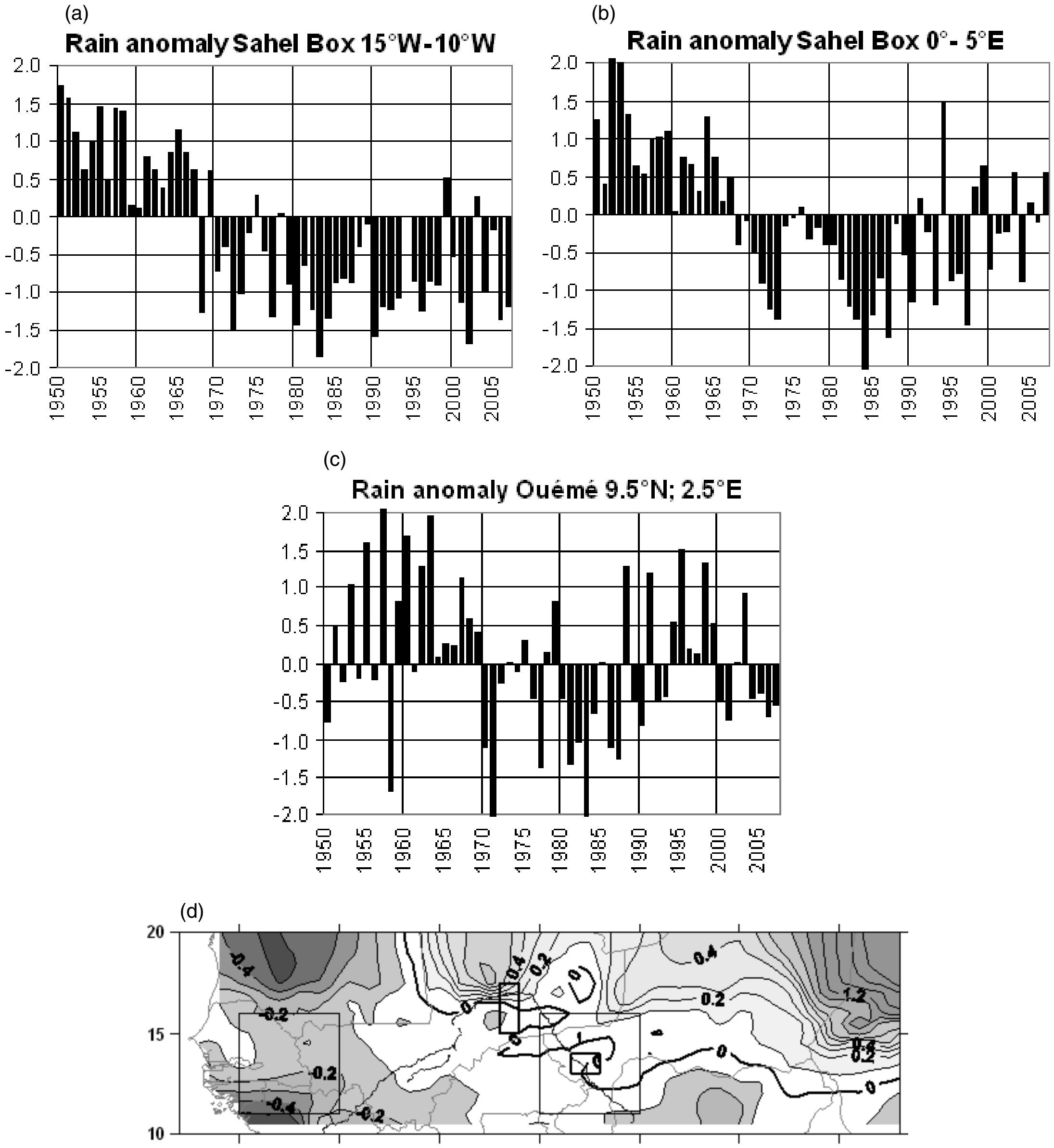


Figure 8. EOP rainfall. (a) to (c): Time series of normalised deviations from the 1950–1989 average for: (a) the 5° × 5° western Sahel box shown in map (d); (b) the 5° × 5° central Sahel box shown in map (d); and (c) the Ouémé catchment (14 600 km$^2$ – see location in Figure 4(a)). (d) Average annual rainfall (Sahelian domain) over the three EOP years (2005–2007) expressed as the normalised difference △ from the average annual rainfall over the reference period 1950–1989: △ = {(P2005–2007 – P1950–1989)/P1950–1989}. This figure is available in colour online at www.interscience.wiley.com/journal/qj

strong rainfall deficit over the Sahel, and the source of severe famines in places); however, given the good time-distribution of rainfall, local runoff was not so strong and the peak discharge was limited to 1740 m$^3$ s$^{-1}$ in early September; the second peak flow traditionally observed in December–January, and corresponding to the runoff produced during the core of the rainy season in the mountains of Guinea, was limited to 1680 m$^3$ s$^{-1}$, reflecting a lower than normal rainfall in the southwestern part of the AMMA domain.

- The rainy season started very late in 2006, corresponding to a delayed monsoon onset linked to a late appearance of the cold tongue in the Gulf of Guinea (Figure 6). This late start was followed by a healthy rainy season (Janicot *et al.*, 2008), especially in the northern Sahel, the annual rainfall finally being close to average over the central Sahel (Figure 8(b)) but displaying a strong negative anomaly over the western Sahel (Figure 8(a)). In the Sahel, the vegetation was able to recover and the biomass production was close to that of 2005 in the north of the region but significant millet yield deficit was observed in other parts of the Sahel. This year was also characterised by heavy floods in several parts of our study area, most notably in the Aïr region (second half of August) and in northern Togo and Ghana in early

