FRENCH WHITE BOOK

ON AFRICAN MONSOON & ITS VARIOUS COMPONENTS

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Preliminary

This document was prepared by the French community to provide a description of the scientific objectives for a comprehensive study of West African monsoon and its different components: atmospheric dynamics, continental water cycle, atmospheric chemistry, and continental and oceanic surface conditions. The main French agencies (CNES, CNRS/INSU, IRD, Meteo-France) have declared to support such integrated project.

It is anticipated that other countries will be interested to contribute to this open initiative and that the project will become a coordinated international effort. Many researchers from different countries (African countries, Germany, UK and USA) have already declared their interest, as a logical consequence of their involvement in high-level research over this region during the past years.

I Motivation and background

Rainfall over West-Africa is notoriously unreliable, especially in its northern part. The famines that struck the Sahel in the 70's (1972-1974) and in the 80's (1983-1985) have prompted a number of authors (e.g. Folland et al, 1986; Fontaine and Janicot, 1996; Lamb, 1983; Lamb and Peppler 1992; Nicholson, 1981) to investigate possible mechanisms responsible for these dramatic events. In fact, these two sequences of a few extremely dry years were part of a longer drought that lasted continuously from the end of the 60's to the mid 90's, as illustrated in Figure 1. This unusual dry spell was not limited to the Sahel but was felt down to the Guinea Coast as well (Lebel et al 2000), the average rainfall deficit of the 70's and 80's with respect to the 50's and 60's being 180 mm in average over the area shown in Figure 2. The consequences of the related abrupt decrease of water resources were devastating to both populations and economies. In the Sahel, the cattle population was divided by two, some exportation cultures disappeared. In the more humid regions to the South, a severe shortage of electricity was caused by hydropower plants being shut down, during the summers of 1984 and 1998, following the weakness of the preceding rainy seasons. It was estimated that the solid economic growth (at a rate of over 5% a year) of a country like Ghana was stopped in 1999, due to this water resources related problem.

This drought is but one manifestation of the climate variability of West-Africa, spanning a large range of scales from intraseasonal to decadal. Given its strong impact on human activities at the regional scale and its climatic effects at larger scale – discussed below – there is an imperious need for a better understanding of this variability and for improved seasonal forecasting skills. As a matter of fact, we currently have considerable difficulties in analyzing, simulating and forecasting that variability, even though we know that it is under the control of a dominant atmospheric feature: the West African Monsoon (WAM). The central reason of these difficulties lies in the complex interactions between the atmosphere, the biosphere and the hydrosphere that are controlling the dynamics of the WAM and the life cycle of the associated rain producing systems. Recent modelling work in this area have shown that the oceans (e.g. Semazzi et al 1996), the vegetation (Zheng and

Eltahir 1998; Wang and Eltahir 2000) and the topography (Semazzi and Sun 1997) very likely play an important role in the establishment of a monsoonal circulation over West Africa.

While atmospheric dynamics act as the ultimate direct controlling factor on rainfall, the human behaviour – linked to large scale economic activities– might have a significant, however indirect, influence as well. Charney (1975) pointed out that overgrazing was causing an increase of albedo in the Sahel impacting on the Hadley circulation. Lately, Zheng and Eltahir (1998) stressed that the degradation of the vegetation cover over Sudano-Guinean West Africa might have a still larger impact on the rainfall regime of the region.

Beyond the regional motivations exposed above, one has also to consider the role of Africa – and singularly West Africa – in a more global context. This role has generally received little attention. However Africa is one of the major heat source of the earth climate, characterized by a strong meridional migration, which impacts on the annual cycle of other tropical and mid-latitude regions. The significant correlation existing between Atlantic hurricanes and West Sahelian rainfall (e.g. Landsea and Gray 1992) is but one example of the links between the WAM and the climate of other regions of the world . Similarly, from a global atmospheric chemistry point of view, there are strong evidences that the African monsoon region is critical in the emission of ozone precursors and of aerosols and their redistribution over the whole troposphere. Trace gas and aerosol emissions in the African Tropics are strongly affected by human activities. Biomass burning in savanna and forest ecosystems is the most important source of atmospheric pollution (Hao et al 1996), emitting huge amounts of reactive gases and particles (including soot and organic carbon) that have a direct impact on regional radiative budget (Fig 3). The savanna burning over Africa is estimated to correspond to 0.7 GT Carbon by year (i.e. around 20 % of the global biomass burning). Atmosphere dynamics and chemistry, vegetation dynamics and the continental water cycle are thus closely interrelated and have to be studied in conjunction if one is to better understand and predict the West African rainfall variability.

From a purely scientific viewpoint it is worth noting that, due to unique geographical and vegetation features leading to a first-order zonally symmetry (Fig 4), the West African Monsoon (WAM) represents probably the less complicated monsoon system to study *on both observational and modeling aspect*s. In this perspective, it is challenging that General Circulation Models poorly simulate the WAM climate and its variability (e.g. Lebel et al 2000; Thorncroft et al 2001). This is indisputably linked to the numerous interactions that have to be taken into account if one is to better represent the WAM in atmospheric or coupled atmospheric-hydrologic models. The problem, however, is that many processes or state variables controlling the interactions between the land and ocean surfaces and the atmosphere are ill-documented in this part of the world.

Time has come for an integrated research project on the West African Monsoon and its related atmospheric, biospheric, hydrologic, and oceanic components. Such a project will be interdisciplinary by nature, given the motivations and context detailed above. It will have to link observations, data analysis and modeling. It will also span a broad range of scales, especially since one important component of the WAM variability is linked to its forcing by fluctuating surface conditions. This component is dominant at the seasonal to decadal scales (and beyond) in a regional context. On the other hand, there is an internal component which is fundamental at the intraseasonal scale, involving numerous interactions. This component is mostly observed at the meso and synoptic scales. Four major field of studies will consequently be considered in this document, in order to get a full and integrated picture of the climate and water cycle variabilities in West Africa: **Atmospheric dynamics** (internal variability of the WAM), **Continental water cycle**, **Atmospheric chemistry**, **Surface conditions** (forced variability of the WAM both by the continent and by the ocean).

I.1 Monsoon dynamics

The WAM is a land-ocean-atmosphere coupled system in a particular geographical context (low latitudes, coastal geometry and orography). At first order, it can be considered, as a zonally symmetric and thermally direct circulation driven by the horizontal meridional gradients of dry and moist static energy (MSE) that take place in the boundary layer between the Atlantic Ocean (Gulf of Guinea) and the continental regions of West Africa (Plumb and Hou 1992, Eltahir and Gong 1996). Basically, the course of events can be viewed as follows (Fig. 5). During spring, sun elevation is high over Sudan-Sahel; the MSE atmospheric contents increase mainly through surface warming, and dry convection allows for the (adiabatic) conversion of enthalpy into geopotential energy, a necessary starting condition for generating a direct overturning in the divergent circulation over Sudan-Sahel. This makes easier the advection of water vapor from the Atlantic and favors humidity convergence in low levels and ascendance; the (adiabatic) conversion can then sustain deep convection and rainfall. The WAM can then be viewed as a duple time engine. In spring through sensible-heating driven convection in low levels, it generates the atmospheric conditions that maintain in summer its thermally direct circulation through the adiabatic ascents due to latent heat release in the high troposphere.

The monsoon circulation consists of four main wind axes (Fig. 6) : the south-westerly monsoon flow in low levels, the African Easterly Jet (AEJ) in the mid-troposphere due to the existence of strong south to north thermal gradients near to the surface, and to a transverse circulation controlled by the Saharan heat low, and in the upper levels, the Tropical Easterly Jet (TEJ) from June to September by 5°-10°N and the subtropical westerly jet by 30-35°N. AEJ has hence a strong thermal component and can be considered as a dynamical signal of land surface conditions : in March it blows just south of the Guinea coast (Eq-4N) where MSE values are maximum in mid-levels; from March to August its northward migration follows the greatest MSE contents in mid-troposphere before reaching its highest speeds in June, by 10°N. The deep convection within the rainbelt (located by 10° north in July-September) is clearly connected with two subsidence zones (by 5° South and 30° North respectively) through divergent circulation of Hadley-type. This meridional circulation transports moist air from the Atlantic and dry air from the Sahara : in low levels the monsoon flow converges into the Saharan heat-low where dry convection extends up to 600hPa and sustains AEJ in mid-levels (Thorncroft and Blackburn 1999). In upper levels the deep convection occurs in an apparent zonal break of the Tropospheric Easterly Jet (Redelsperger et al 2001), the resulting main ascent seems thus located between the upper-level relative outflow and inflow at its east and west sides of TEJ.

More generally the WAM is a system where scale interactions between convection (moist convection in the ITCZ, dry convection in the transverse circulation of the thermal depression), easterly waves, AEJ and moisture flux convergence in low-levels are predominant. The main known and unknown interactions between the various dynamical feature are summarized in Figure 7. As mentioned above one can distinguish the internal variability of the WAM system from its forced variability. The former is dominant at convective to seasonal time scales.

At synoptic and convective time-scales, the cross-circulation advects inside the Monsoon layer moist air from the Guinea Gulf and advects dry air at low and mid-tropospheric levels from Sahara region. The mixture of humid and dry air occurs mainly at low levels near the intertropical front and at mid-tropospheric levels in the ITCZ. As a result, the gradients of potential vorticity are of opposite sign along the meridional plane, a necessary condition for the development of easterly waves through barotropic instability (Burpee 1972, Reed et al 1977, Thorncroft 1995). Along the vertical, the positive potential temperature gradient at low levels interacts with the negative gradient of potential vorticity at mid-tropospheric levels, a source of baroclinic instability (Thorncroft and Blackburn 1999). This generates and maintains very specific disturbances at either side of AEJ. These easterly waves (periodicity of ~3-5 days and horizontal wavelength of ~3000 km) interact with the Mesoscale

Convective Systems (MCS's). Northward of the AEJ axis another type of easterly wave (periodicity of ~6-9 days; horizontal wavelength of ~6000 km) but more intermittent, modulates moist convection in a different way (Diedhiou et al 1999). The development of synoptic features at the TEJ level remains an open question.

When considering the intra-seasonal time-scales, the transient phenomena and weather regimes become more important. The onset of rain on the continent is characterised by an abrupt northward shift that takes place by the end of June (Sultan and Janicot 2000; Le Barbé et al 2001). This might correspond to a transition between the two equilibrium regimes (a radiative-convective equilibrium regime and an angular momentum conserving regime) identified by Eltahir and Gong (1996). Then the intra-seasonal variability is made of a succession of active and inactive phases of ~10-20 days during the mature period (July-September), showing some links with easterly disturbances of synoptic scale (Janicot and Sultan 2001).

At interannual and decadal time-scales, the intensity of the meridional gradients of entropy (or MSE) seem to play a major role in the variability of the WAM. It will be important to explore the links between this large scale variability and the internal variability. For instance Le Barbé et al (2001) detect only minor changes in the onset regime between the wet (50s, 60s) and dry (70s, 80s) decades, but they find that the dry period was marked by a decrease in the number of rain events without any significant change in the mean cumulated amounts per rain event, a fact already noted for the Sahel by Le Barbé and Lebel (1997). Since rain events are predominantly associated to MCS's, this finding raises the issue of how the properties of the MCS's (life cycle, axes of propagation, spatial distribution) are linked to large time scale variability. Recent works on the mean diurnal and seasonal cycles of the West African MCS's (Hodges and Thorncroft 1997; Mathon and Laurent 2001) provide a basis for future work in this area.

It should also be noted that convective phenomena exert a “return-influence” at larger scales since they modify the horizontal temperature gradients (mass) and the energy gradients, that in turn determine the intensity of the monsoon circulation. A better understanding of convection – triggering and development of mesoscale convective systems (MCS's) – is also very important for the study of the continental water cycle, since MCS's are the main source of precipitation in West Africa (see e.g. Mathon and Laurent 2001).

Studying these scale interactions, requires to investigate the dynamics of the continental water cycle - the variability of the convective systems and of the associated rain events plays an essential role in this dynamics, which, in turn, feeds back to the atmosphere - and of the surface conditions themselves. As a matter of fact surface conditions are a key forcing factor of the WAM. They are characterized by a marked interannual variability (Sea surface temperature and seasonal cycle of the vegetation) and long term trends (degradation of the vegetation, warming of the tropical oceans in the southern hemisphere) which are hardly well known.

I.2 Continental water cycle

The continental water cycle of West Africa was severely affected by the drought of the 70's-80's, as can be seen from Figure 8. Everywhere in the Sahel or in the Sudano-Guinenan area, the relative streamflow deficit over the large catchments, expressed in relative values, was twice as large as the rainfall deficit. On the Senegal and Upper Niger, for instance, a 20-to 30 % decrease in annual rainfall resulted in a decrease as high as 60% of the mean annual discharge (Mahé and Olivry 1999). This illustrates that water resources availability is strongly and non linearly dependant on rainfall variability, and thus on the monsoon efficiency. At the same time, a number of examples show that changes in the vegetation might have a major impact on how the continental water cycle reacts to the rainfall variability.

One thing to consider in this respect is how the rainfall regime was affected by the drought. Le Barbé and Lebel (1997) have shown that, in the Sahel, the rainfall deficit of the 70's-80's was associated to a decrease in the number of rain events, mostly during the period when deep convection is prominent, that is July and August. At the decadal scale this finding holds for the Sudano-Guinenan area as well (Le Barbé et al 2001). It seems also to be verified for the interannual variability, at least in the Sahel (D'Amato and Lebel 1998). Since the average rainfall produced by each event remained somewhat constant, this means that in dry years the hydrologic systems are submitted to a rain forcing of relatively unchanged magnitude, but at a decreased occurrence rate. From recent studies, it seems that the impact of such a rainfall regime variability on the water cycle is scale-dependant, as well as surface condition dependant.

While large river basins amplify the rainfall deficit, producing increased streamflow deficits as shown in Figure 8, different behaviors were observed on smaller watersheds (less than 20 000 km^2). Le Barbé et al (1992) report a strong reduction of the discharges over the catchments from Benin, while Mahé et al (2001) find, for a few Sudano-Sahelian watersheds, a dominant trend of surprisingly increasing runoff during the last half-century. A significant example in this respect is the Hapex-Sahel area, where the underlying Continental Terminal phreatic aquifer has undergone a continuous rise during the past decades (Favreau 2000). This aquifer being recharged by shallow ponds, the observed rise can easily be explained by the enhanced runoff capacity of the overlying watersheds. This enhanced runoff capacity is attributed to the increase of cultivated areas, estimated from 25 % in 1950 up to 75 % in 1990. The proportion of natural vegetation areas (high vegetation cover) has dropped from 70 % to 5 %; and fallow turnover has decreased (Loireau 1997). This intensification of land use results in soil crusting, erosion, and subsequently higher runoff capacity.

These results stress the need to account for long-term space-time vegetation dynamics, concurrently to rainfall variability, in order to improve our understanding of the main processes affecting the continental water cycle in West Africa. As will be discussed below in the following section, the interactions between rainfall variability, vegetation change and modification of the continental water cycle are multi-scale. Their study require some specific observations.

I.3 Surface conditions

As already discussed, theoretical and empirical evidences (e.g. Eltahir and Gong 1996; Zheng and Eltahir, 1998; Fontaine et al , 1999) were found that stronger (weaker) than normal meridional gradients of entropy are favorable (unfavorable) conditions for the excursion of the humid monsoon deep into the continent and thus for wetter (drier) conditions over, for example, the Sahel region. This is a strong motivation for better characterizing the surface conditions, whether on the ocean or on the continent, that control these gradients of entropy. As a matter of fact the meridional energy gradients in the boundary layer, between the Atlantic ocean (Gulf of Guinea) and the continent are controlled by the combined variations of sea surface temperature (SST) in the Gulf of Guinea and land surface properties (albedo, soil moisture, vegetation).

Surface conditions also play an important role in the dynamics of the continental water cycle, mostly through vegetation, and greatly influence the atmospheric chemistry of the region due to human action leading to the release in the troposphere of aerosols in large quantities.

Various time scale regarding the variability of the continental surface conditions have to be considered in this project. At decadal and interannual time scales, the SST anomalies in the tropical Atlantic (i.e. typically the interhemispheric mode, the “ dipole ”, and the equatorial mode of variability, often called as the “Atlantic El Niño” Servain 1991), the evolution of vegetation cover and land use (natural bushes and fallows transformed in cultivated lands, deforestation in the Guinean region) have to be considered first because they modify the land-sea contrasts and the sensible and latent vertical heat fluxes. Seasonal rainfall amounts over West Africa depend strongly on SST anomalies, not only in the tropical Atlantic (Lamb 1978a, 1978b), but on a global scale (Folland et al 1986; Rowell et al 1995). In particular, the Sahel rainfall interannual variability is linked to ENSO-induced teleconnections (Janicot et al 2001; Rowell 2001), warm ENSO events leading to Sahel rainfall deficit. Over land, this arises through the Charney mechanism (increasing atmospheric subsidence in response to increasing surface albedo and hence radiative deficit, Charney 1975), but also through soil moisture and processes linked to surface roughness (Charney et al 1977; Laval and Picon 1986; Xue 1997; Zheng and Eltahir 1998). The vegetation of the region is known to have undergone profound changes over the past 50 years. For instance, in the Nakambé basin, the natural vegetation coverage has decreased from 43% to 13% between 1965 and 1995, while the ratio of cultivated and bare soils has increased from 57% to 87 %. However, apart from a few areas of intensive studies like the Nakambé basin or the HAPEX-Sahel square, a reliable quantification of these changes is missing. This quantification is needed to study in parallel the modifications of the rainfall regime and the evolution of the vegetation, modeling studies (e.g. Polcher 1995) indicating that desertification and deforestation lead to rainfall deficit over most of West Africa, especially through a decrease of the number of convective event. On the other hand, the results of Lebel et al (2000) showing a relatively even distribution of the rainfall deficit during the 70's-80's period are not necessarily in good agreement with what could have been expected from recent modeling studies or from our vision of the regular seasonal migration of the ITCZ. Also, since the vegetation is not specially recovering from the degradation of the past decades, we could expect that some changes of the rainfall regime observed recently would persist in the future. There is not clear indication in that direction for the moment.

Paleoclimate scale is also a fruitful source of investigation for the WAM mechanisms by considering very different boundary conditions due to modified Earth's orbital parameters, and by comparing with observational paleodata. For instance a lot of experiences have been performed by using seasonal and latitudinal distribution of insolation at 6000 BP (insolation was increased by 5% in northern summer and decreased by 5% in northern winter). Simulations with atmospheric general circulation models have shown an enhancement of the Afro-Asian monsoon, in accordance with observational evidences (Kutzbach and Guetter 1986; de Noblet et al 1996; Hall and Valdes 1997). However it has also been shown that astronomical parameters alone are not sufficient to simulate the right rate of monsoon enhancement; the introduction of real past SSTs and of a coupling between atmosphere and vegetation dynamics is necessary to improve the agreement between the models results and the data (Texier et al 1997).

At smaller time scales (seasonal), the spring evolution of the meridional (and zonal) MSE gradients in the boundary layer is particularly crucial for the development of the monsoon in terms of intensity and northward migration. Knowledge of these gradients (that may be affected by the equatorial and/or coastal upwellings) significantly improve the prediction of the main rainy seasons both in the Guinean (peaking in June and October) and Sahel (peaking in August) regions (Fontaine et al 1999). For example, operational statistical forecasts of June-September cumulative rainfall are quite successful when based on MSE gradients (e.g. Philippon and Fontaine 2000). On the other hand, the set-up of the WAM in May-June is a main factor for the development of the equatorial upwelling in the Guinea gulf, positive feedbacks acting to support an equilibrium between upwelling, cloud radiative forcing and atmospheric circulation, to maintain the ITCZ on the African continent (Mitchell and Wallace 1992; Waliser and Somerville 1994; Philander et al 1996). In the eastern Atlantic (coastal upwellings), the weak depth of the surface mixing layer increases the SST variability at both the interannual and seasonal scales.

Vegetation dynamics might also exert an influence on rainfall at still smaller scales. A significant interaction seems to exist between precipitation, vegetation growth and evaporation at convective scales, as was shown by Taylor and Lebel (1998) working on the EPSAT-Niger rainfall data. High event rainfalls were observed on those raingauges that already received high amounts in previous events. In 1992, this persistency maintained strong local rainfall gradients through the season, resulting in an annual rainfall gradient of 300 mm (more than half the yearly total) over less than 10 km. This phenomenon might be explained by humidity gradients associated to the ground trace of convective cells, impacting in turn the boundary layer, possibly resulting in enhanced convective instability. Such small scale retroactions need further study, based on small scale observations and modeling of the rainfall-vegetation-evaporation system.