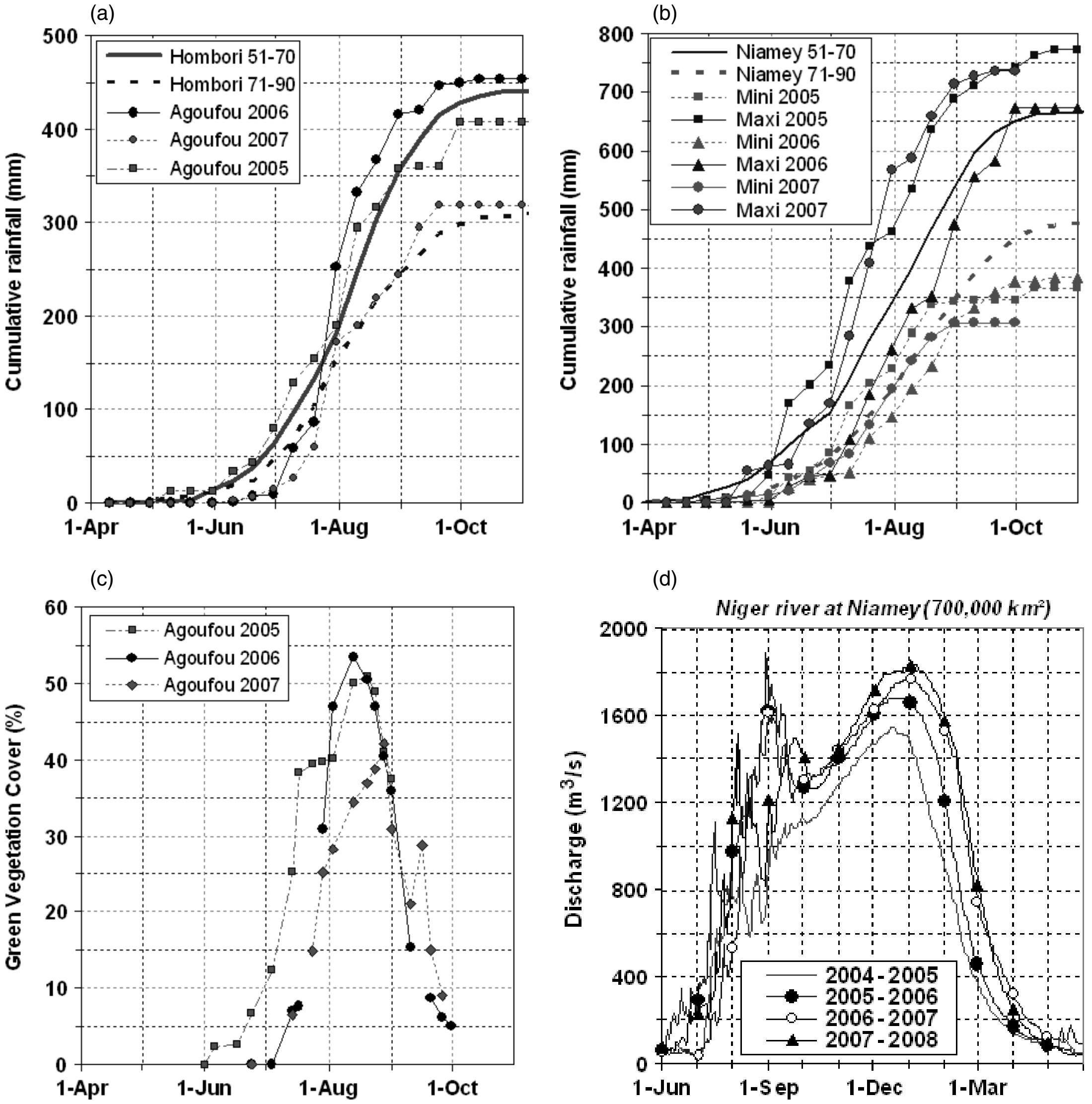


Figure 9. Seasonal cycle of the three EOP years: rainfall, vegetation, hydrology. (a) Rainfall in the Gourma meso-site; (b) Rainfall in the southwest Niger meso-site; (c) Herbaceous vegetation cover at the Gourma central super-site; (d) Mean daily discharge of the Niger river at Niamey. This figure is available in colour online at www.interscience.wiley.com/journal/qj

September, with significant losses for the local communities. As a result, the first flood peak of the Niger river occurred at the end of August and was above normal at 1890 $m^3$ $s^{-1}$, while the early January flood was at 1770 $m^3$ $s^{-1}$, thus significantly smaller than the September flood.

- The year 2007 displayed strong heterogeneities over the domain under study. Rainfall started late in the Gourma, as in 2006, but this was not compensated by above-normal rainfall in August, so that the annual anomaly was strongly negative there, explaining why the Gourma has a close to average rainfall in Figure 8(d), the above-average rainfall of 2006 being balanced by the strongly below-average rainfall of 2007, with 2005 being close to average. The vegetation cover was consequently much lower over the Gourma in 2007 than it was in 2005 and 2006. By contrast, the 2007 rainfall was both on time and abundant in the southwest Niger meso-site. The Niger river discharge curve reflects these heterogeneities, with two lower peak flows in early August (1520 $m^3$ $s^{-1}$) and early September (1480 $m^3$ $s^{-1}$) and a larger peak flow in January (1830 $m^3$ $s^{-1}$), reflecting the good rainy season over the southern part of the domain.

From a hydrological perspective, it is worth noting that two out of the three years witnessed a larger peak flow in September than in January, in strong opposition with the hydrologic regime of the wet period of the 1950s and 1960s, when the December peak flow was in the order of 2000 $m^3$ $s^{-1}$ while the September peak flow was in the order of 1200–1300 $m^3$ $s^{-1}$. The larger streamflow during the first flood of the Niger river – the flood produced by the Sahelian rainfall – is commonly explained by the vegetation reduction in the Sahel, source of much stronger runoff coefficients (for more details, see Descroix *et al.*, 2009; Lebel and Ali, 2009).

#### 4.4.4. *Spatial variability*

The strong gradients of the annual rainfields over short distances have been extensively studied from the long-term recording rain-gauge network that has covered the southwest Niger meso-site since 1990 (see e.g. Balme *et al.*, 2006). An illustration of this variability is given in Figure 9(b), where the seasonal cumulative rainfall curves are plotted for the station which recorded the maximum rainfall and the station which recorded the minimum rainfall of each EOP year. It can be seen that each year the spread between the maximum station and the minimum station is larger than the spread between the average rainfall of the 20 wet years and the average rainfall of the 20 dry years, recorded at the Niamey synoptic station. This underlines how risky a diagnostic on the abundance of the rainy season is, based solely on a single station, since for the EOP each year could have been classified as very dry or very wet, depending on the station chosen.

## 5. The overall SOP deployment

The SOP periods represent the most intense observational activity of the AMMA programme and were aimed at providing comprehensive studies of the important higher-frequency processes which shape the monsoon system. The SOPs were implemented through a denser sampling of the three-dimensional (3-D) West African 'box', based on (1) the enhancement of the EOP networks (provision of new instruments and the operation of existing instruments in a more intense mode, as described in previous sections) and (2) the deployment of new instruments (Table II).