I.4 Atmospheric chemistry

The campaigns conducted during the last fifteen years (GTE/ABLE 2A and 2B, LBA in Amazonia, DECAFE-EXPRESSO, STARE-SAFARI, SAFARI 2000 in Africa, TRACE-A over the tropical Atlantic) and the international networks such as IDAF/DEBITS and AERONET confirmed the importance of the tropics on the atmospheric composition and chemistry at global and regional scales. These experiments mainly focused on the emissions of tropical ecosystems and on the chemistry and photochemistry of lower and middle troposphere (Fig. 9). Recently, interest has increased in the question of the origin, chemistry and fate of the upper tropical troposphere. In particular, there is an urgent need to document the upper troposphere over the West African continent where the signature of convection is particularly strong. Intense photochemistry, particularly active heterogeneous chemistry, scavenging of emitted chemical species during wet convective transport and strong stratosphere-troposphere exchange around the Tropical Easterly Jet (TEJ) further complicates the interpretation of the convective cloud outflow in this region. Another growing concern deals with the direct and indirect radiative impact of particles especially the contribution of absorbing aerosols. Indeed, aerosol effects continue to represent one of the largest uncertainties in the climate change understanding. All these questions are particularly interesting over West Africa due to the gazeous and aerosol mixture emitted by biomass burning, soil dust, natural sources including lightnings, vegetation and fossil fuel sources. Different patterns of evolution are expected depending on the direction of horizontal flow (Monsoon vs. Harmattan) and the altitude (boundary layer vs. free troposphere).

Convection facilitates the vertical exchange between the boundary layer and the upper troposphere. For example, convective clouds can increase the upper tropospheric CO and NO_X concentrations inducing a post-convective ozone formation in the middle and upper troposphere over continent (Pickering et al , 1996). Recent studies showed that the upper tropical troposphere is photochemically more active than previously thought, due to the existence of HO_X radicals which would result from the fast convective transport of precursors in the air from the lower layers toward the upper troposphere (Prather and Jacob, 1997; Brasseur et al 1998; Jaeglé et al 1997; Wennberg et al 1998). The effect of convection on HO_X seems to be greatest over the tropical continents where convection and biogenic emissions from vegetation and anthropogenic sources are colocated (Collins et al , 1999) which is the case over West Africa. 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 halogenous compounds into forms more liable to deposit processes. Nitrogen oxides (NO_X) also play a central role in the upper tropospheric chemistry as they determine the atmosphere's oxidizing or cleansing power and the troposphere's ozone production regime at local and global scale (Jaeglé et al 2001; Faloona et al 2000; Jacob et al 1996). Africa accounts for a large portion of the total biomass burning (30% at least) and thus provides a strong source of NO_X from combustion and soils. Lightning in the convective clouds is another potential source of NO_X which intensity is still poorly known and has never been investigated over the strong continental convection of West Africa. Finally, West Africa is of particular interest for the study of upper tropospheric chemistry as it is an unique superimposition of contributions from different African sources that will enter the ITCZ convection: monsoon moist air passing over South Atlantic ocean and the tropical rain forest (biogenic emissions), harmattan dry air flowing over arid areas, polluted air from growing human activities.

From a stratospheric point of view, tropical region is the area of formation of stratospheric ozone and a source of chemical species emitted at ground level that are injected into the stratosphere via convective transport followed by large scale ascent of the Brewer-Dobson circulation. In the tropics, various STE processes are involved such as tropopause folds (Ioannidou et al 2001) along the subtropical westerly jet, the breaking of Rossby waves with formation of stratospheric filaments in the equatorial troposphere. However, the species injected through the tropopause must be distinguished according to their lifetime. Those having long lifetimes (10 to 100 years: N_2O, CH_4, CFC, Halons), behave as pure tracers before reaching several years later the middle stratosphere where they are oxidized or photodissociated to yield NO_x, HO_x, ClO_x, or BrO_x radicals, the abundance of which is known to be a control factor of the ozone long-term evolution. A particular category among these long lifetime species is composed of those which can be affected by the convective injection mechanism: it is the case of H_2O trapped by the very low temperatures in the vicinity of the tropopause or the acids, HCl, HNO_3, soluble in droplets and ice crystals. The second type of chemical species injected into equatorial stratosphere is made of the chemical species of short lifetime (a few days to a few weeks). They are normally destroyed before reaching the tropopause but, because of the convective transport velocity, they can be found intact in lower stratosphere where their lifetime lengthens. Among these species, one finds NO_X CO, formaldehyde and methyl bromides, chlorides and iodides, issued either from large equatorial cities, biomass burning sources or simply from the oceans. Extremely reactive for some of them, they could be the cause of the rapid reduction of ozone, during the last years, in the layer immediately above tropopause. A particular group is made of the sulfur species (SO_2 and CS_2) which after oxidation are able to yield the formation of sulfated aerosols which will spread over the whole globe and give rise to many chemical conversions due to heterogeneous reactions which can take place on their surface. The last element which could play an important part in the chemistry of these areas, however not much is known about it, consists in the equatorial stratospheric clouds (ESC). These clouds could be formed in the vicinity of a tropopause at the temperature as low as –92°C to –94°C, or in the "sub-cirrus" in the upper troposphere, clouds with very low optical thickness ($<10^{-2}$), but offering important surfaces which allow, there too, to imagine an active heterogeneous chemistry. There is clearly a lack of experimental data to document all these important processes over tropical continents.

There is a also crucial need to document direct and indirect radiative effect of aerosols over Africa. Direct effect deals with the heating and/or cooling effect on the radiative balance whereas indirect effect describes the modification of radiative properties of clouds (albedo) and the effects of anthropogenic aerosols on the cloud lifetime (Haywood and Boucher, 2000). Feedbacks of cloud and water vapor modifications which can affect the hydrological cycle and dynamics are also unknown. In Africa, aerosols sources are among the most important that can be found in the world, with two main origins: terrigenous particles from the desertic zones of Sahara and Sahel and biomass burning that produce huge amount of black and organic carbon. This considerable available aerosol surface combined with extensive cloud cover and the recurrence of convective activity favours heterogeneous processes in this area, strongly interfering with ozone chemistry. In cloud free situation, gas-particle interaction between dust and acid gases (HNO_3) have been already underlined in Sahelian samples (Galy-Lacaux et al., 2000). Depending on the season aerosols particles are a mixing, in variable proportion, of mineral dust and of carbonaceous aerosols. Such mixtures have never been really studied : however recent experiments and modeling have shown the great impact of fossil fuel emission mixtures on particle optical and physical properties (Haywood and Shine, 1995; Penner et al , 1996; Hignett et al , 1999 during TARFOX experiment). Results of INDOEX (over the Asian continent, Lelieveld et al , 2001) have shown the importance of regional differences for the composition of these mixtures. Up to now, crude parametrization exits in global and regional models to threat wet deposition by convective rains : during the monsoon season in Africa, the observed black carbon particulate concentration can not be nicely reproduced by models (Liousse et al , 2001). Moreover, particle hydrosolubility is roughly unknown especially the impact of the presence of soluble particles in the aerosol mixture (Levin et al , 1996). Vertical aerosol distribution plays also an important role in the estimation of the direct radiative impact of aerosols: absorbing particles have a different impact when situated above or below clouds (Kaufman et al , 1997). A few studies only exist on the indirect effect of aerosols. Recently relationships between aerosol optical depth, cloud optical depths and droplet size have been found, also for smoke particles (Remer et al , 1999). But, many studies suggest the important role of absorbing aerosols inside clouds, a process which is not documented. More research is also needed concerning the middle and high levels clouds. Aerosol could be ice nuclei with a possible effect on cirrus formation.

Finally, the West African monsoon experiment in which dynamical, microphysical and hydrological features are planned to be studied in detail will offer an ideal framework to further investigate multiphase chemical, photochemical processes and radiative impact occurring in the tropical troposphere. Moreover, dramatic anthropogenic changes are likely to occur in this region in the next decades. This program will be an observatory of the effect of rapid anthropogenic changes on atmospheric chemistry.

II Scientific objectives

Many research topics pertain to the four domains of investigation considered here, as was shown in section 1. It is thus difficult to list scientific objectives on a domain-by-domain basis, especially when it comes to processes linking the continental surfaces to the atmosphere (rainfall, evapotranspiration and associated transport of chemical species). On the other hand, there are a number of advances which are needed in each field in order to better apprehend their interactions. Therefore this section first provide an overview of scientific objectives in each domain, before making in section II.5 some proposals regarding integrative science.

II.1 Monsoon dynamics

Considerable difficulties are currently experienced in analyzing, simulating and forecasting the West African climate variability. This is mainly due to the scarcity of in situ data and to the deficiencies of the dynamical climate models which, most notably, predict a too early monsoon onset. Obviously some key physical processes (i.e. interactions with the surface, cloud parameterization, …) are not well represented in these models. It is therefore important to focus on the physical and dynamical processes relevant to explain the evolution of the WAM in terms of mean diurnal and annual cycles, and other scales of variability. We have also to take into account a large range of mechanisms and interactions in the coupled ocean-atmosphere-land system, on a large range of space (regional, synoptic, meso-scale) and time scales (quasi-decadal, interannual, intraseasonal, 3-10-day). In this context we need first to document the interactions between the monsoon dynamics and the continental hydrological cycle.

II.1.1. Water and energy budgets

The hydrological cycle over the continent is strongly linked to the monsoon circulation (intensity, northward expansion) and hence depends from the location and intensity of the energy sources and sinks located in the eastern part of the tropical Atlantic. If the monsoon flow is firstly driven by the St. Helena anticyclonic cell in the southern tropical Atlantic, its interaction with land surface becomes predominant when it penetrates over the continent. This affects the convergence of the moisture and moist static energy (MSE) fluxes over land and, through evaporation and mixing processes, is closely linked to the seasonal variations of SSTs in the Gulf of Guinea. A paradoxical statistical feature regarding the interannual variability of the Sahelian rainy season (JAS for July-August-September) recently came to light (Phillipon and Fontaine 2001): JAS rainfall is not significantly linked to the rainfall recorded the year before over the region (JAS –1) or even during the preceding months elsewhere (AMJ). Rather, it is statistically associated with the intensity of the previous second Guinean rainy season (SON -1). The existence of such a ~6-month memory through the dry rainy season is viewed to be associated with soil wetness reservoirs impacting on the meridional (and zonal over the western Sahel) energy gradients during the boreal spring. At the same time, the increasing anthropogenic pressure on land-use affect the repartition between crops, fallows and bushes, and this also modifies the land-atmosphere interactions. In order to better understand the role played by these various factors of variability in the WAM system, regional observations and modeling studies of the atmosphere are required, taking into account the variability of the surface conditions (see also II.4 and II.5).

Proposal:

1. To improve the quantification of water and energy budgets at the surface and in the atmospheric boundary layer on a regional and sub-regional (i.e. Sahel versus Soudano-Guinean Region, for instance) scales, in relation with the evolution of the surface conditions. This cannot be achieved through the current sensitivity experiments on AGCMs, or by the presently available reanalysis (NCEP/NCAR; ERA/ECMWF) products since the variables linked to the water cycle do not take into account the spatial heterogeneities in surface properties and are too model-dependent (different physical parametrisations such as surface schemes). This requires to significantly enhance the atmospheric radio-sounding network over the region for a period of at least two years.
2. To obtain a better understanding of the role of spring to summer evolution of MSE gradients in the boundary layer and of their intraseasonal persistence on monsoon dynamics at all scales with special attention to i) the estimation of the vertical sensible and latent heat fluxes that regulate the energy gradients in the atmosphere and are sources for convection, and ii) the retroactions with soil moisture and surface/deep reservoirs.
3. To evaluate as carefully as possible the performances of the statistical and dynamical forecast models. This evaluation should include a wide range of time (10-day to seasonal) and space (natural zones or regions, 100*100 km^2) scales, and include a diagnostic of the atmospheric and surface conditions for which the forecast is satisfying or not.

II.1.2 Convection and its environment

The monsoon circulation, cannot be reduced to moisture or energy advection in the boundary layer. Specific atmospheric processes (easterly waves, organized cloud systems, squall lines) implying the synoptic weather regimes and/or the convective scales have been identified for a long time. Recently clear intra-seasonal variations (active and inactive monsoon phases) have been documented. This shows that the scale-interactions problem, which is of paramount importance, cannot be treated by a simple coupling between general circulation models and hydrological models (impact of the global change on the continental hydrological cycle). We have first to improve our knowledge on the basic interactions linking the easterly waves, the moist and dry convection and the 3-D structure of winds (AEJ, TEJ, subtropical jet).

Proposal:

1. To document the different types of convective systems (organized or not) after having separating them from the other precipitating systems (i.e., stratiform systems), with emphasis on the estimation of associated precipitation and apparent sources of heat, moisture and horizontal momentum
2. To document the life cycle of convective systems (initiation, propagation and dissipation phase) regarding the coupling with surface properties (positive feedback between convection and continental surface properties)
3. To analyze the processes leading to convective organization in focusing on the respective roles of

   -moisture advection and distribution over the continent with a focus on the period 15-30 June during the abrupt northward transition of the rainbelt

   -mesoscale vortices during August-September (August for analyzing the many occurrences of meso-vortices and September for studying the relationship with the generation of Atlantic storm or cyclone precursor)

   -waves and westward propagating vortices

   -topography and vertical wind shear

   -microphysical characteristics and radiation interaction
4. To analyse the retroactions between
   - mesoscale convective systems and the monsoon flux through the water and energy cycles at regional and meso scales
   - dry and moist convection and the 3D structure of the jets (AEJ, TEJ, subtropical westerly jet)
   - the synoptic activity and the mid-latitude synoptic systems including the specific role of the subtropical westerly jet.

II.2 Continental water cycle

The recent drought had contrasted impacts on the continental water cycle, depending on the scales and sub-region of West-Africa considered. Given the fact that the 70's and the 80's were characterized by a simultaneous decrease of precipitation and modification of the vegetation cover, it is not obvious to determine which of these two processes played the major role in determining the fluctuations of the hydrological cycle. The central objective of the project is thus to better understand the complex interactions between scales in the partitioning of the continental water budget. Three items have to be considered in this respect: i) the scales of variability of the rainfall forcing; ii) the continental water cycle *stricto sensu* ; iii) the feedback towards the atmosphere. This project provides the opportunity to tackle these three domains of investigation in a coherent framework, linking observation and modeling strategies. In parallel to the implementation of specific observations, it is critical to compile and synthesise existing rainfall, runoff and aquifer level data acquired over the past 50 years or so, in order to obtain information on the variability of the continental water budgets over the region.

II.2.1 Rainfall forcing

It has long been known that rainfields exhibit a strong variability at convective scales. Recent studies based on experimental data sets have shown that this variability is in fact strong over a broad range of scales, both in space and time. The response of hydrologic systems to rainfall forcing is controlled by the scaling properties of rainfields, on the one hand, and those of the continental surfaces, on the other. A first step in the study of the continental water cycle is thus to investigate the variability and scaling properties of rainfields in West Africa, both in relation with the atmospheric circulation generating this variability and with an aim at characterizing the hydro-meteorological events over the region. *Note that there exists a common area of research with II.1.2, regarding the documentation of the life cycle of convective systems.*

Proposal:

1. To maintain rainfall observations at high space-time resolution, covering the two main rainfall regimes of the region (Sahelian and Soudanian) in order to document the variability over a range of scales
2. To develop scaling approaches in order to link the structure of ground rainfields with the atmospheric structures (jets, easterly waves, MCS's) controlling each scale of variability;
3. To provide a global and coherent framework to derive rainfall regimes models from the simulations of atmospheric models; such models will be used to force hydrologic models in order to produce scenarios of the hydrological impact of climate variability;

II.2.2 Continental water cycle

Process studies are necessary to fully understand why, as a reaction to the long lasting drought, runoff and discharge were increased or decreased depending on the scale or the region (Sahel versus Sudano-Guinean) considered. This means characterizing the hydro-meteorological events, including rainfall, runoff, infiltration, water table recharge, root uptake (mainly during inter-storm periods) and water and energy fluxes back to the atmosphere. These studies have to be undertaken at the process scales, that is in most cases at the watershed or hillslope scale (fine scale : 100 - 1000 m). Specific observations are thus a prerequisite. However new modeling approaches are also required, in order to: i) account for scaling properties in hydrologic fields (runoff, aquifer recharge) which control the impacts at larger scale of infiltration, runoff, vegetation dynamics and fluxes; ii) obtain models that are as transposable as possible to various climatic and ecosystem contexts. An important component of this research is to provide the ground for the development of coupled atmospheric-hydrologic models (see section II.2.3 below).

Proposal:

1. To document the hydrologic variability over scales ranging from the convective forcing to the seasonal cycle in order to understand the links between these two very important scales in term of water resources (impact on agriculture and water table recharge)
2. To study how scaling models of some major water fluxes (infiltration, evaporation) might account for the observed behavior of West-African catchments for scales ranging from 1 to 10000 km^2
3. To develop integrated models of runoff, vegetation dynamics and water and energy transfer models; beyond the methodological interest of building a generic modeling platform, these

models are also essential for water budget closure at the surface; *this objective should be viewed as a contribution of hydrologists to the integrative science of building coupled models.*

II.2.3 Continental water partitioning and memory effects

As mentioned in section 1, the feedback effect of the continental surfaces on the dynamics of the WAM is often assumed to have played an important role in the drought of the 70's and 80's. Understanding this role implies the identification of the main hydrologic processes involved in the continental water cycle, that can be different from a climatic/geologic region to an other. Here also scales should be in focus. While the theories of Charney (1975) or Eltahir and Gong (1996) address this question at the regional scale, other studies (see e.g. Taylor and Lebel, 1998) raise the hypothesis of continental surfaces feedbacks at convective scales. Both atmosphere dynamics and continental water dynamics (interactions between horizontal water transfer, soil water storage, and vegetation dynamics) are important to consider. Due to the horizontal distribution of water by runoff, water recycling in a watershed may be highly variable in space: under certain conditions, soil infiltration and deep percolation (aquifer recharge) is increased in pervious areas where important runoff amounts are concentrated; evapotranspiration fluxes increase in areas with dense vegetation and large water inflows (e.g. valley bottoms). Increased infiltration, in turn, favors vegetation development, that locally impact runoff capacity. Therefore considering these water-vegetation interactions at local scale is a key point. At the same time, developing coupled atmospheric/hydrologic models is also a necessity to represent all the interactions involved in these feedback effects.

Proposal:

1. To acquire local observations of rainfall partitioning on the ground, dependently on the vegetation and its dynamics
2. To develop modeling approaches allowing coupling of global or regional atmospheric models with hydrologic models. Methodological approaches must be develop to jointly upscale the working scale/resolution of hydrologic models[a] and downscale those of atmospheric models (mainly regional ones). However, it is believed that, even reduced, a scale/resolution gap between these types of models will persist. As an alternative to fully integrated models representing explicitly the atmospheric and hydrologic scales, new parameterization of surface processes at larger scales could be derived from the development of a new type of hydrologic models working at a finer scale than the atmospheric models.

II.3 Surface conditions

One central goal is to contribute to a better understanding of the partitioning between purely climatic impacts and effects of changes in the vegetation cover (including anthropogenic effects) on the evolution of the continental hydrologic cycle observed over the last 30 years. Similarly, characterizing the evolution of the surface conditions, both over the continent and the ocean, over the past 50 years is necessary to assess possible synergies between rainfall variability and surface conditions variability. Associated to processes knowledge acquired at fine scale (see section II.2. above), long term observation are required to characterize the land cover changes. Based on previous studies in Africa, a ten-year observing period appears to be a minimum in this respect. Vegetation, and land cover evolution data may exist, but the harsh work of compiling, interpreting and

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[a] hydrologic models are considered here in the general case, as models of functioning of the continental surface, including simulation of water and energy fluxes (runoff, infiltration, groundwater recharge, evaporation, transpiration) and vegetation growth and dynamics

synthesizing the raw data (e.g. existing aerial photographs covering the whole sub-continent) must be undertaken.

II.3.1 Land surfaces

Two main categories of objective are envisioned. One is to produce large scale maps or global indicators regarding the evolution of the vegetation during the past 50 years or so and the current dynamics of vegetation over West Africa. The other is to proceed to local eco-physiological studies in relation with the quantification of continental water budgets at small scales.

Large-scale mapping is dramatically needed since very little is known on the evolution of vegetation over West-Africa over the past decades.

Proposal:

1. To produce vegetation index and surface humidity maps over West Africa, blending the various satellite data available
2. To determine the evolution of vegetation during 20th century in using all data available including the aerial photographs of the second halve of this century
3. To study in details the evolution of biomass, vegetation cover (pattern, density, species), evapotranspiration, surface humidity at local scale and the scale of GCM grid mesh (few hundred kms)
4. To understand how the vegetation cover controls the dynamics of the continental water cycle

II.3.2 Ocean

As previously mentioned, the SST (Sea Surface Temperature) in the equatorial Atlantic, is one of the key parameters upstream of the African monsoon. The thermal state of the ocean surface interacts with the atmospheric boundary layer. It modulates the meridional energy gradients and the ITCZ dynamics. It is thus of prime importance to monitor surface SST variability and better understand the physical processes governing that variability at different time scales (from intraseasonal to interdecadal via interannual scales), .A better understanding of the interannual equatorial Atlantic signals would lead to improvement of the seasonal climate forecast over West Africa.

In the tropical Atlantic, several climate signals dominate (e.g. Tourre et al., 1998). Among them the seasonal (up to 5°C) and the interannual (up to 2°C) signals are observed in the equatorial Atlantic and Gulf of Guinea, where strong equatorial and coastal upwellings are present. These upwellings, associated with the Ekman divergence and a shallow thermocline (due to the trade wind regime over the whole equatorial Atlantic basin that induces a shoaling of the thermocline in the eastern part of the basin), yield to intense vertical mixing between cold subsurface and warm surface water masses. while SST anomalies are closely linked to interactions with the atmosphere, processes controlling the SST variability in the Gulf of Guinea are also associated with the oceanic circulation that modulate the thermocline depth and the surface mixed layer thickness (McCreary et al., 1984; Gouriou et Reverdin, 1992).

Paradoxically, oceanic circulation and its variability in the Gulf of Guinea is not well known While the mean currents are well identified (see Figure 10), and in spite of the FOCAL/SEQUAL experiments (1982-83-84) their behavior in the Gulf of Guinea and their variability are still poorly documented. For example, our knowledge on the relative contribution on the currents variability of the different physical processes (as vertical and horizontal advection, equatorial waves, remote processes…) is still to be improved. 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 (unpublished work). Furthermore, the effect on SST of the low sea surface salinity (SSS) encountered in the Gulf of Guinea, due to high precipitation but also 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).

Proposals :

1. To investigate with available in-situ and satellite data, as well as Re-analyses, the role of the Gulf of Guinea on the West African monsoon dynamics, from intra-seasonal to interannual time scales : quantification of heat and momentum surface fluxes, study of the nature of the forcings and/or the couplings between ocean and atmosphere, computations of the hydrological cycle, analysis of the nature of the convection and its interactions with SST and moisture fluxes.

2. To document the variations of the oceanic circulation in the Gulf of Guinea with available in-situ and satellite data, at intra-seasonal, seasonal and interannual time scales, and to study the corresponding variations of the heat, salt and momentum budgets in this oceanic basin and the role of heat transports by oceanic currents, in analysing particularly the impact of the barrier layer on the oceanic heat budget and on SST.

II.4 Atmospheric chemistry

Considering the importance of the African monsoon region in the emission of ozone precursors and of aerosols and their redistribution over the whole troposphere, the main foci of this project for atmospheric chemistry could concern the emissions and depositions of chemical species, the budget of the $H0_x$ radicals, the characterization of the heteregeneous chemistry in the convective clouds, the influence of aerosol emission without clouds and on the cloud structure and the coupling between the troposphere and the stratosphere. This program should contain a strong modeling component (see also section III.5) involving different models ranging from detailed photochemical box model for describing the cloud chemistry or the fast photochemistry of the upper troposphere, meso-scale transport-chemistry model capable of describing the convective transport and the associated radiative and chemical processes and global scale model to estimate the import and export of chemical species in the domain of interest. The latter models can also be coupled with space observations and be used for the experiment planning.

II.4.1 Emission and deposition of chemical species

The emission of trace gases by savanna and forest fires have been characterized during DECAFE and EXPRESSO experiments. The emissions of dust particles have been described in details in african desert areas. However, due to important interannual variability in biomass burning and dust events, updatings are needed. Also, better determination of burnt biomass especially the biomass load has to be considered. There is also urgent need to study sources which are still poorly documented such as african urban sources, domestic fires, natural emission by ground and vegetation. To better assess the budget of the chemical species, important questions are still remaining on the wet and dry deposition processes.

Proposal :

1- To perform emission inventory of chemical species with a key role in the monsoon region
2-.To improve parametrization of wet and dry depositions

II.4.2 Budget of the HO_x radicals in the free troposphere

The variability of the HO_x concentration is a key quantity to understand the future evolution of the methane and ozone concentrations in the tropical region. This budget has been already studied in oceanic tropical regions, especially during the PEM Tropics experiment over the Equatorial Pacific by the NASA DC-8 aircraft measuring both the HO_x concentrations and the longer lived species controlling their sources and sinks. It was found that the upper troposphere was more chemically active than previously thought even though this experiment took place in a remote region.

Proposal:
A field experiment will focus on two points:

1- Chemistry in the outflow of convective systems and HO_X budget in the upper troposphere
2- Quantification of the role of lightning on NO_X production in the troposphere

Convection in this region is often associated to intense lightning activity then producing a significant amount of NO_x which will strongly impact the ozone production but also the loss mechanisms for HO_X radicals. A better quantification of the NO_X budget perturbation induced by the development of the convection over western Africa should then be obtained by a combination of aircraft and satellite measurements (GOME, SCHIAMACHY). The characterization of the HO_X budget itself requires a large aircraft equipped with as many chemical measurements as possible : NO_X, O_3 CH_2O, CH_4, CO, acetone, peroxides and if possible OH and HO_2.

II.4.3 Characterisation of the heterogeneous chemistry in the convective clouds

The cloud system developing with the intensification of the monsoon circulation modifies the chemical composition of the air mass by both microphysical processes (washout) and chemical transformation in the aqueous phase. It is expected that the output concentration of soluble species like HNO_3, H_2O_2 or even CH_2O should be controlled by these processes. Cloud models now exist and can simulate the chemical transformation of the chemical species. The emission of the trace gases by the African forest and savanna have been characterized in the past (e.g. the DECAFE and EXPRESSO experiments) but the redistribution of the trace gases by the wet convection is still poorly known for this region.

Proposal: A field experiment should address the question of trace gases and aerosol redistribution by convection in order to study:

1- The chemical evolution of traces gases in air masses entering and exiting convective systems
2- The chemical evolution of aerosol particles of various origins within convective clouds.

A good knowledge of the wind field in the convective cell can be useful to determine the residence time of the gases in the cloud structure. The mixing of different aerosol sources (mineral dust and organic aerosol) should also be considered as the convective area is moving across western Africa. The measurement strategy during the SOP will be mainly based on the comparison of measurements performed by two different aircrafts and ideally by surface network. One aircraft will sample the air entering the convective system either from the North due to the transverse circulation associated to the thermal low or from the south in monsoon flow. The other aircraft will sample the outflow region as described in the first objective.

II.4.4 Influence of aerosol emission on cloud structure

The recent measurements of the Large scale Biosphere Atmosphere experiment (LBA) in Amazonia have shown that during the wet season the effective radius of the cloud droplet is rather large (> 20 µm) and the cloud structure is similar to oceanic clouds. It is expected that the cloud structure will be more continental in Africa since emission of particles and gaseous species are larger than in South America. In addition larger convective updraft and lower available moisture might also play a role. The continental structure of the cloud system will reduce the amount of rainfall compared to Amazonia. The transport of condensation nuclei in the cold upper troposphere should also be important in the formation of cirrus cloud in the tropical region. Considering the important radiative impact of these clouds in the tropics and subtropics, such an effect should be better understood. Remote sensing measurements from space (MODIS on TERRA, POLDER on ENVISAT, Y-CENA) or from aircraft (IR radiometer and lidar) should provide the physical characteristics of the cloud and aerosol layers, but the role of the chemical composition in the cloud formation should be based on in-situ measurements. This is likely to be difficult for the cold upper troposphere unless a high altitude aircraft like the Geophysica is available. However aerosol measurements performed in the mid troposphere should be valuable for assessing their potential impact on the cloud formation. It is also important to note that physical and chemical characterization of the aerosol mixture (dust, black carbon and total organic carbon aerosols including SOA formation) are needed to correctly perform remote sensing determination of aerosol layers and the calculation of their direct radiative impact.

Proposal:

1- To investigate the links betweeen aerosols and clouds (including cirrus clouds) in a continental tropical zone.
2- To assess the direct and indirect radiative impact of aerosol and clouds layers at regional scale.

II.4.5 Troposphere/Stratosphere coupling

The interaction between the convection and the tropopause structure is still not very well understood. Because the tropopause is not only controlled by the radiative-convective adjustment but also by stratospheric processes (dynamical heating, ozone and water stratospheric distribution), the top of the convective clouds is sometimes below the tropical tropopause altitude creating a 3-5 km layer where water vapor and other long lived trace species are injected. Fast convective transport of chemical species at the tropopause level may change the lifetime of species which are normally destroyed in the troposphere. The transport to the middle stratosphere is then controlled by the Brewer-Dobson circulation in the equatorial band or by faster meridional motions near the subtropical tropopause. The latter is generally induced by the interaction of the subtropical jet with mid-latitude disturbances propagating southward. Tropical convection developing above the Atlantic ocean might also interact with the subtropical jet modifying the dynamical characteristics of the tropopause region and inducing exchange of air masses across the jet. These mechanisms were studied using the vertical distributions of ozone as diagnostics of such perturbations in recent measurement campaigns south of the Canaries Islands (e.g. TRACAS and PICO3 experiments).

Proposal: The experiment will focus on:

1- The characterization of the chemical composition of the intermediate region between the cloud top and the tropopause both below the tropical pump region in the region influenced by the easterly jet and in the 10N-20N latitude band above the African easterly jet where meridional transport across the subtropical jet becomes possible.

2- The assessment of troposphere-stratosphere exchanges in the vicinity of cloud systems through balloon borne or aircraft measurements

Beside species like H_2O, ozone, and carbon monoxide, other species should be measured either to identify the impact of the convection (Radon) or to estimate the chemical reactivity in this region (NO_X). The main requirement to achieve this objective is to involve a high altitude aircraft flying above 15 km or balloon borne experiments. Trace gas measurements from balloon borne measurements at the tropopause and above in the tropical band will help to understand how the reactive species enter the stratosphere: overshooting of the convective cells above the tropopause, accumulation of trace gases in an intermediate tropopause region before its transport either by meridional motions across the subtropics or by upward motions induced by the stratospheric wave activity.

II.5 Integrative science through multiscale observations and modeling

In order to address the objectives of the project, an improved understanding of processes involved in each component of the WAM (dynamics of the atmosphere and of the continental water cycle, atmospheric chemistry) is obviously needed. Nevertheless, their interactions at different space-time scales are a critical area of investigation. This requires a synergistic approach cutting across disciplines and across spatial and temporal scales. Many issues listed in the 4 previous sections can be viewed as integrated research topics. Careful attention to enhancing interdisciplinary work and communication will consequently be sought. Integrated science is necessary to ensure that progress in the understanding of the WAM variability and its impact on the continental surfaces will be much greater than by simply adding the results obtained separately in each component. As already mentioned, gradients of moist static energy in the planetary boundary layer are playing a key role in the WAM dynamics. These gradients develop in response to heat and moisture fluxes from the underlying surface, thus providing a mechanism for feedbacks on rainfall at time scales up to interannual. One major objective of integrative science in this project will therefore be to better understand the feedback processes at the regional and sub-regional scales. While the whole observation strategy -described in section III below- is designed to document the main key processes controlling the WAM dynamics, the focus on feedbacks requires specific actions with regard to observations and modeling.

III Experimental and numerical strategies

To address the issue of numerous space-time scales involved in the WAM, the project strategy from observational, modeling and assimilation perspectives, is designed as a multi-year program structured in 3 observational periods and 5 space scales, to which will correspond different numerical modeling approaches.

The observational periods are:

- The Long term Observation Period (LOP) aims at studying the interannual variability of the main aspects of the WAM. Another key objective is to collect the data required to better understand what is the part of the long term WAM variability that is controlled by large scale factors and which part is controlled by the land cover changes at the regional scale. Regional observations - satellite data since the late 60's and ground rain and streamflow observations since the beginning of the 20th century – and mesoscale observations started in the 90's, are available to that end.
- The Enhanced Observing Period (EOP) is designed to serve as a link between the LOP and the Special Observation Periods. Its main objective is to document over a climatic transect the seasonal cycle of the surface conditions and of the atmospheric state variables at convective-to-synoptic scales. The EOP duration should be of 2 or 3 years at least, in order to capture the memory effects from one season to the next (through continental and oceanic conditions) and the conditions prevailing during two contrasting years.
- The Special Observation Periods (SOP) will allow to get detailed observations of some specific processes during most of the rainy season and to evaluate and improve the accuracy of analysis based on the smaller number of in-situ observations gathered during the EOP and the LOP.

Five regions corresponding to 5 different scales can be considered (Fig.11):

- The « supra regional scale » includes the West African sub-continent with neighboring land and sea surfaces. This is typically the relevant scale to study the local teleconnections of the WAM with oceanic processes over the Atlantic ocean (NAO for instance), or with extra-tropical North Africa. Linking with existing projects such as PIRATA (observations over the tropical Atlantic) and IMPETUS (observations on the Draa wadi in Southern-Morocco), is obviously necessary here. This is also a scale where linking with the other tropical regions of Africa is possible, an action encouraged by the Clivar panel on the Variability of the African Climate System (VACS).
- The regional scale corresponds to West Africa, which means approximately 6,000,000 km². Global water and energy budget between continent and atmosphere must be conducted at this scale to encompass all the local specificities of the meridian climatic and land cover gradient between the Guinean gulf and the rims of the Sahara. That should be performed in using mainly modelling and assimilation approaches and spatial observations.
- The sub-regional scale comes mostly from operational limitations in monitoring and documenting the entire regional scale. This scale is related to the concept of meridional and zonal transects. The North-South transect should be built from the current CATCH window,

extending it South to the gulf of Guinea and North to the Sahara. A East-West transect should also be considered from the eastern Atlantic to the central Sahel (Niamey) via Dakar and Bamako. This transect is already equipped with PIRATA sites (Pilot Research Moored Area in the Tropical Atlantic), meteorological radars, radiosondes and surface stations. The sub-regional scale is also relevant for characterizing the West-African rainfall regimes and their variability (see Le Barbé et al , 2001).

- The meso-scale is typically related to hydrometeorological observations focusing on rainfall field characterization and nested catchment water budgets. It is also a relevant scale for studying the dynamics of the convective systems. A few observatories are already well and specifically documented for environmental and hydrology studies. Their size ranges from 10,000 km² to 40,000 km². Two such sites have been operated for several years within the CATCH window: one is the Niamey square (since 1990) covering 12,000 km² in a Sahelian environment and the other is the upper Ouémé (since 1997) covering 14,000 km² in a Sudanian environment. Extension of the hydrologic modeling to the whole Ouémé catchment (38000 km^2) is part of the CATCH project. The Nakambé basin (21000 km^2) in Burkina Faso is another site to consider, because it is seated on a crystalline bedrock, as opposed to the Niamey square. This catchment has been the object of numerous monitoring and modeling programs over the past 20 years.
- The local-scale is dedicated to heavy monitoring of surface processes. Small areas within the two meso-scales sites of Niamey and the upper Ouémé (Figure 12) belong to this category (rainfall supersite and Wankama catchment in Niamey, Donga and Aguima catchments within the Ouémé). Other sites will have to be considered, whether for a more comprehensive documentation of hydrological processes or for building a transect of flux measurements. The size of these local-scale sites range from one to a few hundreds km².

To the different observational periods and scale regions will correspond different modeling and assimilation approaches. Modeling and assimilation will be the major tools to integrate the various measurements carried out at various spatial and temporal scales. Downscaling or upscaling models will be important in relating the measurements carried out over various space scales.

Special attention is also given in this proposal to satellite observations as it is another major tool to integrate the different time and space scales. In this regard, two aspects can be outlined: i) the need for gathering and using past satellite data in order to monitor the climate and surface changes, and the unprecedented effort of satellite earth observations (specially clouds) coming in the next years.

III.1 Long Term Observation Period

The long term observations considered here are of two types. First, there are a number of observations that have been obtained during the past 50 years and could be of great help for studying in parallel the decadal rainfall fluctuations and the dramatic land cover changes that occurred all over this period. Secondly the project aims at promoting supplementary long term observations required to document and analyse the strong interannual variability of the WAM. Remote sensing is an essential, but not unique, source of observation in this area. A recent study by Le Barbé et al. (2001) has demonstrated that ground rainfall observations of the past 50 years can teach us a lot about the dynamics and the variability of the WAM, hence the necessity of archiving as many as possible of past ground data.

III.1.1 Historical archives and data sets from operational networks

In West Africa, numerous data were collected during the colonial period and later by National Services as well as by the scientific community. Some of these data are available (for instance at the Institut Français d'Afrique Noire, at AGRHYMET, at Meteo-France, …) but no detailed inventory is available so far. It is thus proposed to set up a Data Management Working Group (DMWG) in charge of collecting, organizing and documenting the various types of long term data. The first priority of the DMWG would be to update the existing archives. It will also be responsible for the data collection (for instance the hydrometeorological data from various countries) and processing (for instance standard product from remote sensing such as METEOSAT tracking). Two preliminary actions should be started in the short term:

- ❑ Building data bases of hydrometeorological data from the regional to the meso-scale, based on the existing initiatives of AGRHYMET, FRIEND-AOC and HYCOS-AOC.
- ❑ Organizing remote sensing metadata with links between original images, standard product and expertise, based on a WEB interface.

Another important mission of the LOP will be to ensure that data from operational networks collected during the LOP are made available to the scientific community involved in the project, especially over the CATCH window.

- ❑ Building data bases of hydrometeorological data from the regional to the meso-scale, based on the existing initiatives of AGRHYMET, FRIEND-AOC and HYCOS-AOC.

III.1.2 Specific data sets

During the last decade, several observing systems, covering a wide range of scales and processes, were set up in West Africa in domains relevant to this project. The aim is to facilitate the coordination between these observing systems, thus developing their coherency.

Regional scale

The **IDAF** (IGAC DEBITS AFRICA) network has been created in 1994, in the framework of the IGAC activity: The main goal of DEBITS (Deposition of Biogeochemically Important Trace Species) is to promote existing and new activities in the final step of the biogeochemical cycles. The DEBITS scientific activities are mainly based on measurements of controlled quality of precipitation chemistry to quantify wet deposition, aerosol and gases concentrations to estimate dry deposition. Amongst the ten African sites, six are located in Western and Central Africa. An additional site is needed in the Ouémé catchment in order to cover preoperly the CATCH transect.

AERONET (AErosol RObotic NETwork) is an optical ground based aerosol monitoring network and data archive. The network hardware consists of identical automatic sun-sky scanning spectral radiometers. The AERONET stations located in West Africa are located in Niger, Senegal, Cape-Verde, Burkina Fasa) and Nigeria.

Sub-regional scale

This scale is related to the concept of transect and as mentioned before proceed from operational considerations. Three experimental transects have been defined (Fig. 11):

The CATCH window covers 5° in longitude and 9° in latitude over the climatic continuum from the gulf of Guinea to the Sahel,. This transect, defined in 1996, is mostly dedicated to hydrometeorological measurements over the two meso-scales sites of Niamey and Ouémé (see below). An upgrade of the present setup will be sought in the following directions:

- ❑ **Digitised rainfall records.** Presently the window is covered by the daily rainfall networks operated by the DMN's of Benin, Togo, Niger and Burkina Faso. A transect of a dozen recording raingauges, extending from Cotonou (6°N) to Agadez (18°N) will be installed in order to study the space-time distribution of rain at small time steps in connection with rainfall variability at large scales.