### 5.1. Platforms and co-ordination

#### 5.1.1. *Ground-based SOP deployment*

At the surface, three main actions were undertaken:

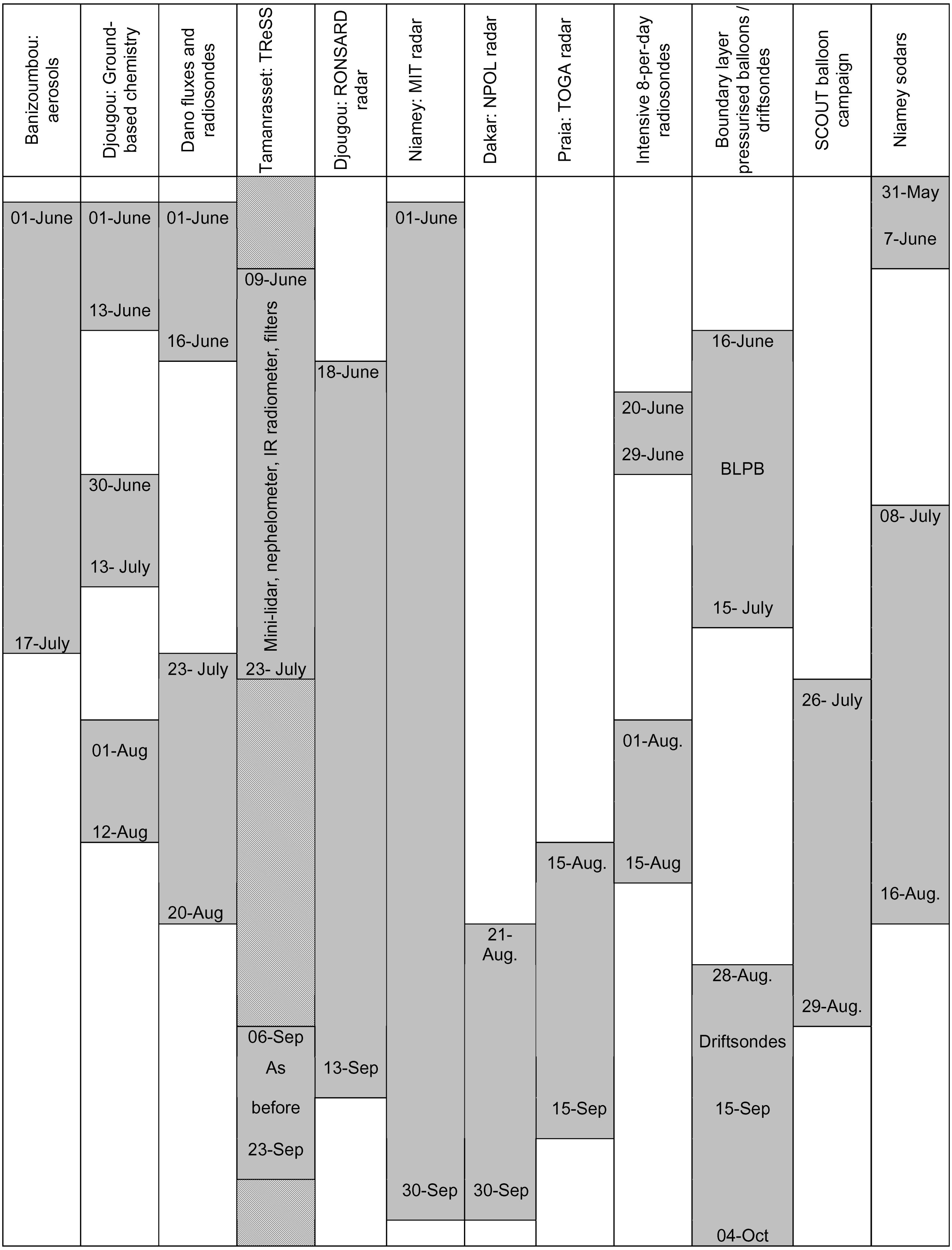
- On the sea, coverage of the tropical Atlantic by three ships was undertaken for one month before and during the monsoon onset (see section 4.2 above).
- The regional coverage on the continent was enhanced by adding to the EOP deployment three additional meso-sites (Figure 3(a)): the Dakar site, equipped with the US radar NPOL, is a land–ocean transition site, which was further developed in August–September 2006 by the installation of the TOGA C-band radar at Praia in the Cape Verde Islands; at Dano (Burkina Faso), surface-layer monitoring and a mobile radiosonde station were installed, aimed at documenting the east–west variability in the land–atmosphere coupling (relative to the southwest Niger and Ouémé meso-sites); to the extreme north, at Tamanrasset, the Transportable Remote Sensing Station (TReSS) was deployed to measure aerosol and cloud radiative properties through a synergy of backscatter lidar, radiometry and *in situ* sampling within the Sahara (Cuesta *et al.*, 2008).
- Two of the meso-sites became 'super meso-sites'. The southwest Niger site was upgraded for aerosol/radiation measurements with the ARM Mobile Facility (Miller and Slingo, 2007) installed at Niamey airport for the whole of 2006 and the Banizoumbou super-site being equipped with an impressive and unique set of instruments dedicated to a high-resolution and high-frequency sampling of the aerosol loading and optical properties (AMMA-ICIG, 2006). Also installed at the Niamey airport was the C-Band MIT Doppler weather radar, for fine-resolution precipitation measurements and for studying the dynamics of convective systems, in conjunction with aircraft surveys. On the Ouémé meso-site, the Donga super-site in Bénin was equipped with two Doppler and polarised weather radars, two profilers, and various other vertically pointing instruments, as well as a lightning detection network, providing a detailed sampling of the atmospheric variables conditioning the water and energy budgets at the mesoscale. Aerosol and chemistry measurements were also enhanced at Djougou to provide an ancillary aerosol (of predominant biomass-burning origin) site in a more humid environment.

#### 5.1.2. *Atmospheric SOP deployment from balloons and aircraft*

In the atmosphere, the SOP observations were obtained by a combination of balloons and aircraft flights:

- Through the partnership between AMMA and the SCOUT programme (http://www.ozone-sec.ch.cam.ac.uk/scout_o3/), 19 ozone sondes, six combined $H_2O$, ozone and backscatter sondes, three combined ozone and backscatter sondes, one sonde from the University of Wyoming and six CNES stratospheric balloons (with a variety of payloads devoted to water vapour, chemistry, aerosols and cloud measurements in the tropical tropopause layer) were also launched from Niamey in SOP2. The 'fixed' profiling network was also supplemented by soundings from 'mobile' platforms. In total, 510 dropsondes were released from research aircraft over the continent and the adjacent ocean, with the majority of these being transmitted to the Global Telecommunication System. During SOP3, six driftsonde gondolas were successfully launched from Zinder (Niger) and these deployed a total of 129 dropsondes as they moved westward over the continent and the tropical Atlantic (the last dropsonde was released on 4 October). Finally, 15 boundary layer pressurized balloons were launched from Cotonou, to move generally northeastward in the monsoon flow, between 15 June and 15 July 2006.
- Six research aircraft were deployed in the region for a total of 14 operational deployments for individual aircraft, as summarised in Table III. The aircraft

Table II. Deployment details for ground-based instruments during SOP1–SOP3: text indicates the start and end dates of operations and basic description of instrumental fit. Successful operation rate during the indicated periods were generally over 85% (see http://aoc.amma-international.org/reports/status/).



| Banizoumbou: aerosols | Djougou: Ground-based chemistry | Dano fluxes and radiosondes | Tamanrasset: TReSS | Djougou: RONSARD radar | Niamey: MIT radar | Dakar: NPOL radar | Praia: TOGA radar | Intensive 8-per-day radiosondes | Boundary layer pressurised balloons / driftsondes | SCOUT balloon campaign | Niamey sodars |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 01-June<br>17-July | 01-June<br>13-June<br>30-June<br>13- July<br>01-Aug<br>12-Aug | 01-June<br>16-June<br>23- July<br>20-Aug | 09-June<br>Mini-lidar, nephelometer, IR radiometer, filters<br>23- July<br>06-Sep<br>As<br>before<br>23-Sep | 18-June<br>13-Sep | 01-June<br>30-Sep | 21-Aug.<br>30-Sep | 15-Aug.<br>15-Sep | 20-June<br>29-June<br>01-Aug.<br>15-Aug | 16-June<br>BLPB<br>15- July<br>28-Aug.<br>Driftsondes<br>15-Sep<br>04-Oct | 26- July<br>29-Aug. | 31-May<br>7-June<br>08- July<br>16-Aug. |

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Table III. Deployment details for aircraft during SOP1–SOP3. For each deployment, the start and end dates of operations are given, followed by the number of flights (bold type) and basic description of instrumental fit, while operational bases are colour-coded (red = Niamey, blue = Dakar, yellow = Ouagadougou). Note that science transit flights before or after each deployment are not counted.

| ***Aircraft*** | ***ATR42*** | ***BAe146*** | ***DC-8*** | ***Falcon F20*** | ***Falcon D20*** | ***Geophysica*** |
|---|---|---|---|---|---|---|
| *Operator* | *SAFIRE, France* | *FAAM, UK* | *NASA, USA* | *SAFIRE, France* | *DLR, Germany* | *EEIG* |
| SOP1: 15 May - 30 June 2006 | 01/06/06<br>**10:** Aerosol (including dust) and turbulence<br>15/06/06 | | | 01/06/06<br>**12:** LEANDRE 2 and dropsondes<br>15/06/06 | | |
| SOP2: 1 July - 31 August 2006 | 01/07/06<br>**10:** Aerosol (including dust) and turbulence<br>15/07/06<br>25/07/06<br>**19:** Aerosol & chemistry in clear air and clouds; turbulence<br>21/08/06 | 17/07/06<br>**24:** Chemistry, aerosol and dropsondes<br>17/08/06 | | 01/07/06<br>**4:** LEANDRE 2 and dropsondes<br>15/07/06<br>10/08/06<br>**10:** Chemistry and dropsondes<br>21/08/06 | 01/07/06<br>**5:** WIND<br>14/07/06<br>01/08/06<br>**8:** Chemistry and aerosols<br>16/08/06 | 01/08/06<br>**5:** Chemistry and aerosols<br>13/08/06 |
| SOP3: 15 Aug - 30 Sep 2006 | | 21/08/06<br>**6:** Chemistry, aerosol and dropsondes<br>29/08/06 | 15/08/06<br>**13:**<br>14/09/06 | 06/09/06<br>**8:** RALI and dropsondes<br>15/09/06<br>16/09/06<br>**12:** RALI and dropsondes<br>30/09/06 | | |

were successfully operational during all of the periods shown in the table.

### 5.1.3. *Operational co-ordination and decision-making*

The operational co-ordination of the huge number of measurement platforms operating at remote locations all over West Africa with aircraft flight and sea cruises was operationally speaking the most challenging part of the SOP year. This was carried out through the multi-site AMMA Operational Centre (AOC); the headquarters of the AOC were located in Niamey at a refurbished villa of the Niger Direction de la Météorologie Nationale. Antennas of the AOC were located in Ouagadougou (Burkina Faso), Djougou (Benin) and Dakar (Senegal). Operational products such as satellite images and weather prediction model outputs are not routinely available in West Africa. Also, there was no meteorological centre able to provide the necessary weather forecast for flight decision making. Thus, in addition to the classical decision-making organisation and associated logistical co-ordination that it requires, which is found in any field experiment involving scientific aircraft, two original and pivotal elements were set up by the AOC. First, images from some key AMMA instruments and operational products, as well as a table of the instrument status were gathered on a Web site (http://aoc.amma-international.org/) operated from Météo-France in Toulouse with a mirror at the AOC in Niamey. Secondly, a unique and original forecasting experiment was set up. A new forecasting method WASA/F was designed (Lafore *et al.*, 2006) during a dry run exercise in 2005 and ensuing training schools. During the 'wet' SOPs, from June to September, meteorologists from many different West African countries came to Niamey to form forecasting teams, producing the WASA and WASF at the African Centre of Meteorological Application for Development (ACMAD), Niamey. They would present their analyses and forecasts at the early morning and evening meetings to the AMMA scientists, which generated fruitful interactions between the forecasters and the researchers. Developing new forecasting techniques and training were thus two important aspects of this activity which will have long-term benefits for the West African community of meteorologists. Whereas accurate forecast were no longer necessary in 2007 for flight co-ordination purposes, ACMAD continued to produce WASA and WASF reports.

## 5.2. SOP0 – The dry phase of the WAM

The SOP0 period (January and February 2006) was focused very specifically on smoke from biomass burning and mineral dust aerosols in West Africa. Primary objectives included making high-quality measurements of the physical and optical properties of mixtures of these aerosols and their associated effect upon the radiation budget over the region from a variety of surface and airborne platforms (Haywood *et al.*, 2008). The British BAe146 aircraft made *in situ* and remote-sensing measurements on 15 flights from Niamey during the Dust and Biomass Burning Experiment (DABEX), and from Dakar during the Dust Outflow and Deposition to the Ocean (DODO) campaigns, while a French lidar-equipped ultralight aircraft operated from Niamey (Chazette *et al.*, 2007). Many of the flights performed by these aircraft were co-ordinated with ARM and SOP0 instrumented surface sites at Niamey, Banizoumbou, Djougou, and M'Bour. For the Niamey region for instance, it was found that the monthly-mean surface solar radiation is reduced by more than 50 W $m^{-2}$ owing to the presence of dust/biomass burning, and that distinct, discrete layers of biomass-burning aerosol frequently overlie layers of mineral dust.