- ❑ **Flux measurements.** Specific observations of soil moisture and surface fluxes are required at different points on the transect between the tropical forest to the South and the desert to the North. These observations need to continue over several annual cycles in order to sample the interannual variability. These measurements should be linked with spatial observations in order to develop methods of land surface monitoring from space. Flux measurements over the nearby ocean have also to be considered. As far as possible these flux measurements will be associated to the atmospheric soundings and hydrologic measurements listed in sections II.1 through II.4, in order to compute as precisely as possible balanced water and energy budgets.
- ❑ **Radio soundings.** During the EOP (see below) a radio sounding transect will be operated for at least two years. It is highly desirable that this radio sounding transect continue to operate over the LOP

An ecological transect is also needed. Ideally this transect should be located in the CATCH window. However, the only ecological research station operational since 1962 is located in the natural reserve of LAMTO in Ivory Coast, that is outside the CATCH window. The vegetation cover is a Guinean savannah. This site is well documented for long term vegetation dynamic studies. The LAMTO site must be completed by at least two other experimental sites located to the North in order to achieve a meridian transect encompassing the main vegetation zones of West Africa. Several sites located in Burkina Faso were pre selected to become part of this transect. A third site could be Gourma located in Mali. There, the evolution of the vegetation is followed since 1984 and some patches have been used for remote sensing calibration since 1999. Meteorological and AERONET stations have been installed in 2001. In addition to vegetation monitoring, these three sites should be equipped with basic hydrometeorological equipment.

Finally, the need for **a zonal transect** dedicated to meteorological objectives was also identified. This transect would run from Dakar to Niamey including the 4 meteorological stations of Dakar, Bamako, Ouagadougou and Niamey. These stations should be upgraded in order to dispose of reliable meteorological radars, radiosounding stations and surface stations. This transect would be a complement over land of the PIRATA (Pilot Research Moored Area in the Tropical Atlantic) sites over the ocean.

Meso-scale and local scale

Within the CATCH window, the EPSAT/HAPEX-Sahel site (region of Niamey, 13° N) has been operational since 1990. Rainfall and ground water levels have been continuously recorded with a high space-time resolution over the past 12 years. Runoff measurements over small endoreic catchments are also available for several years. A dense rainfall-recording network was also set up on the Ouémé catchment (9.5° N) in 1997 and a set of nested catchments has been equipped with streamflow recording stations.

At a lower scale, a piezometric network was installed in 1999 on the Donga sub-catchment (500 km²) to study the dynamics of the water table within crystalline weathered rocks. Then, the catchment of Aguima (20 km²) has been selected by the German IMPETUS project to monitor the water budget of a small catchment. This catchment should be instrumented during the year 2000: streamflow station, meteorological stations, a set of raingauges, soil moisture, water table.

The two meso-scale sites of Niamey (Sahelian climate on sedimentary deposits) and of Ouémé (sudanian climate on a crystalline bedrock) do not encompass all the morphoclimatic contexts of West Africa. Therefore, the monitoring of some other catchments should be envisaged.

The proposal is to continue to monitor the two existing sites over the LOP and to include in the project setup the Nakambé basin (20800 km^2) in Burkina Faso which has been intensely monitored over the past decade. It is also recommended that the dynamics of land-cover of the sites of Niamey and Ouémé -at least on some local sites- be monitored during the operational phase to ensure the calibration of SVAT models.

III.2 Enhanced Observation Periods

III.2.1 Global view

The Enhanced Observing Period (EOP) is designed to serve as an intermediate between the LOP – the aim of which is to study the interannual variability of the main components of the hydrological cycle – and the SOP – which aims at a detailed observation of some specific processes. Its main objective is to document over a climatic transect the seasonal cycle of the surface conditions and of the atmospheric state variables at convective-to-synoptic scales. In line with the aggregative philosophy of the proposed experiment, the EOP also aims at documenting the corresponding regional energy gradients, atmospheric transport of chemical species and continental water cycle.

The EOP duration should be of two years at least, in order to possibly capture the conditions prevailing during two contrasting years and the memory effects from one season to the next linked either to the continental surfaces or to the ocean. In space, EOP measurements will consist in a densification of long term observations as well as in a larger extension. They will thus constitute a major source of validation for various satellite missions and modeling.

The area covered by the EOP is primarily the sub-regional area, i.e. along the meridional direction the existing CATCH window, extended to the North for atmospheric soundings in order to reach the Saharian heat low (25°N) and along the zonal direction at 12.5°N to document various synoptic features such AEJ and AEWs.

Various diagnostic studies have already been completed or should be promoted in preparation of the EOP. For instance, comparing ERA and NCEP reanalyzes show coherent areas of heavy divergence which might have a great influence on the regional water cycle and energy budgets, thus orienting the reinforcement of atmospheric soundings. The UK JET-2000 campaign that covered the CATCH area during the last two weeks of August 2000 demonstrated that a good description of the meridional gradients at the AEJ level is possible with a resolution of 50 km. The results of 4 years (1990-1993) of high resolution precipitation measurements over the Niamey region will help in designing the setup of mesoscale precipitation sites. Testing tracking algorithms over the Sudano-Guinean region may also provide information for targeting areas of intensified precipitation ground measurements. More generally the preliminary documentation of the surface conditions using geophysical soil survey, vegetation characterization and high resolution terrain mapping is required.

EOP would also serve to monitor seasonal variations of the chemical composition of the atmosphere over West Africa, since biogenic and biomass burning sources of atmospheric minor constituents are controlled by the alternation of rainy and dry seasons. The savanna fire pattern largely determines the variations of the atmospheric pollution at the continent scale in Africa. As we want to understand the redistribution in altitude and at the large scale of the pollutants produced at the surface, to analyze their impact on the chemistry of the troposphere and of the lower stratosphere, it is essential to know the variations of both emission fluxes and atmospheric concentrations of pollutants in inter-tropical Africa. The availability of these data over several years can provide a detailed view of the space-time variations of the chemical composition of the atmosphere over the West-African monsoon area and will help to define a field experiment and to replace this experiment in a more general climatic and chemical scope.

III.2.1 Atmosphere Dynamics

To improve our knowledge of water and energy budgets, the first objective of the EOP is to improve the radio-sounding network along two of transects cited above (meridional along 2.5°E and zonal along 12.5°N). The map of existing / operational soundings (Fig. 11) show a deficit South to Niamey for the meridional transect and gaps in the zonal transect between Lake Chad and Dakar. It is proposed to fill in these gaps in the following way: i) along the meridional transect, soundings should be carried out in Cotonou and Parakou by the teams of IMPETUS German program. The frequency and timing of these sounding remain to be determined precisely. Along the zonal transect, the objective is to secure more regular soundings from existing stations, especially N'djamena, and Ouagadougou. The network of pilot balloons over Niger could be extremely helpful and its maintenance and upgrading to be promoted. The operational surface meteorological stations received at ECMWF (Fig. 13) show a rather good coverage though some areas are not covered.

It is also proposed to extend the meridional transect to the South into the Guinea Gulf using the infrastructure of the PIRATA moorings. Therefore maintaining and extending the PIRATA network should be part of the EOP.

As far as atmospheric water and energy budgets are concerned two satellite missions are of special interest for the EOP. One is MSG, with its higher time-space resolution (one image every 15 minutes, nadir resolution of 3 km, down to 1 km in the visible) and increased number of channels. MSG will provide low level winds over the Guinea Gulf and the continent allowing for monitoring Sc and Cu to the South of the ITCZ. It will also provide "water vapour" winds in altitude. Downward radiative fluxes, short-wave and long-wave, are also computed, as well as surface parameters like sea and continent temperatures and visible albedo. The EOP will obviously benefit from these information. It also provides an opportunity to validate some of them. For instance it is proposed to establish a meridional transect for validating the radiative fluxes, using ground based radiative stations in the Ouémé catchment (this is already part of the IMPETUS program), Niamey and Tamanrasset. (One problem with MSG is the need for a new equipment of the reception stations. A European project (PUMA) has been set up to build such stations along with archiving facilities.

The other remote sensor of interest for the study of the West African monsoon is the ATOVS onboard the NOAA satellites. They provide vertical profiles of temperature and humidity four times a day. The integrated water content of the 0-2 km layer is computed over 25*25 km^2 pixels. A reception/validation station exists in Dakar.

III.2.3 Atmospheric chemistry.

Observations to be conducted during EOP, will be based on satellite measurements, ozone sounding, commercial aircraft measurements, and on already operational in-situ monitoring networks for aerosols, radiation and rainwater chemistry. Their objective is to provide, before the SOP, detailed emission inventories for the main sources of trace gases and aerosol and data to validate emission and deposition schema of meso and global scale models through pre-modeling exercises.

Emission inventories should cover the continental area between 20°S and 20°N. They include biogenic emission of VOC from vegetation and NO_x from soils, biomass burning emissions and also emissions from fossil fuels and human activities which are certainly significant, close to the center of the experimental zone (Nigeria). Such inventories should benefit from pre-existing data bases on soil and vegetation and of field experiments conducted in the last 20 years, and also from satellite data providing parameters like vegetation index (NDVI) and leaf area index (LAI). An important use of satellites for emission inventories is fire detection and estimation of burned areas through algorithms developed on data from sensors such as AVHRR (NOAA) and ATSR (ERS1).

Another objective of EOP is the monitoring of seasonal variations of atmospheric pollutants, for which different operations could be planned:

- the launching of an ozone sounding once a week, from one the two mesoscale sites of Niamey and Parakou, providing the evolution of ozone profiles in the heart of the experimental zone;
- the climatology at continental scale of key species such as ozone and CO from satellite measurements. Satellite schedule will allow to benefit from measurements from GOME (O_3 columns) and MOPITT (CH_4 and CO columns at 22 km resolution and a global survey completed in three days, plus CO profiles with seven levels in the troposphere), and then SCHIAMACHY on ENVISAT (same data than GOME and MOPITT with a better resolution). It will thus be necessary to analyze these observations for at least the two EOP seasonal cycles over West Africa. A special attention will be given to CO, a tracer of biomass combustion (insoluble and quasi-stable for the considered time scales). These observations will be complemented by measurements of ozone and CO on board commercial aircraft (MOZAIC III program). The MOZAIC flights cover the tropical Atlantic (12% of the flights) and Africa (10% of the flights). The database MOZAIC III should allow to establish a climatology, over several years, of the exchanges between low troposphere - high troposphere - low stratosphere at the ITCZ location;
- the climatology of aerosol optical thickness based on the data of stations in west Africa of the AERONET network. An additional station should be installed at Parakou.

The last objective of EOP in terms of atmospheric chemistry is the monitoring of dry and wet deposition which is covered by the IDAF network (see LOP section).

III.2.4 Hydrology and surface conditions

➢ Precipitation at the convective scale

Ground based rainfall measurements are part of the LOP program. This includes two mesoscale sites equipped with digitized high resolution raingauges (basically 30 to 40 gauges over each site, see maps in the LOP section). During the EOP, it is envisioned that at least one of these two sites - the Ouémé catchment which did not benefit from previous high resolution observations made during HAPEX-Sahel over the Niamey region – will be equipped with additional gauges and radars. The number of gauges will be increased to 60 and a Doppler polarized X-band radar will be installed in the region of Djougou (in the East of the catchment). This radar will be one of the component of a more important radar setup to be operated during the SOP (see SOP section).

Two other operations with a lower priority can be identified: i) re-activation of the C-band weather radar at the Niamey airport; ii) operation of a radar transect Niamey-Bamako-Dakar. The later operation would require to digitize the Bamako radar.

In addition to the specific scientific objectives of the *precipitation at convective scale* action, the above listed measurements, in conjunction with Meteosat 7/MSG data, will allow to monitor the ITCZ migrations and to test and improve satellite estimation algorithms.

➢ Hydrologic cycle at the watershed scale

Most specific observations of the hydrologic cycle at the catchment scale are part of the LOP program. Soil moisture measurement in conjunction with aircraft missions are part of the SOP. Two specific actions are recommended for the EOP. One is a continuous monitoring of soil moisture on a few sites, based on tensiometers, TDR and possibly neutron probes. Such campaigns are extremely heavy in term of time and personnel but they are seen as important contributions both for the hydrology and for the atmospheric studies. The second action is a finer monitoring of the aquifers, implying an increased number of piezometers. A campaign of geochemical tracing is also needed but it does not need to happen exactly during the EOP since it pertains to a study that requires a preliminary feeling of infiltration processes in the region of interest.

- **Vegetation**

There is a large consensus that ground monitoring of the vegetation is needed in order to calibrate satellite images and to produce meaningful maps for computing humid static energy gradients over the continent. Ground validation campaigns were carried out during the HAPEX-Sahel EOP and they proved to be of great help in quantifying the changes of vegetation that had happened since the 50's. Similar campaigns must be promoted in this project. Over the Ouémé catchment, the IMPETUS german programme will perform ground observations (more or less in the framework of the LOP). Special recommendations are issued in order to monitor the cropping calendar during at least the two years of the EOP over the test catchments and, as far as possible over the mesoscale sites.

Summary of parameters to be monitored during the EOP :

- radiative budget at the surface and at the top of the atmosphere, the sea and land surface temperatures
- vertical profiles of temperature and humidity
- large scale water vapor transport
- variations of the tropospheric ozone
- estimated winds from MSG measurements (from clouds and water vapor)
- latent heat flux and surface wind over the Guinea Gulf
- ITCZ position and cloud classification
- detection of precipitating clouds and rainfall estimation
- ground water (both storage and dynamics)
- vegetation coverage and estimation of soil moisture

III.3 Special Observation Periods

III.3.1. Goals

The objective of the SOPs will be to document different aspects of specific phases of the West African monsoon, based on both enhanced observations at the "supra-regional" scale and on dedicated ground-based and airborne instruments at regional, meso- and small scales. To that purpose, key phenomena related to the heat and moisture budgets, the control of weather systems by synoptic processes, the role of continental and nearby oceanic surfaces and the chemical processes in the unperturbed environment and in relation with precipitating systems will have to be, as far as possible, simultaneously considered. This is a prerequisite to any attempt at understanding how these important and various aspects of the West African monsoon system are intimately linked.

III.3.2. Timing of the Special Observing Periods (SOPs)

It is hardly conceivable to have all desirable equipments available during the whole monsoon season (i.e. from April to September). It is therefore necessary to concentrate the experimental efforts to the most critical phases of the monsoon seesaw over West Africa. A consensus has been reached among the different scientific themes to focus on the following periods :

SOP 1 – Monsoon Onset (e.g. 15 May – 15 July) during which the humid southerly flow in the first kilometer of the atmosphere penetrates more or less progressively northwards from the Gulf of Guinea up to the Sahelian domain, replacing the dry northerly Harmattan. Two steps are noticeable during the monsoon onset. First, the arrival of the Inter-Tropical Front (ITF; low-levels boundary between wet southwesterlies and dry northeasterlies) at 15°N is approximately concomitant with the occurrence of isolated convection signing the beginning of useful rains for farmers, that is rainfall not followed by a too long dry sequence of days (for instance 20 mm in two days, not followed by more than one week without rainfall). This step is highly variable but seems to occur most of the time during May. The second step is the real set-up of the African monsoon through a sudden "jump" of the ITCZ, from 5°N to 10°N. It is characterized by a large extent of the monsoon layer both in latitude and in depth, and a rapid increase of rainfall north of 10°N. This step occurs most of the time in June (the mean date is June 24th on the period 1968-1990). Important changes also occur in altitude during the whole phase of monsoon onset, with the northward displacement of the subtropical westerly jet, the appearing of the African Easterly Jet in the mid-troposphere and of the Tropical Easterly Jet in the high-troposphere. In this context, it is necessary to have a good knowledge of the meteorological conditions before and after the arrival of the monsoon flow.

SOP 2 – Monsoon Maximum (e.g. 15 July – 15 August) during which a wide variety of precipitating systems occur over West Africa in relation with the presence of a well-established regime (monsoon flow, African Easterly Jet, Tropical Easterly Jet), and in relation with the synoptic influence of easterly waves. Deep convective systems near the northern edge of the monsoon flow play a major role in the formation on rain and in the vertical transports, but less intense and structured cloud ensembles to the south are also worth considering.

SOP 3 – Late Monsoon (e.g. 15 August – 15 September) during which the well-established conditions described above begin to fade. This is however an important period during which the West African perturbations linked to the monsoon environment influence the meteorological conditions over the tropical Atlantic (and even eastern Pacific) ocean. Indeed, strong easterly waves can help to trigger tropical cyclones over the oceanic regions where the necessary conditions are fulfilled. In particular, the relation with the powerful « Cape Verde Hurricanes » which develop close to the western edge of Africa is of high concern.

III.3.3. SOP 1 – Monsoon Onset

During this period, two aspects would be considered with high priority :

- the evolution of the low-level heat and moisture contents and budgets, in relation with the northward propagation of the monsoon flow. The momentum budget related to the African Easterly Jet in the mid-troposphere would also be analyzed.
- the evolution of the chemical characteristics of the low troposphere with the relative influences of biomass burning and aerosol content from the north, and of the clearer air from the south which can however be influenced by urban pollution from big coastal cities.

The main focus will be on the survey of a meridional cross-section with enhanced radiosoundings and surface measurements, and dedicated observations with instrumented aircraft.

In addition, the survey of the surface (e.g. moisture and vegetation) and subsurface (aquifers) conditions in pre-monsoon environment is a prerequisite to correctly handle the seasonal evolution of the water budget.

III.3.4. SOP 2 – Monsoon Maximum

The highest priority would concern the study of :

- synoptic conditions (thermodynamic characteristics, jets, waves, …) ;
- precipitating systems (horizontal and vertical structure, vertical transports, budgets of heat, moisture and momentum, evolution, …) ;
- chemical characteristics (from the surface to the upper troposphere – if possible, to the lower stratosphere, in dry and moist conditions) ;
- surface water budget (with the relative contributions of rain, evaporation, surface runoff, infiltration, vegetation, and the evolution of the different reservoirs) ;
- radiative effects (with the surface characteristics, the aerosol content, the influence of hydrometeors in the mid- and upper troposphere).

The theater of operations will necessarily be wide open. Since intensive ground-based measurements cannot be conducted over too large an area, airborne observations would be intensively used to document the multi-scale and evolving aspects of precipitation, kinematic, thermodynamic, chemical and radiative structures.

III.3.5. SOP 3 – Late Monsoon

The objective would be to identify the factors controlling the generation of tropical depressions, storms, or cyclones, from westward propagating systems and waves in the easterly wind. Special focus would be devoted to the long-lived balanced vortices frequently produced by mesoscale convective and stratiform circulations within precipitating systems, and to the changes associated with the transition from continental to oceanic conditions. To that purpose, airborne dynamic, thermodynamic and precipitation measurements would be conducted at the synoptic and the meso-scales over the western edge of the African continent and over the nearby tropical Atlantic ocean. Concerning the chemical aspects, it would be interesting to quantify possible trans-hemispheric flow of air polluted by biomass burning in Austral Africa.

III.3.6. Required observations

Atmospheric soundings

☐ Higher frequency soundings

The background fields at the scale of West Africa would be provided by analyses from global or regional numerical meteorological models assimilating 12-hourly data from the reinforced operational radiosounding network. It is indeed necessary to have reliable information over a relatively large longitudinal extent at 12-15°N as mentioned in Parts III.1 and III.2 for the LOP and EOP, (e.g. Dakar, Bamako, Ouagadougou, Niamey, Zinder, N'Djamena…) but also at about 5°N (e.g. Abidjan, Cotonou, Douala, Bangui, ...). Supplementary (6-hourly) information on the monsoon flow and the tropospheric jets would be given by a meridional cross-section at about 2.5°E (e.g. Cotonou at 6.5°N, Parakou or Djougou at 9.5°N, Niamey at 13.5°N, …).

- Driftsondes ICARUSS

  Additional soundings could be also obtained from the driftsondes ICARUSS (Inter-Continental Atmospheric Radiosonde Upper-air Sounding System). These balloons flying at an altitude of about 50-100hPa during 5-6 days are able to launch 24 dropsondes. The winds at this altitude are specially favorable to launch such balloons from the East and Central Africa.

- PBL Balloons from Gulf of Guinea

  Complementary measurements could be obtained over the Gulf of Guinea, where the monsoon flow gets the major part of its moisture, from constant-level balloons or radiosoundings launched from a ship (e.g. research vessel servicing the PIRATA buoys network).

- Low-Stratospheric balloons for chemistry

  In the lower stratosphere, which is supposed to strongly interact with the upper troposphere over the tropical continents during the wet season, automated chemical measurements could be conducted onboard dedicated high-altitude balloons (MIR).

- Dropsondes

  Series of dropsondes launched from an aircraft in the upper troposphere would complement the soundings to reveal specific meso-scale perturbations and to quantify the associated dynamic and thermodynamic budgets.

- Profilers ? RASS ?