## 5.3. SOP1 and SOP2 – The onset phase and the peak monsoon

SOP1 and SOP2 represent the core of the AMMA observational programme, in that this period was directed at the most intensive study of the physical processes – and associated bio-chemical processes – which control the monsoon during the wet season. The main scientific objectives of SOP1 and SOP2 were to obtain a comprehensive description of the following:

- Atmospheric dynamics, on time-scales from hours to a few days, including the dynamics of rain-bearing weather systems and the continental-scale dynamics of the monsoon.
- Land–atmosphere coupling, including rainfall feedbacks with soil moisture and with vegetation patterns, as well as the control of biogenic chemical emissions by vegetation and soils.
- Water cycle processes, coupled between the land, ocean and atmosphere systems.
- Chemical and aerosol processes, including emission from the land and ocean, transport and transformation in the atmosphere (including the upper troposphere/lower stratosphere), and the interaction with clouds.

A number of these scientific areas had a strong dependence on EOP activities, notably the co-ordination of SOP1 research flights with oceanic cruises.

In synthesising the diverse research areas concerned with the monsoon system, on short time-scales, SOP1 and SOP2 enjoyed the greatest concentration of personnel and equipment of the AMMA programme. In this combined period, for the first time, a series of comprehensive surveys over the different climatic zones of the West African continent has been made, including the tropospheric state, the land surface and the ocean surface, from the heart of the Saharan heat-low out into the equatorial Atlantic. In particular, combined intensive aircraft and ground-based deployment were directed at studying the weather and surface systems which control the West African climate, including shallow and deep convective cloud events, and patterns of soil moisture or vegetation variability. In all, some 120 flights were conducted (around 420 hours; see Table III for operational periods and basic scientific themes), and it is estimated that more than 700 people were engaged in the ground-based, oceanic and airborne programme of SOP1 and SOP2.

During SOP1 and SOP2, research flights were conducted into the Saharan heat-low and adjacent intertropical discontinuity, extending northward to around 20°N, with the SAFIRE Falcon aircraft equipped with the downward-pointing water vapour lidar LEANDRE2 and dropsondes, and the DLR Falcon aircraft equipped with the Doppler wind lidar WIND. The combination of high-resolution atmospheric reflectivity and wind measurements by LEANDRE2 and WIND, respectively, show that dust is mobilized near the surface at the leading edge of the nocturnal monsoon flow before being lofted above the monsoon flow and transported southward by the harmattan (Flamant *et al.*, 2007; Bou Karam *et al.*, 2008). The flights dedicated to the study of the Saharan heat-low and intertropical discontinuity were complemented by measurements from three transit flights, with the UK BAe146 and the DLR Falcon (Messager *et al.*, 2009), and documentation of the seasonal evolution of the monsoon/harmattan interface in the vicinity of Niamey, obtained from the SAFIRE ATR aircraft (Canut *et al.*, 2009; Saïd *et al.*, 2009). Two SAFIRE ATR flights were dedicated to the assessment of mineral dust budgets and properties during squall-line events at the beginning of the monsoon season. The strategy called for coupling between local measurements of erosion and deposition fluxes made at the Banizoumbou site and vertically resolved dust concentration, size distribution and mineralogy (from the ATR).

A number of research flights were also made towards the south from Niamey, extending over the Gulf of Guinea. These were co-ordinated with high-frequency radiosoundings and measurements from the research vessels in the Atlantic (section 4.2 above), sampling the composition of the inflow air to the monsoon, as a boundary condition to the ground-based and airborne studies being carried out further north.

These survey missions to the north and south of Niamey have been complemented with combinations of flights aimed at specific events in the monsoon system. A majority of such airborne studies, in particular conducted during SOP2 (Tables III and AII), have targeted the response of the atmospheric dynamics and composition to land surface state. Over the wooded zone, generally south of 12°N, these have explored the response to heterogeneous vegetation, making multiple surveys at different times of the day and on different dates, over fixed tracks linked to the surface monitoring stations. Surveys of the atmospheric response to patterns of soil moisture following convective events (typically flying northward of 14°N) have shown strong responses of the daytime atmospheric boundary layer to soil moisture; these responses have been observed in aircraft (e.g. Taylor *et al.*, 2007; Stewart *et al.*, 2008) and ground-based data (Kohler *et al.*, 2009).

Two intensive periods of radiosoundings were performed within a network of six stations (Agadez, Niamey, Tamale, Parakou, Abuja and Cotonou; see Table II for dates). In these two periods, the six stations made three-hourly launches, with around 98% of soundings made successfully. These data are being processed as a contribution to quantifying large-scale forcing of the energy and water budgets in the Ouémé meso-site.

A large number of MCS events were observed by the C-band radars at Niamey (around 50 cases) and Djougou (around 43 cases). Many events were also observed by the aircraft operating from Niamey and Ouagadougou, particularly during SOP2. Notably, a sequence of MCS activity was sampled in the period 14–16 August including pre-storm and post-storm measurements with the BAe146 and ATR, high-altitude observations with the Geophysica, the SAFIRE and DLR Falcons, and downstream measurements with the Geophysica, the Falcons and the BAe146. A significant facet of this sampling has been the use of onboard chemical measurements to infer the impact of the MCS on aerosol properties in the planetary boundary layer (Crumeyrolle *et al.*, 2008) or infer convective transport characteristics – for instance, in the wake of deep convective events, significant levels of isoprene have been observed in and above the characteristic detrainment layer close to the freezing level (Johnson *et al.*, 1996). Furthermore, eight microphysical surveys of the stratiform and cirriform outflow from cumulonimbus systems were conducted with the SAFIRE Falcon equipped with the RALI (radar–lidar) system between 6 and 15 September 2006. These involved a combination of horizontal and vertical surveys co-ordinated with the MIT and RONSARD radars, as well as CALIPSO and CloudSat overpasses (Stephens *et al.*, 2002; Winker *et al.*, 2003).

Finally, long-range transport of atmospheric constituents from the land surface and boundary layer into the global climate system has been measured with aircraft and balloon-borne systems (e.g. Ancellet *et al.*, 2009). During the first two weeks of August 2006, the stratospheric Geophysica aircraft and the DLR Falcon were based at Ouagadougou, downstream of the main operational base at Niamey (Figure 4(a)). Surveys with these downstream aircraft have sampled the tropospheric and lower stratospheric air processed by systems observed in the vicinity of Niamey with ground-based, airborne and balloon-borne sensors (e.g. Voigt *et al.*, 2008).

A complete list of flights pertaining to each category described above may be found in Tables AI and AII of appendix A, which provide details on all the flights of SOP1 and SOP2.

### 5.4. SOP3 – Late monsoon and downstream evolution

The SOP3 programme studied the transition of synoptic and convective weather systems as they move from the land out over the Atlantic, including the evolution of the Saharan Air Layer and the associated plumes of dust, and the impacts on cyclogenesis downstream.

Enhanced observations were set in place over land by the National Aeronautics and Space Administration's NASA-AMMA (NAMMA) project in Cape Verde and Senegal, including radar (NASA Polarimetric S-band

and the NASA TOGA C-band radar), disdrometers, flux towers, a tethered balloon system, infrared/solar and microwave radiometers, lidar measurements, satellite data and additional soundings, as described above and in section 5.1. Surface-based instruments were operating on two characteristic modes: continuous monitoring and targeted operations. NPOL deployed at Kawsara, Senegal was used to document precipitation properties as the MCSs propagate from continental to marine environments during August and September of 2006. A network of 40–50 tipping-bucket rain-gauges were deployed over the coverage area of NPOL with a subset (∼20 gauges) placed in a high density network (scale of 100 m) to capture the small-scale rainfall variability and provide error estimates for both the NPOL and spaceborne (e.g. TRMM) radars. The ground-based networks were augmented by flights with three research aircraft, and the overflight of driftsondes released upstream at Zinder.

In addition to the ground-based efforts, there was an aircraft campaign with British, French and US aircraft (see dates in Table III). Seven African easterly waves were sampled by the DC-8 (as part of the NAMMA effort), four of which became named storms (Ernesto, Debby, Gordon, Helene). Six dust-aerosol flights were conducted with the BAe146, some of which were co-ordinated with the DC-8. In addition, NOAA G-IV and P-3 aircraft made observations of the tropical cyclones and their environment in the western Atlantic as part of the Saharan Air Layer Experiment, concerned with impacts of the Saharan Air Layer on tropical cyclone intensity change. The French Falcon flew after this and sampled several non-developing systems during flights concerned with microphysics and dynamics in this region.

A complete list of the SOP3 flights is given in Table AIII of appendix A.

## 6. Concluding remarks

Preparations for the AMMA field programme began in 2003; at the time of writing of this article, the main long-term observational networks are well established and the EOP campaigns are completed. Therefore this is a good time to take stock of the achievements of the AMMA campaigns, and their likely future evolution.

In comparison with other field experiments, AMMA has some unique aspects. It is not common for a field programme to embrace such a wide range of spatial and temporal scales, nor to involve such a range of scientific disciplines. AMMA is also unusual in the extent to which research measurement networks have been intimately connected with the operational networks – notably the upper-air network, but also in the deployment of profilers, radars and hydrological systems. The fact that this programme has been achieved in an environment which can be very tough on personnel and equipment is a testament to the efforts of many dedicated people, in and from Africa and overseas.

In a programme of such diversity, it is not easy to elaborate all the activities, and their interactions, in a single article. This paper has described the overall field deployment, and has attempted to describe the most fundamental links between the different interacting scales and scientific disciplines. The paper also attempts to give an overview of the diverse, interacting scientific measurements which made up the AMMA EOP and SOPs, and which have been widely used in the articles contained in this special issue. Separate articles describe the conduct and outcome of more specific aspects of the programme, such as the radiosounding campaign (Parker *et al.*, 2008) and the co-ordinated aircraft and oceanic missions (Bourras *et al.*, 2009).

AMMA is a long-term programme of research, and while international research funding is committed until 2009, many of the observing systems will remain in place beyond this time. Further AMMA-related campaigns to capitalise on the enhanced observational infrastructure in the region are being discussed; for example the GERBILS aircraft campaign led by the UK Met Office with the UK BAe146 took place in June 2007 between Niamey and Nouakchott (e.g. Marsham *et al.*, 2008; Grams *et al.*, 2009). The continuation of some longer-term measurement systems will depend in part on the scientific evaluation of the value of those measurements, and in part on the successful integration with international strategy for monitoring in the region. Therefore we will work with THORPEX, GEWEX, CLIVAR and other international programmes to make such evaluations; we feel that AMMA has provided the observational basis to move forward in understanding, monitoring and predicting the West African monsoon.

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## Appendix A

### Tables detailing the flights of SOP1, SOP2 and SOP3

IOP types of SOP1 and SOP2: 1.1: Intertropical Discontinuity (ITD) and heat-low surveys; 1.2: Surface–atmosphere–aerosol: squall-line related aerosol emissions surveys; 1.3: Surface–atmosphere: north–south ‘land–ocean–atmosphere interactions’ surveys; 1.4: Land–atmosphere interactions; 1.5: Vegetation and soil emission surveys; 1.6: Urban surveys; 1.7: Aerosol mixing and hygroscopicity; 1.8: Lower troposphere survey; 2: Dynamics and chemistry of MCSs; 3: Long-range transport surveys; 6: Intercomparison flight. For further details on the objectives of these flights, the reader is referred to Parker and Flamant (2006).

**Table AI**. Detailed list of the scientific flights of SOP1.

| *Date* | *Aircraft* | *IOP type* | *Comment* |
|---|---|---|---|
| 04/06/2006 | F-F20 | 1.1 | ITD flight NW of Niamey |
| 05/06/2006 | F-F20 | 1.1 | ITD flight NW of Niamey |
|  | ATR | 1.1, 1.2 | Banizoumbou |
| 06/06/2006 | F-F20 | 1.1 | ITD flight NW of Niamey |
|  | ATR | 1.1, 1.2 | Banizoumbou |
| 07/06/2006 | F-F20 and ATR | 1.1 | ITD flight NW of Niamey |
| 08/06/2006 | F-F20 and ATR | 1.2 | Convection flight NE and E of Niamey |
| 09/06/2006 | F-F20 | 1.2 | Post-convection flight NE and E of Niamey |
| 11/06/2006 | F-F20 | 1.2 | Convection flight N and NW of Niamey |
|  | ATR | 1.1, 1.2 | Banizoumbou |
| 12/06/2006 | F-F20 | 1.2 | Post-convection flight N and NW of Niamey |
|  | ATR | 1.1, 1.2 | Banizoumbou |
| 13/06/2006 | F-F20 and ATR | 1.3 | Niamey–Cotonou transect |
| 14/06/2006 | F-F20 and ATR | 1.3 | Flight over the Gulf of Guinea (morning) |
|  | F-F20 and ATR | 1.3 | Cotonou–Niamey transect (afternoon) |
| 15/06/2006 | F-F20 | 1.1 | ITD flight NW of Niamey |
|  | ATR | 1.1, 1.2 | Banizoumbou |