  The presence of a UHF-RASS profilers over the continent (e.g. Parakou or Djougou at 9.5°N) would allow to more precisely observe the evolution of wind and moisture in the planetary boundary layer.

Airborne measurements

Over the continent, the kinematic, thermodynamic and chemical characteristics of the monsoon flow would be observed in situ and with remote sensing instruments (e.g., microwave radiometers, water vapor and Doppler lidars, …) from an instrumented aircraft. Airborne measurements would be needed to study the environment, the internal structure, the evolution and the influence of mesoscale precipitating systems. The structure of precipitating systems would be observed by aircraft conducting in situ (kinematic, thermodynamic, chemical, radiative) and Doppler radar measurements. The chemical impact would be analyzed from adequate observations in the low levels (inflowing primary species, e.g., NO_x, hydrocarbons, aerosols, …) and in the upper troposphere (outflowing reactive species : HO_x, peroxydes, aldehydes, O_3, NO_x, …). Measurements of tracers (e.g., Rn, CO, water vapor, black carbon, …), in combination with radar-derived three-dimensional wind fields would help to determine the vertical transports associated with the precipitating systems. Considering its impact on NO_x budget, it would also be necessary to estimate the lightning activity within the observed systems.

To fulfil these requirements, at least 3 instrumented aircraft would be needed :

- ☐ An aircraft for measurements in the low to mid-troposphere : in-situ kinematic and thermodynamic fields, remote sensing with lidars and radiometers, chemistry, surface characteristics, photogrammetry, microphysics of the low level clouds, … . This aircraft could be the new French turboprop.
- ☐ One or two mid-tropospheric aircrafts equipped with airborne Doppler radar, and in situ kinematic, thermodynamic, microphysical, chemical and radiative measurements, …
- ☐ A high altitude aircraft for dropsounding, and in situ microphysical, radiative and chemical measurements. Two aircraft might be needed to these purposes, since the flight track required for a synoptic survey with dropsondes would be hardly compatible with more localized measurements in the vicinity of precipitating systems. One aircraft to consider is the remotorized French Mystere 20.

During the first two SOPs, these aircraft would probably be based at international airports in the vicinity of the meridional cross-section near 2.5°E (e.g. Cotonou in Benin, Niamey in Niger). Dakar (Senegal) would probably be a better base to study phenomena occurring near the western edge of Africa (SOP 3). Of course, other international airports in West Africa could be considered for transits during long duration SOPs.

During each of the SOPs, Intensive Observing Periods (IOPs) of 2- to 4-day duration would be conducted to document the different aspects of the considered perturbations, as well as their evolution. Considering climatology, it is not unrealistic to consider that one or two IOP(s) could be conducted each week during each of the SOPs.

Ground-based Doppler radars

- ☐ The installation of a X-Band polarimetric Doppler radar is scheduled as part of the CATCH long term observing system in the region of Djougou (Upper Ouémé)
- ☐ C-Band polarimetric Doppler radar ? (e.g. RONSARD)

  Considering that such a radar might have problems with severe rain attenuation, the possibility of installing a C-band polarimetric Doppler radar (e.g. Ronsard from CETP) is worth considering. Information on the moisture fluxes in the boundary layer would also be important to quantify the possible link between surface conditions and precipitation efficiency.

Ground stations

Surface measurements are required for chemical, meteorological and hydrological studies. Additional stations (e.g. in Niger and Benin) would reinforce the already existing DEBITS/IDAF network, aimed at determining the chemical characteristics of dry and wet deposits. In Benin (Djougou, near Parakou), a dense network of raingauges, streamgauges and aquifer measurements in association with an X-band polarimetric Doppler radar will give information on the surface water budget (see above). Surface flux measurements are also necessary in some locations representative of main type of surface conditions. Other measurements dedicated to the validation of satellite products would be also necessary.

Oceanic measurements

In the framework of CLIVAR (Climatic variability and predictability), the French ECLAT (Etude Climatique en Atlantique tropical) program aims to better undertand the role of the tropical Atlantic in the climatic variability. In this way, the PIRATA moorings array (4 ATLAS buoys in the eastern tropical Atlantic, Figures 13 and 14) has to be maintained and extended. Following the EQUALANT cruises, the EGEE project proposes to carry out from 2003 biannual operational cruises in the Gulf of Guinea (Figure 14), running through the PIRATA mooring sites. The objective is to monitor the seasonal to interannual variations of the upper layers and ocean-atmosphere interface conditions (SST, SSS, currents, Tair, wind, XBT and XCTD profiles, surface drifters deployments, water samplings for salinity, nutrients and CO2 system parameters analysis…). Such in situ measurements are also of prime importance in a region where the oceanic surface conditions are very difficult to access due to the high cloud coverage, for satellite data calibration and validation –i.e. Eumetsat, Envisat….Data should be daily transmitted for data assimilation in the operational numerical models, and for validation/calibration of satellite measurements.

In the framework of the 2004 boreal spring SOP, an oceanic meridional section will be carried out in the continuity of the continental CATCH window section, around 3°50'E, during an EGEE cruise. Additional atmospheric measurements will be necessary during this campaign, similar to what was done during the EQUALANT campaign in 1999. A mast can be instrumented to provide high frequency (50 hz) measurements of turbulence, and thermodynamical and radiation data (0.1 hZ), in order to define parametrizations of turbulent heat and momentum fluxes adapted to PIRATA data, and to study the impact of SST on fluxes, and their interactions with the boundary layer and convection. Upper air soundings can be launched several times per day to complement the in-land radiosounding network and document the vertical flow profile entering over West Africa. Depending on available research vessels, similar campaigns can be implemented during the two other SOPs

III.4 Satellites

Satellites will contribute to various objectives of the project both for process analysis and for large scale -long term studies : some series of satellites (Meteosat, NOAA, ..) 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 this section, we give an overview of the satellites and retrieved products which are of interest for the West African Monsoon program, then we discuss the maturity and needs for development and validation of retrievals. In the third and fourth subsections, we present respectively the use of satellites for mesoscale studies and links with the in situ observations for process analyses, and for long term / large scale studies, as well as links with modeling studies and surface network monitoring. In fact, the setup of a multi-scale observing system over the region will provide a unique opportunity for satellite validation over continental tropical areas. Finally, preliminary specifications for a data base are given.

III.4.1.Space missions and retrievals

Since 1980 several satellites of particular interest for West Africa have been flown. Among others, we may notice:

1980	METEOSAT series	surface (vegetation cover, surface temperature),
	NOAA series	& atmosphere (clouds, radiation)

1987	DMSP/SSMI	ocean surface (wind), atmosphere (water vapour, clouds, precipitation)
1991	ERS1	surface (temperature, wind over ocean, waves, land surface characteristics)
1995	ERS2	same, + atmosphere (O_3 and NO_2 columns)
1997	TRMM	atmosphere (clouds, precipitations, lightening, radiative budget), surface (temperature)
1999	EOS/TERRA	surface (temperature, color), atmosphere (trace gases)
1999	ADEOS1	ocean surface (wind), atmosphere (radiative budget)
2001	ODIN	atmosphere (UTLS O_3, water vapor)

Operational meteorological satellites have operated continuously, and their sensors are being changed from time to time (METEOSAT, NOAA), in order to improve the quality of their measurements, and to add other sensors,. The ESA platforms (ERS1/2) will be followed by the ENVISAT platform which will provide the same measurements, except for the scatterometer, and the addition of several other sensors of interest (biosphere color, atmosphere chemistry). The launch of several new satellites by the major space agencies (ESA, NASA/NOAA, NASDA) will offer an enormous amount of data in the coming years, and will thus contribute to the project. For example, ADEOS2 (4 sensors, launch 2002) for atmosphere and surface, Y-CENA/ CLOUDSAT (lidar and radar, launch 2003), for non precipitating clouds, EOS/AURA (4 sensor, launch 2003), CARBOSAT; COBRA for atmospheric chemistry…

Thus, depending on the sensor type, various informations on atmospheric and surface properties could be derived over 10 – 20 years, whereas some other will be available only over a short period. For instance, using the existing and next satellites, the parameters that could be monitored over West Africa are :

- the radiative budget at the surface and at the top of the atmosphere, the sea and land surface temperature
- the vertical profiles of temperature and humidity above land and ocean
- the large scale water vapor transport
- the variations of the tropospheric and UTLS ozone and other gases (NH4, CO, NO2)
- the estimated wind from MSG measurements (from clouds and water vapor)
- cloud classification
- vegetation coverage and estimation of soil moisture and soil structure
- the detection of precipitating clouds and rainfall estimation
- latent heat flux and surface wind over the Guinea Gulf
- fire detection

However, new studies will have to be performed to increase the number of retrieved parameters, to improve their quality and validate them, and to combine satellite data with each other, with in situ measurements and with model simulations.

III.4.2.Maturity of retrievals – needs for specific validations

Among the above retrieval list, some parameters are already operationally obtained over the globe, as the surface temperature using infrared sensors, the integrated water vapor content over ocean from microwave radiometers, the TOA radiation budget from broad band radiometers, among others. For most of the retrievals, however, the development and validation must be checked in the area of interest, because of the climate and surface characteristics. In particular, the frequent occurrence of aerosols in the atmosphere has to be taken into account for retrievals based on the visible channels ; landscape analysis (vegetation cover and type), soil humidity will have to be adjusted, from methods developed in temperate latitudes ; cloud water profile and precipitation rate retrievals still require specific developments, as well as the boundary layer profiles of temperature and humidity.

The routine in situ measurements, as well as the planned enhanced observation network, and finally the SOP detailed measurements will offer a proper framework to improve / validate satellite retrieval methods. It is therefore important to take this need into account in the experiment plans (e.g. aircraft operations at satellite overpass time, addition of specific measurements for cloud ice detection or other parameters)

III.4.3 Process analysis – link with in situ observations

At the small to the meso-scale, satellite data can be compared and used in complement of in situ measurements. First validation must be performed, to ensure the good quality of satellite products. Then, the satellite data will help interpreting the in situ measurements, by providing the horizontal and time variability of processes. Such a close use of both types of data is particularly important for hydrology (heterogeneity of vegetation and soil humidity, and link with precipitation occurrence), life cycle and horizontal variability of convective systems, gas emission in relation with fires, among others. In the satellite data processing, particular attention will therefore be paid to fine resolution retrievals. Depending on the parameter of interest, resolutions of 1 km up to a few km will be necessary. Such studies will be mainly performed during the SOP, but case studies could be made on past data, for which the relevant in situ measurements are available (hydrology).

III.4.4.Long term / large scale analyses – link with modeling studies and surface network

As shown in section III.4.1, a number of satellites of interest have been flying for more than 10 years, and geostationary data have been available since 1980. Efforts must be engaged to exploit these data sets for monitoring seasonal to interannual evolution of the west Africa atmosphere and surface properties. Existing networks (the CATCH hydrology domain, MOZAIC ozone and other trace gas measurements, meteorological measurements) will be used to validate and possibly improve the retrievals. Comparisons with climate/meteorology models will be either used to complete validation of satellite retrievals, or in reverse, to evaluate the model simulations, and to initialize them. The relevant time / space resolution will range from a few tens of km up to 1 degree, and the area of interest will largely cover the west Africa, from the gulf of Guinea to the Sahara, and from East Atlantic to East Africa. Among the problem to solve are the differences between the various satellites, and the difficulty to assess retrievals at such large scales. The selection of case studies, prior to the SOP date, is important to compare and validate retrievals at the mesoscale before extending them to larger scales.

III.4.5. Goals Preliminary specifications of the satellite data base

In order to reach the above objectives, a large number of satellite data will have to be archived. They include calibrated radiances / brightness temperatures / back scatter coefficients from which retrievals will be developed, as well as existing operational retrievals when existing (surface temperature, profiles, ozone content,…).

For small / mesoscale products, the full resolution of sensors will be kept, as well as the satellite imaging geometry in most cases. For large scale products, the problem of horizontal interpolation will be studied, in order to optimize the quality of retrievals, as well as the possibility of combining various satellite data, and / or satellite/model combinations and comparisons. Additional information will be complementary, as topographic maps, and operational model analyses.

Further discussions will be necessary to make priorities in the data base preparation and development of specific retrievals. New satellites will moreover give the opportunity to improve the methods, or to compare satellite products. Hence, it would be fruitful to link the development of the data base to those dedicated to these new missions. This way, the intended studies will contribute to the preparation of the next space missions in which, as Y-CENA/CLOUDSAT (cloud microphysics and radiative properties), SMOS (surface soil humidity) and MEGHA/TROPIQUES (convective systems and radiative budget).

III.5 Modeling and assimilation

The main goal of the present project is the study of the multi-scale processes involved in the various components of the WAM: atmospheric dynamics, hydrology, biosphere and atmospheric chemistry. Their interactions at different space-time scales are as much critical to increase our knowledge on the different aspects. To improve our understanding of such a complex dynamical system, a fully integrative approach is thus highly desired to couple the four main components of this system. As the numerical modeling and assimilation provide a unique tool to study these interactions, they will be an essential component of the project.

Models will be specially useful to make more successful the SOP. Before the SOP, models will be needed to design the experimental strategy and to help to focus it on the most crucial processes and parameters as revealed by theoretical and sensitivity modeling studies. During the SOP, meteorological and chemical models will be used for forecasting and optimizing the aircraft plans.

For all considered observational periods (LOP, EOP, SOP) where numerous data will be collected on, modeling and assimilation will be needed to help their interpretations and to replace them in a larger context.

The situation is quite different for the 4 components of the system due to their contrasting physical properties. For instance the biosphere and hydrosphere are characterized by strong inhomogeneities and complex physical processes that rise important difficulties to model them at scales compatible with the atmosphere. On the contrary the atmospheric dynamic and chemistry can be now treated in a same modeling framework.

III.5.1 State of the art and Objectives

Atmosphere 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; either GCMs, mesoscale models and cloud resolving models (CRM). Coupling between these atmospheric and chemistry models is in a highly developed state. They inherently face the same uncertainties concerning the representation of the Monsoon and its impact on the climate. The final report of the WAMP European project (Thorncroft et al 2001) allowed to point out the skills and weakness of those tools to reproduce the major WAM features. It has been shown that GCMs have difficulty in simulating in particular the seasonal cycle of rainfall with wet biases in spring resulting in an early onset to the rains. Two weakness have been pointed out. First models simulate the Saharan heat low too strongly due to a poor simulation of the low-level temperatures there. This results in erroneous horizontal moisture fluxes into the Sahel. Second models simulate too many intense rainfall events. This may be consistent with too much local recycling.

These GCMs weaknesses show the importance of dry convection and of rain-producing weather systems in the WAM. A multi-scale approach is required using CRMs and mesoscale models to study these phenomena and their interactions with the synoptic flow. Improvement of the representation of convective processes at cloud scale in terms of the dynamics and thermodynamics is crucial, also to understand the impact of convective clouds on the vertical transport and scavenging of gases and aerosols. At regional and synoptic scale, atmospheric and chemistry models focus on the dynamics of the African Easterly Jet, the meridional gradients and surface fluxes, and the dry and wet convection. These major dynamical features have a great impact on the origin and chemical composition of the air masses in the convective outflow and thereby transported over large distances over the globe. In return, spatial, chemical and size redistribution of aerosols in West Africa represent a complicated superposition of contributions from different African source regions (oceanic, combustion, urban pollution and desert). Chemistry models have to take into account this variety to evaluate the radiative impact of the aerosols and their important effect on the dynamics. The numerical strategy will be based on a multi-scale approach from the local scale of a convective cell to the climatic impact. This approach (Moncrieff et al 1996) has been followed successfully during GCSS (GEWEX Cloud System Studies).

The global operational analysis and reanalysis (NCEP and ECMWF) are also essential for the project. Their represent well the major feature of the WAM in terms of their location and magnitude. Nevertheless they present a low-level wet bias resulting in greater conditional convective instability. They fail to correctly reproduce some major WAM feature such as the diurnal cycle of low-level specific humidity and of the AEW-related wind variance, the dry season on the Guinea Coast. This is likely to be due in part to the well-known sparseness of routinely available observations. The combination of using 3D or 4D variational assimilation schemes and a higher resolution is expected to significantly improve the quality of the reanalysis. Such techniques and others (Kalman filter) are now applied to assimilate chemistry fields using satellite data (MOPITT). Further effort is needed to improve in priority the analysis of humidity and chemistry fields by exploiting the high spatial and temporal resolution provided by satellites.

Biosphere and hydrosphere

Various SVAT (Soil Vegetation Atmosphere Transfer) have been developed for use in General Climate Model, Regional Climate Model, Numerical Weather Prediction Model, 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. Hydrological models (rainfall-runoff model) use rainfall and potential evaporation data to simulate the hydrological cycle (surface runoff, percolation to groundwater and river flow). They use data on rainfall and potential evaporation. The output from these models includes: overland flow, impermeable area runoff, soil moisture storage, groundwater storage, and actual evapotranspiration. 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 issue for the integration of land-surface processes model 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 requires 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 constitute valuable information that may be used as either input to the model or for updating. A specific effort is needed to assimilate those remote data to initialize the vegetation, albedo, soil moisture (surface and depth) fields in the models.

III.5.2 Specific tasks

The analysis and modeling will be key components of the integrative approach to study the different interactions of scales and processes involved in the WAMP and thus to prepare the field experiment. Due to the numerous and essential tasks to perform during this preparation stage, a high level of coordination has to be produced between the different partners of the project. Al list of tasks to perform before the experiment is thus provided. They are classified depending on their relationships with the observational periods.

LOP

Global analysis and GCM simulations will be the main tools to reach the goals of the Long Term Observation Period. Thus a major effort must be devoted to improve and validate them in particular by taking advantage of satellite data (retrieved fields of vapour, clouds… and synthetic brightness). It will be important to characterize the accuracy of the analysis as a function of the considered temporal and spatial scales, to assess the uncertainties of the resulting budgets. More specifically we recommend:

- To compare ERA (ERA-15 and 40) and NCEP reanalyzes.
- To develop and to improve GCM parameterizations of SVAT and dry and wet convection trough a multi-scale approach as successfully applied in GCSS.
- To use atmosphere-ocean coupled GCM simulations to study the variability of the WAM and to identify extreme scenarii (dry and wet) as studied in detail at higher resolution with other models. Budgets (water, energy and angular momentum) need to be computed in these numerical experiments.

EOP

The major effort must be dedicated to prepare the EOP that will study two whole monsoon seasonal cycles. We stress the following tasks.

- To validate the hydrological simulations at different scales (up to the basin scale for GCMs).
- To evaluate the chemistry models over the West Africa in using MOPITT satellite data. It will provide a guide to improve models and to design the experimental strategy (optimization of the observation locations). A multi-scale approach is planned to compare the convective transport parameterizations and budget of chemical species in convection from the mesoscale to the global scale.
- To study the impact of a better representation of the WAM on the northern hemisphere meteorology and chemistry. This is important to determine the interest of the project for other regions than Africa, and thus to motivate other research teams and numerical weather services.
- To study the zonal variability of the monsoon to assess the representativity of scheduled observational meridian and zonal transects.

- To develop and to improve assimilation techniques in particular for humidity of both soil and atmosphere. It will be crucial to get accurate budget of the water budget during the field experiment.
- To investigate carefully the data really assimilated by operational models and where efforts should be preferentially brought. The transmission of radiosonde data over the global telecommunication system (GTS) seems rather irregular and needs to be examined.

Eventually we want to promote idealized modelling approaches to study in a simplified framework the interactions between different scales (convection, jets, AEW, Hadley…) and processes (surface, topography…). It will contribute to the EOP and also to the SOP set-up, in helping to identify and focus on the key processes and scales.

SOP

At this scale we will concentrate on some specific key processes, such as the coupling between the soil and the atmosphere (recycling), the convective systems MCSs and their interactions with the synoptic structures. These studies are not independent on the others and will have feedbacks on the other mentioned modelling efforts. The major objectives will be:

- To compute trajectories in the monsoon and 50-100hPa layers to optimize the launching location and frequency of the driftsondes ICARUSS and low-level balloons respectively. The impact of such data on the analysis and on the budgets (water and energy) accuracy needs to be studied.
- To promote modeling of coupling between the atmosphere, hydrosphere and biosphere components, in order to provide better surface parameterization to atmospheric models (albedo, humidity, vegetation ...). The adequate scale to test a fully coupling seems to be the mesoscale.
- To study the coupling between continental surface and convection and its diurnal cycle, through CRM simulations of case studies. The ultimate goal is the improvement of the parameterizations of convection and induced surface fluxes following the GCSS strategy.
- To use the CRM simulation of MCSs to study the vorticity generation and their impact on the easterly waves development (SOP3). They could be used to improve satellite retrievals of such convective systems necessary to improve their climatology.