**Table AIIa**. Detailed list of the scientific flights of SOP2a1.

| Date | Aircraft | IOP type | Comment |
|---|---|---|---|
| 01/07/2006 | ATR | 2 | Pre-convection in vicinity of Niamey |
| 02/07/2006 | ATR | 2 | Post-convection in vicinity of Niamey |
| 03/07/2006 | F-F20 and D-F20 | 1.1 | ITD flight NE of Niamey |
|  | ATR | 1.3 | Niamey–Cotonou transect |
| 04/07/2006 | ATR | 1.3 | Flight over the Gulf of Guinea (morning) |
|  | ATR | 1.3 | Cotonou–Niamey transect (afternoon) |
| 06/07/2006 | F-F20 | 2 | Convection flight East of Niamey |
| 07/07/2006 | F-F20 and D-F20 | 1.1 | ITD flight NE of Niamey |
|  | ATR | 1.2 | Post-convection in vicinity of Niamey |
| 10/07/2006 | F-F20+D-F20+ATR | 1.1 | ITD flight NE of Niamey |
| 12/07/2006 | D-F20 and ATR | 2 | Post-convection in vicinity of Niamey |
| 13/07/2006 | ATR | 2 | Post-convection in vicinity of Niamey (two days after the rain event) |
| 14/07/2006 | D-F20 | 1.1 | ITD and heat-low survey between Niamey and Agadir |

**Table AIIb**. Detailed list of the scientific flights of SOP2a2.

| Date | Aircraft | IOP type | Comment |
|---|---|---|---|
| 17/07/2006 | BAe 146 | 1.1 | ITD and Heat Low survey flight between Agadir and Bamako |
| 20/07/2006 | BAe 146 | 1.4 | Flight over banded soil moisture anomalies northwest of Niamey |
| 21/07/2006 | BAe 146 | 1.4 | Flight over banded soil moisture anomalies northwest of Niamey |
| 22/07/2006 | BAe 146 | 1.4 | Flight over banded soil moisture anomalies northwest of Niamey |
| 25/07/2006 | BAe 146 | 1.4 | Mapping of emissions into boundary layer and cumulus layer: day/ night |
| 27/07/2006 | BAe 146 | 1.5 | Emissions over the forest and into shallow cumulus layer (Benin) |
| 28/07/2006 | BAe 146 | 1.4 | Across synoptic scale heat low anomaly: Mali Wetlands, day & night |
| 30/07/2006 | BAe 146 | 1.5 | Mapping of biogenic emissions over southern Benin |
| 31/07/2006 | BAe 146 | 1.4, 2 | MCS initiation over soil moisture: Niger-Mali border north of Niamey |
| 01/08/2006 | BAe 146 | 1.4 | Daytime and night-time flights over soil moisture features: NW of Niamey |
| 02/08/2006 | ATR | 1.7 | Flight between Niamey and Niamtougou |
| 03/08/2006 | BAe 146 | 2 | MCS southwest of Niamey |
| 04/08/2006 | ATR | 2 | Post-MCS flight southwest of Niamey |
| 04/08/2006 | D-F20 & M55 | 3 | Air Composition in the TTL and UTL: Burkina & Ghana; impact of a MCS |
| 05/08/2006 | BAe 146 | 1.5 | Mapping of biogenic emissions over Ghana, Togo and Benin |
| 05/08/2006 | ATR | 2 | Pre-MCS flight southeast of Niamey |
| 06/08/2006 | BAe 146 | 1.4 | Soil moisture and NOx emissions (northeast of Niamey) |
| 06/08/2006 | D-F20 & ATR | 2 | MCS outflow east of Ouagadougou and MCS wake flight: SE Niamey |
| 07/08/2006 | ATR + D-F20 + M55 | 2 | MCS outflow east of Ouagadougou and MCS wake flight: SE Niamey |
| 08/08/2006 | BAe 146 | 1.3 | Niamey–Cotonou transect + flight over the Gulf of Guinea (morning) |
| 08/08/2006 | ATR | 1.7 | Niamey–Niamtougou transect (morning) |
| 08/08/2006 | BAe 146 | 1.6 | Mapping emissions around Lagos, Nigeria (afternoon) |
| 08/08/2006 | ATR | 1.7 | Niamtougou–Cotonou transect (afternoon) |
| 08/08/2006 | M55 | Calipso | CALIPSO validation flight west of Niamey |
| 09/08/2006 | ATR | 1.7 | Flight over the Gulf of Guinea, offshore of Benin (morning) |
| 09/08/2006 |  | 1.3 | Cotonou–Niamey transect (afternoon) |
| 11/08/2006 | F-F20+D-F20+M55 | 2 | MCS outflow flight east of Ouagadougou and west of Niamey |
| 11/08/2006 | BAe 146 | 1.4 | Mapping of $NO_x$ soil moisture after heavy rain, northeast of Niamey |
| 12/08/2006 | ATR | 1.8 | Post-MCS flight over Niger, southeast of Niamey |
| 13/08/2006 | F-F20 + D-F20 +M55 | 3 | Air Composition in the TTL and upper troposphere over Burkina Faso, Ghana, Niger and Benin; impact of a MCS |
| 13/08/2006 | ATR | 1.8 | Composition of air in the lower troposphere: Niger, Benin, south of Niamey |
| 13/08/2006 | BAe 146 | 1.3 | Sampling of biomass outflow over the Gulf of Guinea, south of Benin |
| 14/08/2006 | ATR | 2 | Pre-MCS flight west of Niamey |
| 14/08/2006 | F-F20 | 2 | MCS flight east of Niamey |
| 14/08/2006 | BAe 146 | 1.4 | Northern Benin |
| 15/08/2006 | F-F20 | 2 | MCS outflow flight southwest of Niamey, over Benin |
| 15/08/2006 | ATR | 2 | Post-MCS flight west of Niamey |
| 15/08/2006 | D-F20 | 2 | MCS outflow flight west of Ouagadougou (morning) |
| 15/08/2006 | D-F20 | 2 | MCS flight SE of Ouagadougou, over Togo and Benin (afternoon) |
| 16/08/2006 | F-F20 | 3 | Air Composition in the upper troposphere over Burkina-Faso and Niger |
| 16/08/2006 | ATR | 1.8 | Air Composition in the lower troposphere, above Niger and Benin. |
| 16/08/2006 | ALL 4 aircraft | 6 | Intercomparison flights (afternoon) |
| 17/08/2006 | BAe 146 | 1.5 | Mixing and transport over heterogeneous vegetation of Benin |
| 17/08/2006 | ATR | 1.8 | Air Composition in the lower troposphere: Niger, Benin, south of Niamey |
| 17/08/2006 | F-F20 | 2 | MCS flight over and west of Niamey |
| 17/08/2006 | ATR | 2 | Post-MCS flight north of Niamey (afternoon) |
| 19/08/2006 | ATR | 2 | Post-MCS flight south of Niamey |
| 19/08/2006 | F-F20 | 3 | Air Composition in upper troposphere: Niger, Benin and Gulf of Guinea, off shore of Benin (2 flights, round-trip between Niamey and Cotonou) |
| 20/08/2006 | F-F20 | 3 | Air Composition in upper troposphere: Niger and Burkina Faso, W of Niamey |
| 21/08/2006 | F-F20 | 1.1 | ITD flight NW of Niamey |

**Table AIIc**. Detailed list of the scientific flights of SOP2a3

| Date | Aircraft | IOP type | Comment |
|---|---|---|---|
| 08/09/2006 | F-F20 | Horizontal Exploration | Over northern Benin (morning) |
| 08/09/2006 | F-F20 | Vertical Exploration | Over Niger and Benin, south of Niamey (afternoon) |
| 09/09/2006 | F-F20 | A-Train | West of Niamey, along A-Train track |
| 10/09/2006 | F-F20 | Horizontal Exploration | Over Niger, east of Niamey (morning) |
| 10/09/2006 | F-F20 | Horizontal Exploration | East of Niamey (afternoon) |
| 11/09/2006 | F-F20 | Horizontal Exploration | Over Burkina-Faso, east of Ouagadougou |
| 13/09/2006 | F-F20 | Horizontal Exploration | Over Niger and Benin along north–south transect south of Niamey |
| 14/09/2006 | F-F20 | Horizontal Exploration | Over southwest Niger |

**Table AIIIa**. Detailed list of the scientific flights of SOP3a1

| Date | Aircraft | IOP type | Comment |
|---|---|---|---|
| 19/08/2006 | DC-8 | Cyclogenesis+SAL/Dust | Pre-Ernesto storm flight; AEW no.1 |
| 20/08/2006 | DC-8 | Cyclogenesis+SAL/Dust | Pre-Ernesto storm flight; AEW no.1 |
| 22/08/2009 | BAe 146 | Dust | Over the ocean, along the coast of Senegal and Mauritania |
| 23/08/2006 | DC-8<br>BAe 146 | Cyclogenesis+SAL/Dust<br>Dust | Tropical storm Debby; AEW no.2<br>Over Mauritania, northeast of Dakar |
| 24/09/2006 | BAe 146<br>BAe 146 | Dust<br>Dust | Over the ocean, west of Dakar (morning)<br>Over the ocean, along the coast of Senegal and Mauritania (afternoon) |
| 25/08/2006 | DC-8<br>BAe 146 | Cyclogenesis+SAL/Dust<br>Dust | AEW no.3<br>Over the ocean, along the coast of Senegal and Mauritania |
| 26/08/2006 | DC-8 | Cyclogenesis+SAL/Dust | AEW no.3 |
| 28/08/2006 | BAe 146 | Dust | Over the ocean, along the coast of Senegal and Mauritania |
| 30/08/2006 | DC-8 | SAL/Dust | No AEW |
| 01/09/2006 | DC-8 | Cyclogenesis | AEW no.4 |
| 03/09/2006 | DC-8 | Cyclogenesis | Pre-Gordon storm flight; AEW no.5 |
| 04/09/2006 | DC-8 | Cyclogenesis+SAL/Dust | Pre-Gordon storm flight; AEW no.5 |
| 05/09/2006 | DC-8 | SAL/Dust | No AEW |
| 08/09/2006 | DC-8 | Cyclogenesis | AEW no.6 |
| 09/09/2006 | DC-8 | Cyclogenesis | AEW no.6 |
| 12/09/2006 | DC-8 | Cyclogenesis | AEW no.7; Tropical depression became storm Helene |

**Table AIIIb**. Detailed list of the scientific flights of SOP3a2

| Date | Aircraft | IOP type | Comment |
|---|---|---|---|
| 18/09/2006 | F-F20 | Dynamics | MCS flight south of Dakar, over land and ocean |
| 19/09/2006 | F-F20 | Dynamics | MCS flight south of Dakar, over ocean |
| 20/09/2006 | F-F20 | A-Train | Flight along an A-Train overpass over ocean, SW of Dakar |
| 21/09/2006 | F-F20 | A-Train | Same as above, SW of Dakar, and west of a MCS |
| 22/09/2006 | F-F20 | A-Train | Same as above, W of Dakar, and over a MCS |
| 23/09/2006 | F-F20 | Dynamics | MCS flight south of Dakar, over ocean |
| 25/09/2006 | F-F20 | Dynamics | MCS flight southwest of Dakar, over land |
| 26/09/2006 | F-F20 | Microphysics | MCS flight south of Dakar, over ocean |
| 26/09/2006 | F-F20 | Dynamics | MCS flight south of Dakar, over ocean |
| 27/09/2006 | F-F20 | Microphysics | MCS flight west of Dakar, over ocean |
| 28/09/2006 | F-F20 | Calibration | North–south transect, north of Dakar, over the ocean |
| 29/09/2006 | F-F20 | A-Train | Flight along an A-Train overpass over the ocean, no CLOUDSAT data, dust outbreak |

## Appendix B

### List of acronyms (not defined in the text)

| | |
|---|---|
| AERONET | Aerosol Robotic Network |
| ARM | Atmospheric Radiation Measurement |
| A-Train | A train of six satellites dedicated to documenting the water cycle and the radiative forcing |
| AMMA-ICIG | AMMA International Coordination and Implementation Group |
| AMMA-ISSC | AMMA International Scientific Steering Committee |
| CALIPSO | Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations |
| CLIVAR | CLImate VARiability and predictability |
| DLR | Deutsches Zentrum f&ur Luft- und Raumfahrt |
| ECMWF | European Centre for Medium-range Weather Forecasts |
| EEIG | European Economic Interest Group |
| EGEE | Étude de la circulation océanique et de sa variabilité dans le golfe de Guinée |
| EQUALANT | Co-operative survey of the EQUAtorial AtLANTic |
| GERBILS | Geostationary Earth Radiation Budget experiment (GERB) Intercomparison of Longwave and Shortwave radiation |
| GEWEX | Global Energy and Water cycle EXperiment |
| IASI | Interféromètre Atmosphérique de Sondage Infrarouge |
| IDAF | IGAC (International Global Atmospheric Chemistry) DEBITS (DEposition of Biogeochemically Important Trace Species) AFrica |
| IPCC | Intergovernmental Panel on Climate Change |
| MIT | Massachusetts Institute of Technology |
| MSG | Meteosat Second Generation |
| NOAA | National Oceanic and Atmospheric Administration |
| NPOL | NASA Polarimetric radar |
| PHOTONS | PHOtométrie pour le Traitement Opérationnel de Normalisation Satellitaire (part of AERONET) |
| PIRATA | PIlot Research moored Array in the Tropical Atlantic |
| SAFIRE | Service des Avions Français Instrumentés pour la Recherche en Environnement |
| SCOUT | Stratospheric-Climate links with emphasis On the Upper Troposphere and lower stratosphere |
| SMOS | Soil Moisture and Ocean Salinity |
| THORPEX | THe Observing system Research and Predictability EXperiment |
| TRMM | Tropical Rainfall Measuring Mission |
| VENUS | Vegetation and Environment New micro-Satellite |
| WASA/F | West African Specific Analysis/ Forecast |

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