IV Institutional and Programmatic Linkages

The present document results from initiatives having involved -in the last three years- scientists of various African, American and European countries and institutions. The awareness on how dramatic could be the 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 (CATT, 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 the region to climate fluctuations. On the other hand it has to be 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 of a strong research program on the WAM and its interactions with the water cycle and the biosphere.

IV.1 African institutions and programmes

African regional institutions and African scientific teams, mainly from national Universities, do scientific research on the different components of the "African Monsoon" system, including its dynamic, atmospheric chemistry and hydrology components.

There are basically two regional institutions interested in the study of the West African climate and the associated water cycle. One is ACMAD, whose mandate covers the African continent as a whole. The other is AGRHYMET, focusing on the 11 Sahelian countries which belong to the Comité Inter-états de Lutte contre la Sécheresse au Sahel (CILSS). At the national level, operational services such as the 'Direction de la Météorologie' and 'Direction de l'Hydraulique' in French speaking countries, are in charge of collecting data essential for the monitoring of the atmospheric and hydrologic environments.
Laboratories from national Universities (e.g, located in Abidjan, Cotonou, Brazzaville, Dakar, Niamey…) are doing research in the fields presented above. During the recent years, an active community of West African scientists (though still limited in number), has participated in various international initiatives:

- Field experiments (HAPEX-Sahel, CATCH , DECAFE, EXPRESSO, FIRMA…);
- Network establishment (IDAF, AERONET, WHYCOS-AOC,.);
- Data-base projects (FRIEND-AOC, EXPRESSO,IDAF, APD).

For the success of the present project, it is necessary to engage the African community and to maintain a close collaboration between this community of African scientists and the international scientific community at large. This can be achieved through close contacts with the regional institutions listed above (for instance AGRHYMET is involved in the coordination of FRIEND-AOC and WHYCOS-AOC) and linkages with programs such as FIRMA (Fonds d'Incitation à la Recheche Météorologique en Afrique) managed by ACMAD, AIRE-Développement or CAMPUS both aiming at supporting teams of African scientists working in Africa.

One important issue is the lack of adequate funding for climate research in Africa. By having the African community involved from the very beginning in large international programs might provide some opportunity in that respect, even though originally these international programs do not identify specific support for the African scientific teams.

IV.2 International programmes

WCRP (World Climate Research Program)

WCRP seems to provide an appropriate framework for an international concerted action in West-Africa, since it has linkages to operational services through WMO and to the research community through its ICSU patronage. Two large programmes are particularly relevant to the present initiative: CLIVAR and GEWEX

- CLIVAR

A CLIVAR-Africa panel was appointed in 2000 to promote and coordinate work on the Variability of the African Climate System (hence the name – VACS – of the panel). Although the VACS is encouraging a large array of activities, its first meeting – held in Nairobi at the end of January 2001 – recognised the necessity to encourage field experiments, as far as possible in close coordination with GEWEX. West Africa was identified as a potentially pilot region for a combined experiment and modelling initiative.

The CLIVAR Atlantic group seeks to understand and predict seasonal to decadal climate variability in the Atlantic sector, with a focus on variability in the tropical Atlantic climate system and NAO.

- GEWEX

Several programmes of GEWEX (Global Energy and Water Experiment) present obvious linkages with the present proposal.

CEOP

GEWEX is engaged in a large effort aiming at a simultaneous documentation of Land/Biosphere/ Atmosphere interactions at regional scale for the most important climate systems of the planet. This effort, referred to as the CEOP or Coordinated Enhanced Observing Period, involves the so-called Continental Scale Experiments (CSE). There are 5 CSE's: 3 in America (LBA, GCIP, MAGS), 1 in Europe (BALTEX) and one is Asia (GAME). Two CSE's (LBA and GAME) are studying regions under the control of monsoon circulations which are one main focus of the CEOP. The CEOP is due to start this June (2001) and to end in December 2003. Given the absence of any African region in the CSE coverage and the existence of a preliminary initiative to study the interactions between climate and the water cycle in West-Africa, CATCH was granted a status of associated experiment to the CEOP. It should be considered at that point that CATCH played a seeding role in mounting the project described here and that the inclusion of an African component in GEWEX will now have to be considered from a different perspective. For one, the scientific relevance of associating – even if very loosely – CATCH to the CEOP was heavily dependant on the possibility of reinforcing the sounding network around and inside the CATCH window. Secondly, the new and larger initiative presented here offers a better prospect for the reinforcement of atmospheric measurements in the region. However, the target dates are beyond the CEOP schedule. Obviously such a regional measurement program will have to benefit from an amount of support within WMO, whether through WCRP or through any other component of WMO (for instance the VCP – the Voluntary Cooperation Program). As long as this question is not solved, a significant involvement in CEOP activities is unlikely.

GCSS

The GEWEX Cloud System Study (GCSS) aims to develop better parameterizations of cloud systems for GCMs by an improved understanding of the physical processes. As outlined in several previous sections, a better representation of convective cloud processes is one of key points to improve numerical forecast and climate simulation over West Africa. Furthermore, the GCCS goals are also linked to a better understanding of scale interactions between convection and synoptic flow. For the reasons given above, the West African Monsoon is thought to be an excellent framework in this context.

GLASS

The GLASS (Global Land/Atmosphere System Study) aims to coordinate the evaluation and intercomparison of new generation of land surface schemes, and applying them to scientific queries of broad interest. GLASS aims also to serve as an interface between the land-surface community and other GEWEX projects. The present proposal has clearly identified as a key point the improvement of representation of exchanges between surface and atmosphere. The project is also an opportunity to bring the GEWEX and GLASS community together in evaluating and improving the interactions between continental surface and atmosphere.

ISLSCP

The ISLSCP (International Satellite Land Surface Climatology Project) plays a key role in promoting the development of land surface dataset. Particularly relevant to the present proposal, ISLSCP is leading the Global Soil Wetness Project, a pilot study to produce a global data set of soil wetness and related surface flux estimates. The soil wetness indeed plays a central role over the West Africa from the local scale to the regional scale.

FIRMA

The FIRMA (Fonds d'Incitation à la Recheche Météorologique en Afrique) have for goals to encourage and promote :

1. The African teams research capacity in meteorology and climatology
2. The use of research results in operational programs and applications

This fund is open to any African research team, member or not of a meteorological service. A scientific committee is in charge of the project selection. Support will be granted for a two years period, an intermediary report is due one year after acceptance of the project, and a final report two months after the end.

The major scientific domains during the last two calls for proposal (1996-1997 and 2000-2002) are :

1. Short and medium range weather forecast, at regional scale, with validation of model products or with statistical adaptation
2 Monthly and seasonal forecast
3. Climate monitoring (Study of dynamical fluctuations or Investigations on atmospheric processes and their interactions with the droughts in Africa)
4.Researches intended for application of Meteorology and Climatology to farming, water resources, renewable energy resources, health or environment

During these two phases, 26 proposals have been selected and financially supported by Firma

TMRP (Tropical Meteorological Research Programme)

The WMO TMRP (Tropical Meteorology Research Programme aims to promote and coordinate research activities in tropical meteorology. Its emphasis is on the weather system time scale, except for monsoons and drought related studies, and focuses on variability and prediction at the regional and seasonal scale. The improved knowledge of tropical phenomena, prediction methods and techniques relating to tropical cyclones, monsoons, tropical droughts, tropical limited-area modelling and operational use of numerical products for tropical forecasting is a priority of the programme. Finally, the transfer of scientific knowledge of methodologies and their operational application to ensure the full exploitation of scientific advances to meet the socio-economic needs of tropical countries is a further target of the programme. All these objectives are concerned by the present proposal.

IGAC (International Global Atmospheric Chemistry

BIBEX

The BIBEX (Biomass Burning Experiment) program is directed toward understanding the effects of human activities, especially land-use change and land-use intensification, on trace gas fluxes and atmospheric chemistry. The objectives of the program are:

1- To characterize the production of chemically and radiatively important gases and aerosol species from biomass burning to the global atmosphere,
2- To assess the consequences of biomass burning on regional and global atmospheric chemistry and climate
3- To determine the short- and long-term effects of fire on post-fire exchanges of trace gases between terrestrial ecosystems and the atmosphere, and
4- To understand the biogeochemical consequences of atmospheric deposition of products of biomass burning.

The program has supported numerous field projects: STARE (Southern Tropical Atlantic Region Experiment) TRACE-A (1992, TRansport and Atmospheric Chemistry near the Equator-Atlantic), SAFARI (1992 et 2000, Southern African Fire/Atmosphere Research Initiative), EXPRESSO (1996), LBA NASA/GTE (Global Tropospheric Experiment) and TRACE-P in 2001 (TRansport and Atmospheric Chemistry near the Equator-Pacific), to study transport and evolution of pollutants in southeast Asia with a focus on the role of convection and cold fronts.

DEBITS

DEBITS (**D**eposition of **B**iogeochemically **I**mportant **T**race **S**pecies) has been created by IGAC to serve as a « catalyst »for encouraging existing and new activities in the final step of the biogeochemical cycles : the deposition of the chemical species.

The objectives of the programme are:

1- to determine,primarily through measurements, the atmospheric removal rates by dry and wet deposition ,at regional scale, of biogeochemically important trace species.
2- to establish the chemical and physical factors that regulate these deposition fluxes and develop parameterizations for inclusion in regional and global atmospheric chemistry models.

The DEBITS scientific activities require field experiments dedicated to atmospheric chemistry at regional scale and that include deposition measurements. In addition networks of stations , representative at regional scale and specially instrumented to measure or estimate atmospheric deposition parameters, have to be created for long term follow up.

DEBITS has been created in 1994 in Africa, with the launch of the IDAF (IGAC DEBITS AFRICA) program .Ten sites representative of the great african ecosystems are active in 2001. The african stations use similar sampling and analytical procedures than in Asia and tropical America.

Depositional fluxes are mainly related to the strong biomass burning and desertification atmospheric sources encountered in Africa.

INTEX

INTEX (2004): Intercontinental Chemical Transport Experiment, will focus on the impact of human induced emissions on the composition and chemistry of the atmosphere in the Northern Hemisphere (NH). Its primary objective is to quantify the export and chemical evolution of radiatively and chemically important trace gases and aerosols from eastern North America to western Atlantic and elucidate the mechanisms and pathways associated with these transport processes.

LBA

LBA Airborne Regional Source Experiment (LARS) and Transport and Chemistry near the Equator-Brazil (TRACE-B): to study the influence of tropical South America on global atmospheric composition and climate, including:
- net sources of CO2, CH4, and other radiatively important gases and aerosols
- sources, transformations and export of species determining ozone and the oxidizing power of the atmosphere
- controls on water vapor, aerosols, radicals, NOx, hydrocarbons, and ozone concentrations in the tropical upper troposphere and lower stratosphere

REFERENCES

Brasseur, G. P., D. A. Hauglustaine, S. Walters, P. J. Rasch, J.-F. Muller, C. Granier, and X. X. Tie, MOZART: a global chemical transport model for ozone and related chemical tracers, Part 1. Model description, *J. Geophys. Res.*, 103, 28,265-28,289.

Burpee, R.W., 1972: The origin and structure of easterly waves in the lower troposphere of north Africa. *J. Atmos. Sci.*, 29, 77-90.

Charney, J.G., 1975: Dynamics of deserts and droughts in the Sahel. *Quart. J. Roy. Met. Soc.*, 101, 193-202.

Charney, J.G., W.J. Quirk, S.H. Show & J. Kornfield, 1977: A comparative study of the effects of albedo change on drought in semiarid regions. *J. Atm. Sci.*, 34, 1366-1385.

CLIVAR Africa Task Team, 2000: CLIVAR-Africa Implementation Plan. *http://www.met.rdg.ac.uk/~swsthcri/catt.html* Ed. C. Thorncroft. 33 p.

Collins WJ, Stevenson DS, Johnson CE, et al , Role of convection in determining the budget of odd hydrogen in the upper troposphere, *J. Geophys* . *Res*. 104, 26927-26941, 1999

D'Amato, N., and T. Lebel, 1998: On the characteristics of the rainfall events in the sahel with a view to the analysis of climatic variability. *Int. J. Climatol.*, **18**, 955-974.

Diedhiou, A., S. Janicot, A. Viltard, P. de Felice and H. Laurent, 1999: Easterly wave regimes and associated convection over West Africa and the tropical Atlantic : Results from NCEP/NCAR and ECMWF reanalyses. *Climate Dynamics*, 15, 795-822

Eltahir, E.A.B., and C. Gong, 1996: Dynamics of wet and dry years in West Africa. *J. Climate*, **9**, 1030-1042.

Faloona I, Tan D, Brune WH, et al , Observations of HOx and its relationship with NOx in the upper troposphere during SONEX , J. Geophys. Res., 105, 3771-3783, 2000

Favreau, 2000. Caractérisation et modélisation d'une nappe phréatique en hausse au Sahel: dynamique et géochimie de la dépression piézométrique naturelle du Kori de Dantiandou (Sud-Ouest Niger). PhD thesis, Paris XI University.

Folland, C.K., T.N. Palmer, and D.E. Parker, 1986: Sahel rainfall and worldwide sea temperature 1901-1985. *Nature* **320**, 602-607.

Fontaine, B., and S. Janicot, 1996: Sea surface temperature fields associated with West African rainfall anomaly types. *J. Climate,* **9**, 2935-2940.

Fontaine, B., N. Philippon, and P. Camberlin, 1999: An improvement of June-September rainfall forecasting in the Sahel based upon region April-May moist static energy content (1968-1997). *Geophysical Research Letters*, **26(14)**, 2041-2044.

Gouriou, Y., et G. Reverdin, 1992: Isopycnal and diapycnal circulation of the upper equatorial Atlantic ocean in 1983-1984, *J. Geophys. Res.*, **22**, 25165-25179.

Hall, N.M.J. and P.J. Valdes, 1997: A GCM simulation of the climate 6000 years ago. *J. Climate*, 10, 3-17.

Hao W. M. , D.E. Ward, G. Olbu, and S.P. Parker, 1996: Emissions of CO2, CO and hydrocarbons from fires in diverse savanna ecosytems, *J. Geophys. Res*., 101, 23,577-23,584.

Haywood J, Boucher O, Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review, *Rev. Geophys*., 38, 513-543, 2000

Haywood J/M. and Shine K.P., The effect of anthropogenic sulfate and soot aerosol on clear–sky planetary radiation budget, *Geophys. Res. Lett*., 22, 603-606, 1995.

Hignett P, Taylor JP, Francis PN, et al , Comparison of observed and modeled direct aerosol forcing during TARFOX *J Geophys. Res*., 104, 2279-2287, 1999

Hodges, K.I. and C.D. Thorncroft, 1997: Distribution and statistics of African mesoscale convective weather systems based on ISCCP METEOSAT imagery. *Mon. Wea. Rev.*, 125, 2821-2837.

Ioannidou E., Cammas J.P.; Mascart P. and Legras B., 2000: A contour advection study of a subtropical tropopause fold. *, Q. J. R. Meteorol. Soc.*

Jacob DJ, Heikes BG, Fan SM, et al , Origin of ozone and NOx in the tropical troposphere: A photochemical analysis of aircraft observations over the South Atlantic basin, *J. Geophys. Res*., 101, 24235-24250,1996

Jaegle L, Jacob DJ, Wennberg PO, et al Observed OH and HO2 in the upper troposphere suggest a major source from convective injection of peroxides, *Geophys. Res.Llett*., 24, 3181-3184, 1997

Jaegle L, Jacob DJ, Brune WH, Chemistry of HOx radicals in the upper troposphere *Atmos. Environ*., 35, 469-489, 2001

Janicot S., 1992: Spatio-temporal variability of West African rainfall. Part II : Associated surface and air masses characteristics. *J. Climate*, 5, 499-511.

Janicot, S., S. Trzaska & I. Poccard, 2001: Summer Sahel-ENSO teleconnection and decadal time scale SST variations. *Climate Dynamics*, in press.

Janicot, S. and B. Sultan, 2001: Intra-seasonal modulation of convection in the West African monsoon. *Geophys. Res. Lett.*, 28, 523-526.

Janicot, S., V. Moron and B. Fontaine, 1996: Sahel droughts and ENSO dynamics. *Geophys. Res. Lett*., **23**(5), 515-518.

Johnson, G. C., M. McPhaden, G. D. Rail, and K. E. McTaggart, 2000 : Upper equatorial Pacific Ocean current and salinity variability during the 1996-1998 El Niño-La Niña cycle. *J. Geophys. Res.*, **105**, 1037-1053.

Kaufman Y. and R.S. Fraser, The effect of smoke particles on clouds and climate forcing, *Science*, 277, 1636-1639, 1997.

Kutzbach J.E. and P.J. Guetter, 1986: The influence of changng orbital parametersand surface boundary conditions on climate simulations for the past 18000 years. *J. Atmos. Sci*., 43, 1726-1759.

Laval, K. & L. Picon, 1986: Effect of a change of the surface albedo of the Sahel on climate. *J. Atmos. Sci.*, 43, 2418-2429.

Lamb, P.J., 1983: West African water variations between recent contrasting Subsaharan droughts. *Tellus*, **A35**, 198-212.

Lamb, P.J., and R.A. Peppler, 1992: Further case studies of tropical Atlantic surface atmospheric and oceanic patterns associated with sub-Saharan drought. *J. Climate*, **5**, 476-488.

Landsea, C.W. and W.M. Gray, 1992: The strong association between Western Sahelian monsoon rainfall and intense Atlantic hurricanes. *J. Climate.*, 5, 435-453.

Le Barbé, L., G. Alé, B. Millet, H. Texier, Y. Borel, R. Gualde, 1992. Les ressources en eaux superficielles de la république du Bénin. ORSTOM Ed.,*collection monographie* N° 12, 469 p

Le Barbé, L., and T. Lebel, 1997: Rainfall climatology of the HAPEX-Sahel region during the years 1950-1990. *J. Hydrol,* **188-189**, 43-73.

Le Barbé, L., T. Lebel, and D. Tapsoba, 2001: Rainfall variability in West Africa during the years 1950-1990. *J. Climate,* **In print.**

Lebel, T., and L. Le Barbé, 1997: Rainfall monitoring during HAPEX-Sahel: 2. Point and areal estimation at the event and seasonal scales. *J. Hydrol.*, **188-189**, 97-122.

Lebel T., F. Delclaux, L. Le Barbé, and J. Polcher, 2000: From GCM scales to hydrological scales: Rainfall variability in West Africa. *Stoch. Env. Res. Risk Ass.*

Lelieveld J, Crutzen PJ, Ramanathan V, et al ,The Indian Ocean Experiment: Widespread air pollution from South and Southeast Asia, *Science* 291, 1031-1036, 2001

Levin Z, Ganor E, Gladstein V, The effects of desert particles coated with sulfate on rain formation in the eastern Mediterranean, *J Appl. Meteorol.* 35, 1511-1523, 1996

Liousse C., J.E. Penner, J.J. Walton, H. Eddleman, C. Chuang and H. Cachier, Modeling biomass burning aerosols, in *Biomass Burning and Global Change*, edited by J.S. Levine, pp. 492-508, MIT Press, Cambridge, Mass., 1996.

Liousse C., Quesque P., Barbosa P., Grégoire J.M., Clavier F. and H. Cachier, 2001: Interannual variability of global transport and radiative impact of carbonaceous aerosol in Africa for the 1980 decade

Loireau, M., 1998. Espaces, ressources, usages: spatialisation des interactions dynamiques entre les systèmes sociaux et les systèmes écologiques au Sahel nigérien. PhD thesis, Montpellier III University, France

Mahé, G. and Olivry, J.C., 1999. Assessment of freshwater yields to the ocean along the intertropical Atlantic Coast of Africa. *C.R.A.S.*, 328, 621-326.

Mahé, G., Dray, A., Kone, E., Manga, M., Conway, D., Cres, A., Cres, F.N., Djonkam, J., Maïga, A., Paturel, J.-E., Ouedraogo, M., Servat, E. Submitted. Climatic and anthropic impacts on the hydrological regime of the Nakambe River, Burkina Faso. FRIEND UNESCO quadriennal scientific meeting, Capetown, 2002.

Mathon, V., and H. Laurent, 2001: Life cycle of the Sahelian mesoscale convective cloud systems. *Quart. J. Roy. Meteor. Soc.*, **127**, 377-406.

McCreary, J., J. Picaut, et D. Moore, 1984 : Effects of the remote annual forcing in the eastern tropical Atlantic ocean, *J. Mar. Res.,* **42**, 45-81.

Mitchell, T.P. and J.M. Wallace, 1992 : The annual cycle in equatorial convection and sea surface temperature. *J. Climate*, **5**, 1140-1156.

Moncrieff M.W., D. Gregory, S.K. Krueger, J.-L. Redelsperger, and W.K. Tao, 1997: GEWEX Cloud System Study (GCSS): Precipitating convective cloud systems. *Bull. Amer. Meteor. Soc*., 78, 831-845.

Nicholson, S.E., 1981: Rainfall and atmospheric circulation during drought periods and wetter years in West Africa. *Mon. Wea. Rev.*, **109**, 2191-2208.

Nicholson, S.E., 2000: Land surface processes and Sahel climate. *Reviews of Geophysics*, **38(1)**, 117-139.

de Noblet, N., P. Braconnot, S. Joussaume and V. Masson, 1996: Sensitivity ofsimulated Asian and African summer monsoons to orbital induced variations ininsolation 126, 115 and 6 kBP. *Climate Dyn*., 12, 589-603.

Pailler, K., Bourlès, B., and Gouriou, Y., 2000 : The barrier layer in the western tropical Atlantic Ocean. *Geophysical Research Letter***, 27**, 2069-2072.

Penner J., C. Chuang and C. Liousse, The contribution of carbonaceous aerosols to climate change, in Nucleation and Atmospheric Aerosols, edited by Kulmala M. and Wagner P.E., pp. 759-769, Elsevier Sci., New York, 1996.

Philander, S.G.H., D. Gu, D. Halpern, G. Lambert, N.C. Lau, T. Li and R.C. Pacanowski, 1996 :Why the ITCZ is mostly north of the Equator. *J. Climate*, **9**, 2958-2972.

Philippon N. and B. Fontaine, 2000: 200 West African June to September rainfall: experimental statistical forecasts based on April regional predictors, *Experimental Long-lead Forecast Bulletin*, 9, http://grads.iges.org/ellfb.

Philippon N. and B. Fontaine, 2001: The relationship between the Sahelian and previous second Guinean rainy seasons: a monsoon regulation by soil wetness, *Annales Geophysicae*.

Pickering KE, Thompson AM, Wang YS, et al Convective transport of biomass burning emissions over Brazil during TRACE A, *J. Geophys. Res*, D19, 23993-24012, 1996

Plumb, R.A. & A.Y. Hou, 1992: The response of a zonally symmetric atmosphere to subtropical thermal forcing. *J. Atmos. Sci.*, 49, 1790-1799.

Prather MJ, Jacob DJ, A persistent imbalance in HOx and NOx photochemistry of the upper troposphere driven by deep tropical convection, *Geophys. Res . Lett*., 24, 3189-3192, 1997

Redelsperger, J.-L., A. Diongue, A. Diedhiou, J.-P. Ceron, M. Diop, J.-F. Gueremy and J.-P. Lafore, 2001: Multi-scale description of a sahelian synoptic weather system representative of west african monsoon*, Q. J. R. Meteorol. Soc.*

Remer LA, Kaufman YJ, Holben BN, Interannual variation of ambient aerosol characteristics on the east coast of the United States, J. Geophys. Res., 104, 2223-2231, 1999

Polcher, J., 1995: Sensitivity of tropical convection to land surface processes. *J. Atmos. Sci.*, 52, 3143-3161.

Reed, R.J., D. Norquist & E.E. Recker, 1977: The structure and properties of African wave disturbances as observed during Phase III of GATE. *Mon. Wea. Rev*., 105, 317-333.

Rowell, D.P., C.K. Folland, K. Maskell & M.N. Ward, 1995: Variability of summer rainfall over Tropical North Africa (1906-1992): Observations and modelling. *Quart. J. Roy. Met. Soc.*, 121, 669-704.

Rowell, D.P., 2001 : Teleconnections between the Tropical Pacific and the Sahel. *Quart. J. Roy. Met. Soc*., in press.

Semazzi, F.H., B. Burns, N.H. Lin, and J.K. Schemm, 1996: A GCM study of teleconnections between the continental climate of Africa and global sea surface temperatures anomalies. *J. Climate*, **9(10)**, 2480-2497.

Semazzi, F.H., and L. Sun, 1997: The role of orography in determining the Sahelian climate. *Int. J. Climatol.*, **17**, 581-596.

Servain, J, 1991: Simple climatic indices for the tropical Atlantic Ocean and some applications. *J. Geophys. Res*., 96, 15137-15146.

Sultan, B. and S. Janicot, 2000: Abrupt shift of the ITCZ over West Africa and intra-seasonal variability. *Geophys. Res. Lett.*, 27, 3353-3356.

Taylor, C., and T. Lebel, 1998: Observational evidence of persistent convective scale rainfall patterns. *Monthly Weather Rev.*, **126**, 1597-1607.

Texier, D., N. de Noblet, S.P. Harrison, A. Haxeltine, D. Jolly, S. Joussaume,F. Laarif, I.C. Prentice and P. Tarasov, 1997: Quantifying the role of biosphere-atmosphere feedbacks in climate change: coupled model simulations for 6000years BP and comparison with paleodata for northern Eurasia and norther Africa. Climate Dyn., 13, 865-882.

Thorncroft, C.D., 1995: An idealized study of African easterly waves. III: More realistic basic states. *Quart. J. Roy. Met. Soc*., 121, 1589-1614.

Thorncroft, C.D. and M. Blackburn, 1999: Maintenance of the African easterly jet. *Quart. J. of Roy. Met. Soc.*, 555, 763-786.

Thorncroft et al 2001: Final Report on the WAMP project funded by European communities.

Tourre, Y. M., B. Rajagopalan, and Y. Kushnir, 1998: Dominant Patterns of Climate Variability in the Atlantic Ocean Region During the Last 136 Years, *.J. Climate*, 12(8), 2285-2299.

Wang G. and E.A. B. Eltahir, 2000: Biosphere-atmosphere interactions over West Africa. II: Multiple climate equilibria. Q. J. R. Meteorol. Soc., 126, 1261-1280.

Waliser, D.E. and R.C. Somerville, 1994 : Preferred latitude of the intertropical convergence zone.*J. Atmos. Sci.*, **51**, 1619-1639.

Ward, M.N., 1998: Diagnosis and short-lead time prediction of summer rainfall in tropical North Africa at interannual and multi-decadal time scales. *J. Climate*, **11**, 3167-3191.

Wennberg PO, Hanisco TF, Jaegle L et al , Hydrogen radicals, nitrogen radicals, and the production of O3 in the upper troposphere, *Science*, 279, 49-53, 1998

Xue, Y., 1997: Biosphere feedback on regional climate in tropical North Africa. *Quart. J. Roy. Met. Soc.*, 123, 1483-1515.

Zheng, X., and E.A.B Eltahir, 1998: The role of vegetation in the dynamics of West African monsoons, *J. Climate*, **11(8)**, 2078-2096.

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TABLE 1: Summary of scientific objectives of the west African monsoon project

DOMAIN	MAIN OBJECTIVES	PROPOSALS
Dynamics of the Monsoon	**Water and energy budget**	- Quantification of water and energy budgets at the surface and in the boundary layer on a regional and sub-regional scales, in relation with the evolution of the surface conditions. - Understanding of the role of spring to summer evolution of MSE gradients in the boundary layer and of their intraseasonal persistence on monsoon dynamics - Evaluation of the performances of the statistical and dynamical forecast models.
	Convection and its environment	- Document the different types of convective systems. - Document the life cycle of convective systems and its coupling with surface conditions - Analyze the processes leading to convective organization (moisture advection, mesoscale vortices, , waves, topography and vertical wind shear…etc.) - Analyze retroactions within the whole monsoon system
	Rainfall forcing	- Document the variability of rainfall over a range of scales. - Link the structure of rainfields with atmospheric structures. - Provide a global and coherent framework to derive rainfall regimes from atmospheric models
	Continental water Cycle	- Understanding of the hydrologic variability from convective scale to seasonal cycle - Link between modeled water fluxes and observed behavior of West African catchments. - Development of integrated models of runoff, vegetation dynamics and water and energy transfer models.

	Continental water partitioning and memory effects	- Local observations of rainfall partitioning on the ground, dependently on the vegetation and its dynamics. - Development of modelling approaches allowing coupling of global or regional atmospheric models with hydrologic models
Surface conditions	**Land surfaces**	- Production of vegetation index and surface humidity maps over West Africa, - Characterization of vegetation changes throughout the 20th century - Evolution of biomass, vegetation cover, evapotranspiration, surface humidity at local and GCM grid scale - Understanding of control of dynamics of water cycle by vegetation
	Oceans	- Investigate the role of Gulf Guinea on the monsoon from intra-seasonal to interannual scales - Document the variations of oceanic circulation in Gulf of Guinea and budgets of heat, salt and momentum
Atmospheric chemistry	**Emission and deposition of chemical species**	- Emission inventory of chemical species with a key role in the monsoon region - Improve parameterization of wet and dry depositions
	Budget of HOx in the upper troposphere	- Chemistry in the outflow of convective systems and HOx budget in the upper troposphere. - Quantification of the role of lightning on NOx production in the troposphere
	Heterogeneous chemistry in convective clouds	- Chemical evolution of traces gases in air masses entering and exiting convective systems - Chemical evolution of aerosol particles of various origins within convective clouds.
	Influence of aerosols on the cloud structure and radiative balance	- Investigate the links between aerosols and clouds (including cirrus clouds) in a continental tropical zone. - Assess the direct and indirect radiative impact of aerosol and clouds layers at regional scale

	Troposphere-stratosphere coupling	- Characterization of the chemical composition of the intermediate region between the cloud top and the tropopause - Assess troposphere-stratosphere exchanges in the vicinity of cloud systems through balloon borne or aircraft measurements

TABLE 2: Space/Time extensions of scientific activities

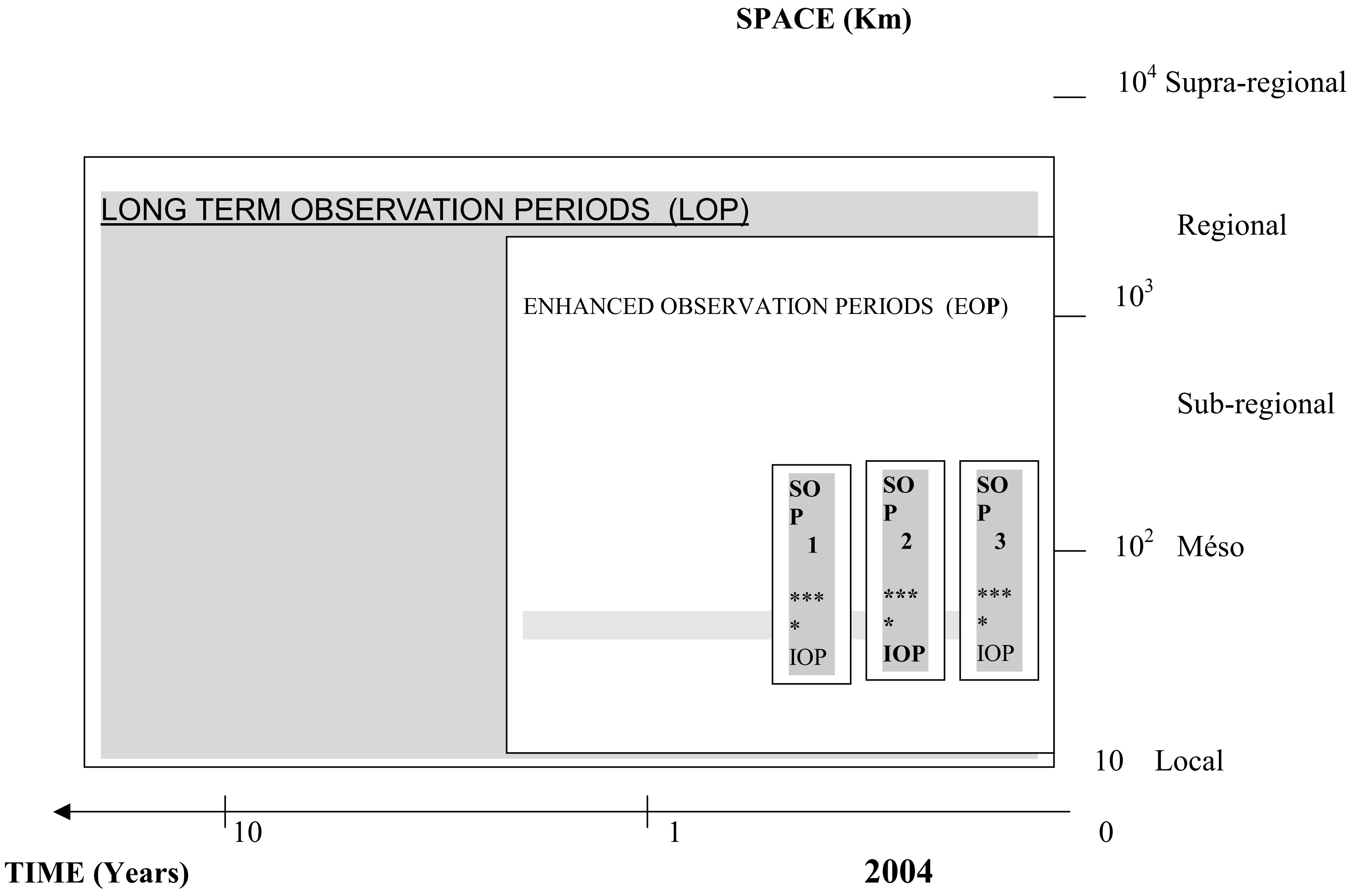

TABLE 3: Summary of scientific activities during the LOP and EOP

Long term Observation Periods: 10 years and more		
Regional scale	**Sub regional scale**	**Meso and local scales**
- Collect and analyze data from regional (countries) hydro-meteorological networks - Develop the IDAF network with an additional site at Ouémé and analyze the spatio/temporal variation of rainwater chemistry and dry and wet deposition at the west African scale - Analyze available data from west African stations of the AERONET network. To derive the climatology of aerosol optical thickness	- Define two meridian transects: in the CATCH window and from Ivory Coast up to Mali and a zonal transect from Dakar to Niamey, - Complete equipment and documentation along these transects and analyze available meteorological, hydrological and ecological data from existing stations	- Insure continuous functioning of Niamey and Ouémé sites in the CATCH Window - Instrument another catchment in the Sahelo-sudanian zone - Increase documentation of land cover dynamics and vegetation ecology of Niamey and Ouémé sites
Modeling	- Compare ERA (ERA-15 and 40) and NCEP reanalyzes. - Develop and improve GCM parameterizations of SVAT and dry and wet convection trough a multi-scale approach as successfully applied in GCSS. - Use atmosphere-ocean coupled GCM simulations to study the variability of the WAM and to identify extreme scenarii (dry and wet)	

Enhanced Observation Periods: 2 years		
Atmospheric dynamics	**Atmospheric chemistry**	**Hydrology and surface conditions**
- Improve radiosounding network along the meridional (CATCH Window) and zonal transects	- Set up an ozone sounding, once a week, in one of the two mesoscale sites (Niamey and Parakou).	- Document precipitation at the convective scale at the two mesoscale sites (rain gauges and radars)

<table>
<tr>
<td colspan="2">- Analyse satellite data dealing with water and energy budgets: MSG and ATOVS (NOAA satellite) for establishing data bases of wind, water vapor and temperature profiles, radiatives fluxes and albedo, latent heat flux and winds over the ocean…etc</td>
<td>- Analyse the climatology of O3 and CO (biomass burning tracer) from satellite observations (GOME, MOPITT, SCHIAMACHY)
- Analyse commercial aircraft observations of O3 and CO (MOZAIC)</td>
<td>- Document the Hydrologic Cycle at the watershed scale
- Ground monitoring of vegetation to calibrate satellite images used to produce accurate vegetation maps.</td>
</tr>
<tr>
<td><i>Modeling</i></td>
<td colspan="3">- Validate the hydrological simulations at different scales (up to the basin scale for GCMs).
- Evaluate the chemistry models over the West Africa in using MOPITT satellite data.
- Study the impact of a better representation of the WAM on the northern hemisphere meteorology and chemistry.
- Study the zonal variability of the monsoon to assess the representativity of scheduled observational meridian and zonal transects.
- Develop and improve assimilation techniques in particular for humidity of both soil and atmosphere.
- Investigate carefully the data really assimilated by operational models and where efforts should be preferentially brought.</td>
</tr>
</table>

TABLE 4: Participating French agencies & laboratories

Agencies

CNES	Centre National d'Etudes Spatiales
CNRS/INSU	Centre National de Recherche Scientifique/Institut des Sciences de l’Univers
IRD	Institut de Recherche pour le Développement
Météo-France	

Laboratories

CESBIO	Centre d'Etudes Spatiales de la BIOsphère (CNRS, CNES, IRD, & Univ. Toulouse))
CETP	Centre d'etude de l'Environnement Terrestre et Planetaire (CNRS & Univ. St Quentin)
CMS	Centre de Météorologie Spatiale (Météo-France)
CNRM	Centre National de Recherches Météorologiques (Meteo-France & CNRS)
CRC	Centre de Recherches de Climatologie (CNRS & Univ. Dijon)
HSM	Hydrosciences Montpellier (CNRS, IRD & Univ. Montpellier)
LA	Laboratoire d’Aerologie (CNRS & Univ Toulouse)
FESE	Fonctionnement et Evolution des Systèmes Ecologiques (CNRS, ENS)
LAMP	Laboratoire Atmosphere Météorologique et Physique (CNRS & Univ. Clermont)
LEGOS	Laboratoire d’Etudes en Geophysique et Océanographie Spatiale
LMD	Laboratoire de Météorologie Dynamique (CNRS, Univ. Paris, Ecole Polytechnique)
LPCE	Laboratoire de Physique-Chimie de l’Environnement (CNRS & Univ. Orleans)
LTHE	Laboratoire d'étude des Transferts en Hydrologie et Environnement Grenoble (CNRS, IRD, INPG & Univ. Grenoble)
LSCE	Laboratoire des Sciences du Climat et de l'Environnement (CNRS & CEA)
MEDIAS-France	Groupement pour le développement de la recherche sur l'environnement global notamment dans le bassin méditerranéen et l’Afrique subtropicale (CNES, CNRS , Meteo-France, University)
SA	Service d’Aeronomie (CNRS & Univ. Paris)

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	F. Roux	rouf@aero.obs-mip.fr	Monsoon Dynamics
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TABLE 6: Acronyms

ABLE	Atmospheric Boundary Layer Experiment
ACMAD	African Center in Meteorology Applied to Development
ADEOS	Advanced Earth Observing Satellite
AEJ	African Easterly Jet
AEW	African Easterly Wave
AGRHYMET	Centre Agro-Hydro-Météorologique (CILLS – Niamey)
AOC	Afrique de l'Ouest et Central
ATSR	Along Track Scanning Radiometer
AURA	3rd scheduled EOS mission, dedicated to monitor atmospheric constituents
AVHRR	Advanced Very High Resolution Radiometer
CARBOSAT	ESA project dedicated to monitoring of the carbon cycle
CARIBIC	Civil Aircraft for Regular Investigation of the atmosphere Based on an Instrument Container
CATCH	Couplage de l'Atmosphère Tropical et du Cycle Hydrologique
CEOP	Coordinated Enhanced Observing Period
CILSS	Comité Inter-Etats de Lutte contre la Sécheresse au Sahel
CLIVAR	Climate Variability Program
COBRA	NASA project for Carbon cycle
CRM	Cloud-Resolving Model
CSE	Continental Scale Experiments
DEBITS	Déposition of Biogeochemically Important Trace Species
DECAFE	Dynamique Et Chimie Atmospherique en Foret Equatoriale et Chimie de l'At
DMSP	Defense Military Satellite Program
ECMWF	European Center for Medium-Range Weather Forecasts
EGEE	Etude de la circulation océanique et de sa variabilité dans le golfe de GuinEE
ENVISAT	ENVIronment SATellite
EPSAT	Réseau "Estimation des Pluies par Satellite"
EOP	Enhanced Observing Period.
EOS	Earth Observing Satellites (TERRA, AQUA, AURA)
ERA	ECMWF Re-Analysis
ERS	European Remote sensing Satellite
EXPRESSO	Experiment for Regional Sources and Sinks of Oxidants
FRIEND	Flow Regimes from International Networks and Data
GEWEX	Global Energy and Water cycle Experiment
GCM	General Circulation Model
GCSS	GEWEX Cloud System Studies
GOME	Global Ozone Monitoring Experiment
GPM	Global Precipitation Mission
GTE	Global Tropospheric Experiment
GTS	Global Telecommunication System
HAPEX	Hydrological and Atmospherical Pilot Experiment
ICARUSS	Inter-Continental Atmospheric Radiosonde Upper-air Sounding System
IDAF	IGAC-DEBITS-Africa
ICSU	International Council of Scientific IGAC International Global Atmospheric Chemistry
IGBP	International Geosphere and Biosphere Program

IMPETUS	Integratives Management Projekt für einen Effizienten und Tragfähigen Umgang mit Süsswasser
INDOEX	INDian Ocean EXperiment
ITCZ	Inter-Tropical Convergence Zone
JET-2000	Aircraft observations of the African Easterly Jet
LANDSAT	LAND observation satellite
LBA	Large Scale Biosphere - Atmosphere Experiment in Amazonia
LOP	Long term Observing Period
MODIS	MODerate-resolution Imaging Spectrometer
MOPITT	Measurements of Pollution in the Atmosphere
MOZAIC	Measurement of OZone and water vapour by AIrbus in-service airCraft
MSE	Moist Static Energy
MSG	Meteosat Second Generation
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration (USA)
NASDA	National Space Development Agency of Japan
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NDVI	Normalized Deviation Vegetation Index
NOAA	National Oceanic and Atmospheric Administration (USA)
ODIN	Swedish satellite mainly dedicated to ozone cycle
PEM	Pacific Exploratory Mission
PIRATA	Pilot Research moored Array in the Tropical Atlantic
POLDER	Polarization and Directionality of the Earth's Reflectances
SAFARI	Southern Africa Fire-Atmosphere Research Initiative
SCHIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SMOS	Soil Moisture and Ocean Salinity
SOP	Special Observing Period.
SPOT	Satellites Probatoire d'Observation de la Terre
SSMI	Special Sensor Microwave/Imager
SST	Sea Surface Temperature
STARE	Southern Tropical Atlantic Regional Experiment
SVAT(models)	Soil Vegetation Atmosphere Transfert models
TARFOX	Tropospheric Aerosols Radiative Forvcing Observational eXperiment
TAV	Tropical Atlantic Variability
TEJ	Tropical Easterly Jet
TERRA	First EOS Satellite
TOA	Top of Atmosphere
TRACAS	TRAnsport of Chemical species Across the Subtropical tropopause
TRACE-A	Transport and Chemistry near the Equator - Atlantic
TRMM	Tropical Rainfall Measurement Mission
UNDP	United Nation Development Program
UNEP	United Nation Environmental Program
UTLS	Upper Troposphere Lower Stratosphere
VOC	Volatile Organic Component
VACS	Variability of the African Climate System (African Panel of CLIVAR)
WAM	West African Monsoon
WAMP	West African Monsoon Project (A past European-funded Project)
WCRP	World Climate Research Program
WMO	World Meteorological Organisation

WWRP	World Weather Research Program
Y-CENA	(Pathfinder Instruments for Cloud and Aerosol Spaceborne Observations-Climatologie Etendue des Nuages et des Aerosols

FIGURES

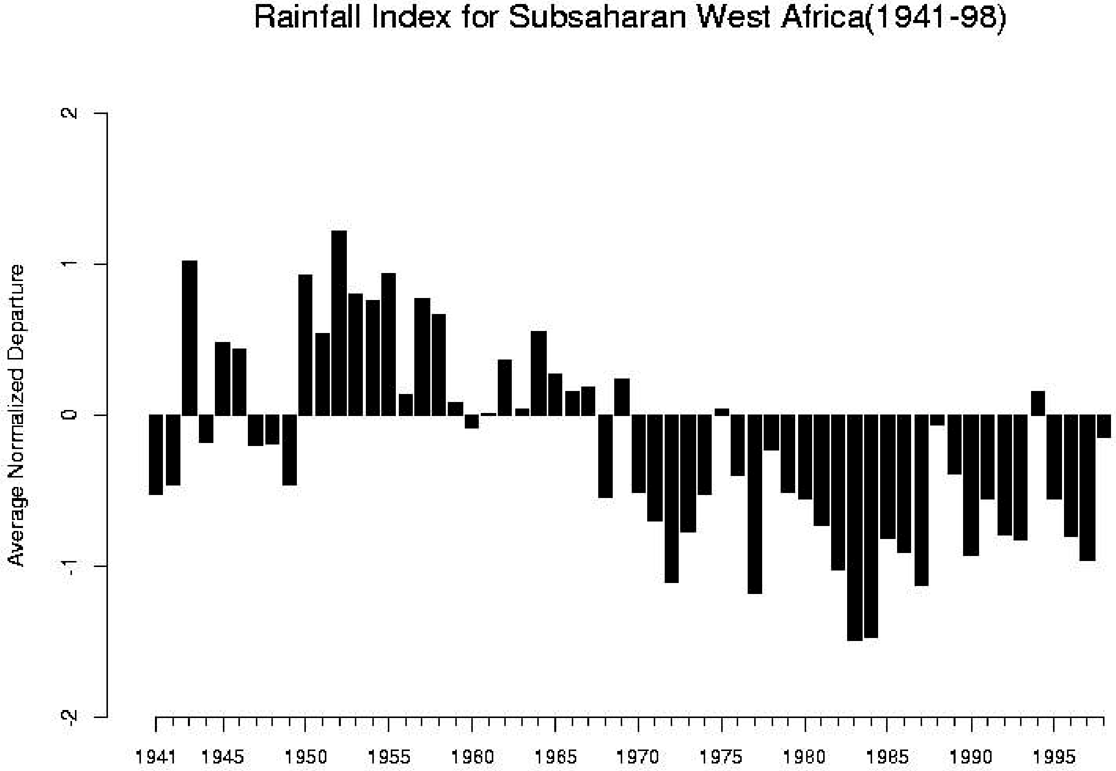

Figure 1: Evolution of the standardized rainfall index over the sub-saharan West Africa between 1941 and 1998.

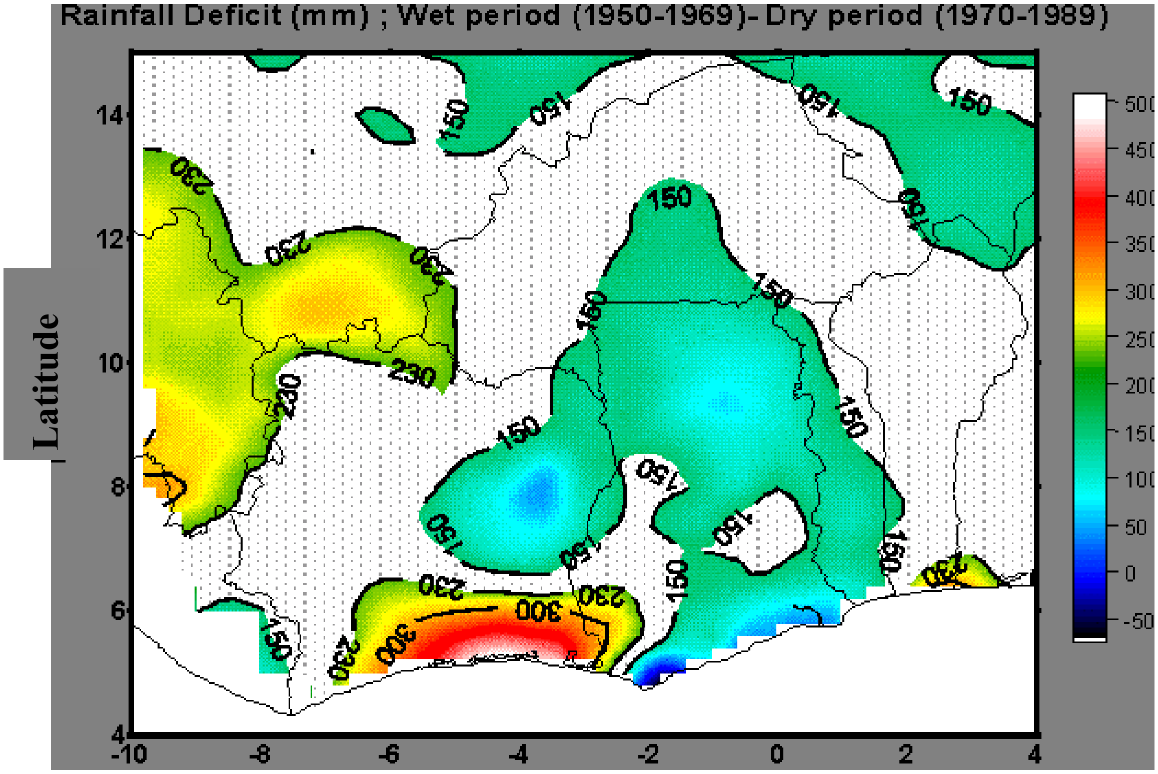

Figure 2: Rainfall deficit (mm) between the wet (1950-1969) and the dry (1970-1989) period. The dotted area corresponds to the area where the deficit is in the range of 150 to 230 mm, the average over the area being 190 mm.

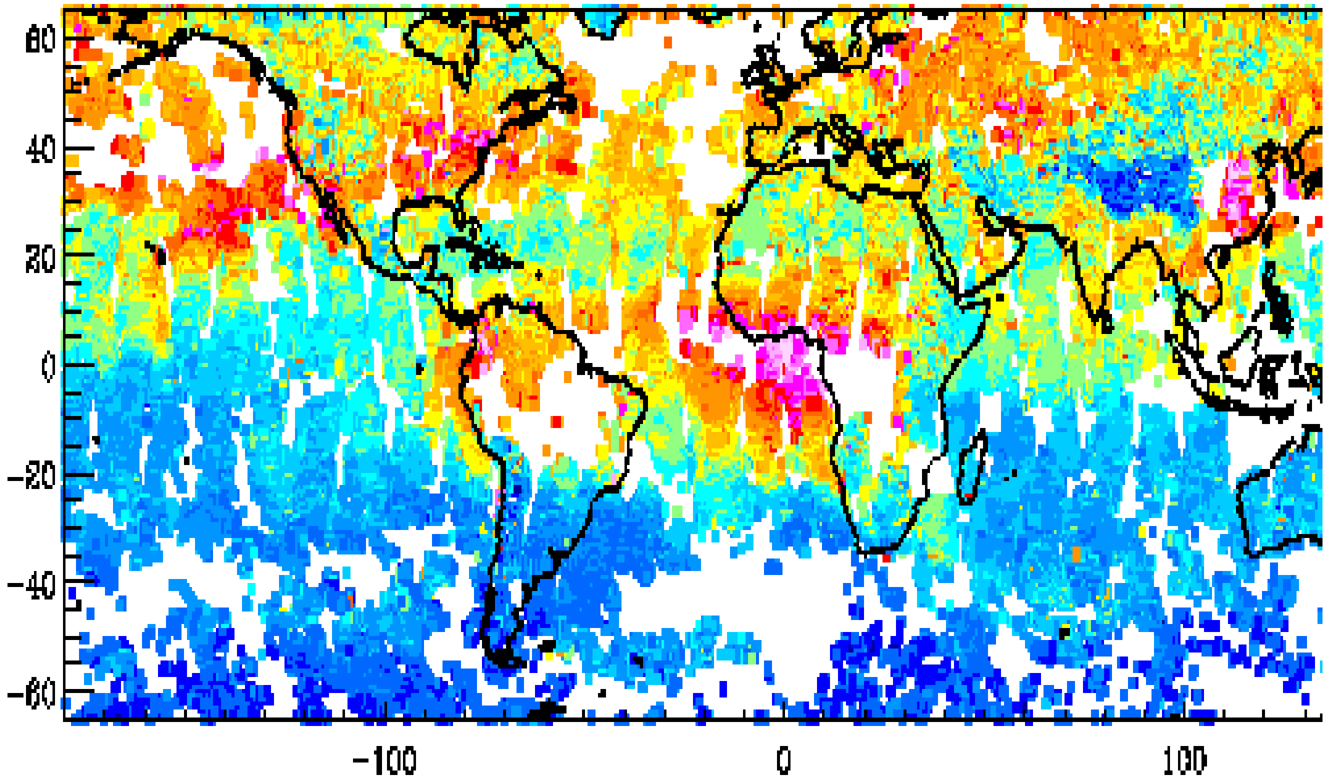

Figure 3: CO total column retrieved from the MOPITT instrument, on board the TERRA Satellite, for March 15-17, 2000. This figure shows the CO plume over Africa due to savannah fire occurring at this period in the northern part of Africa (courtesly from J.C Gille, NCAR)

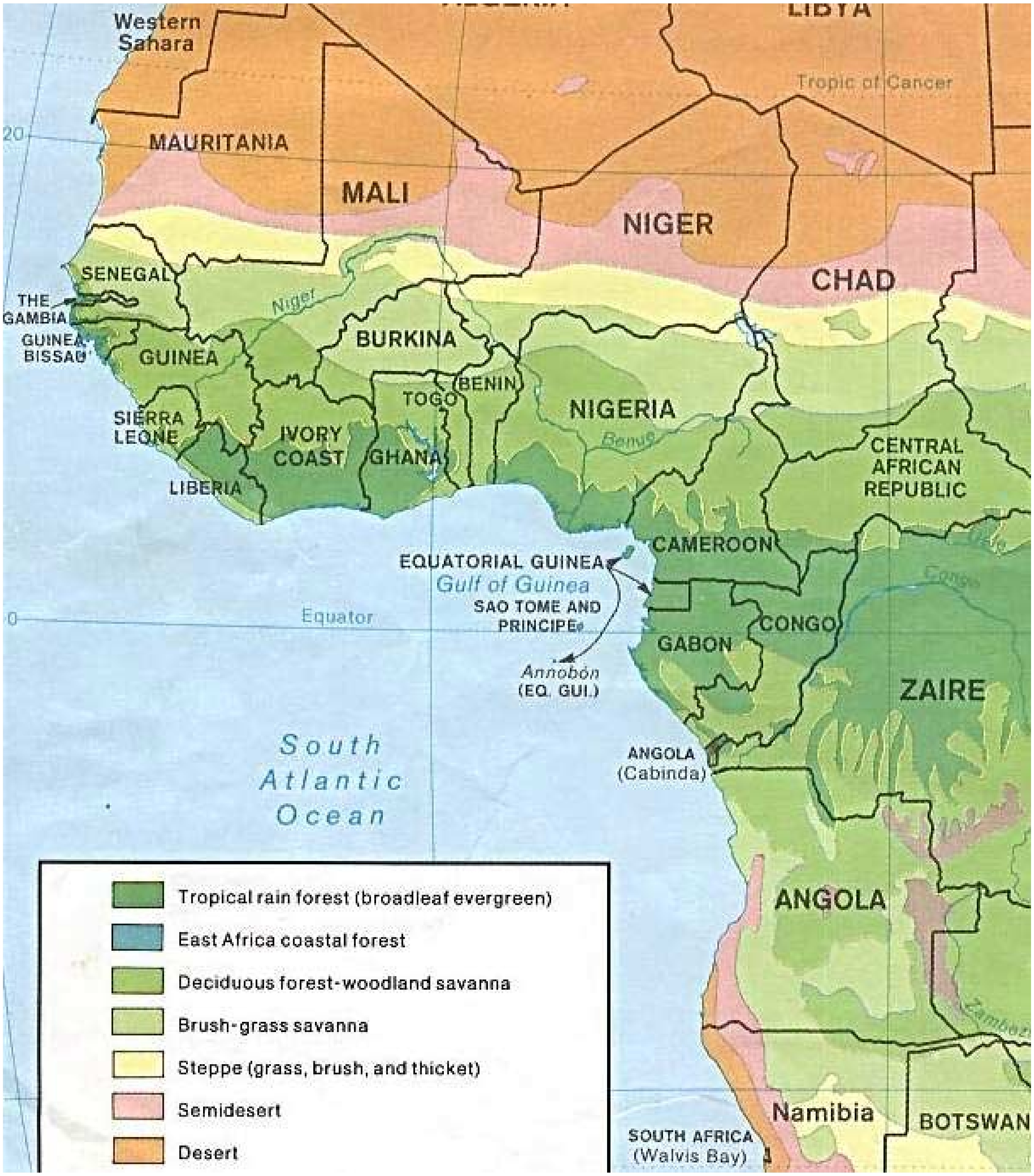

Figure 4: Main vegetation types over West Africa (1986)

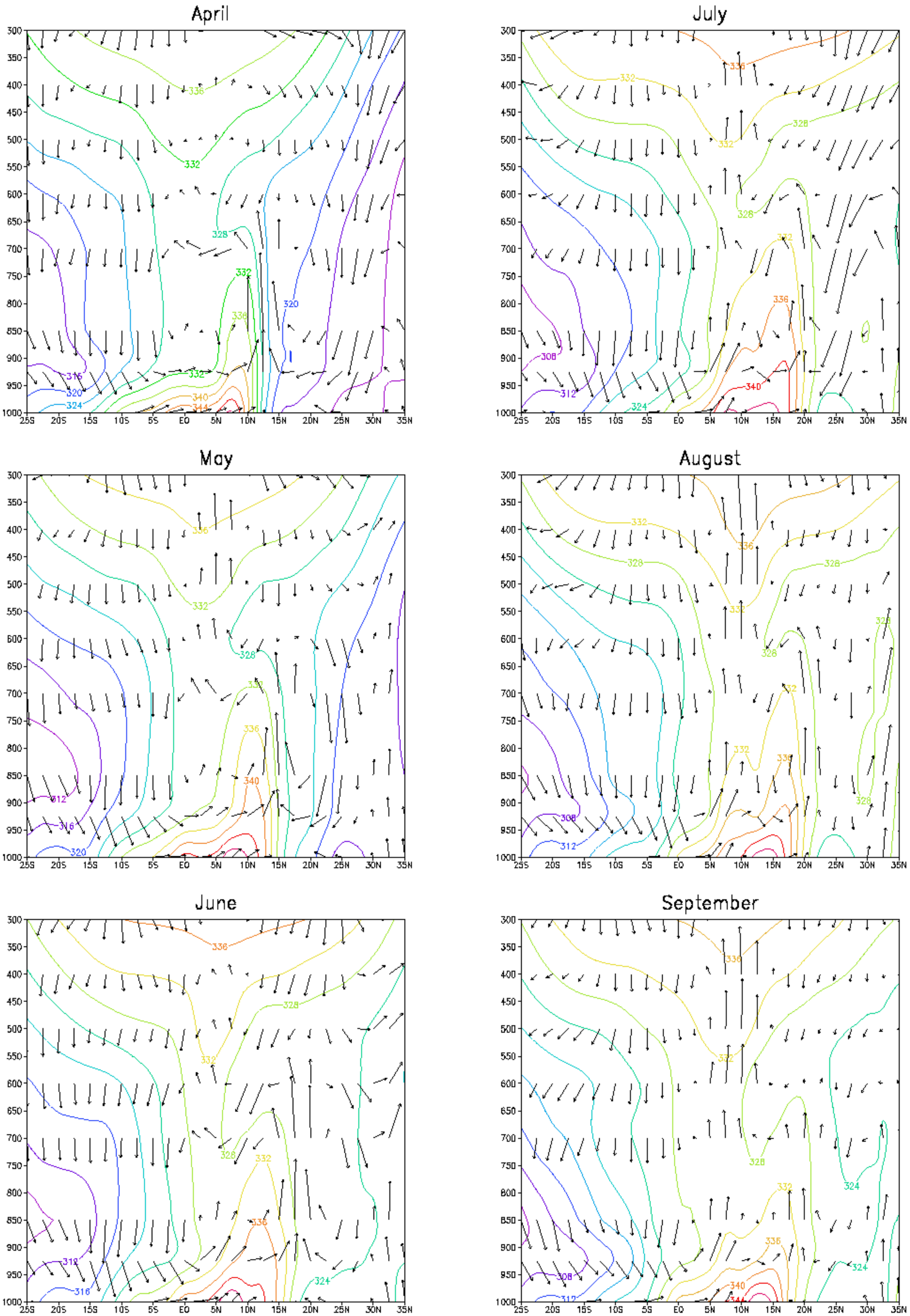
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Figure 5: Wet static energy in a meridional vertical plan as computed from NCEP reanalysis (average on years 1980-1995). The wind velocity in the meridional plan is superposed.

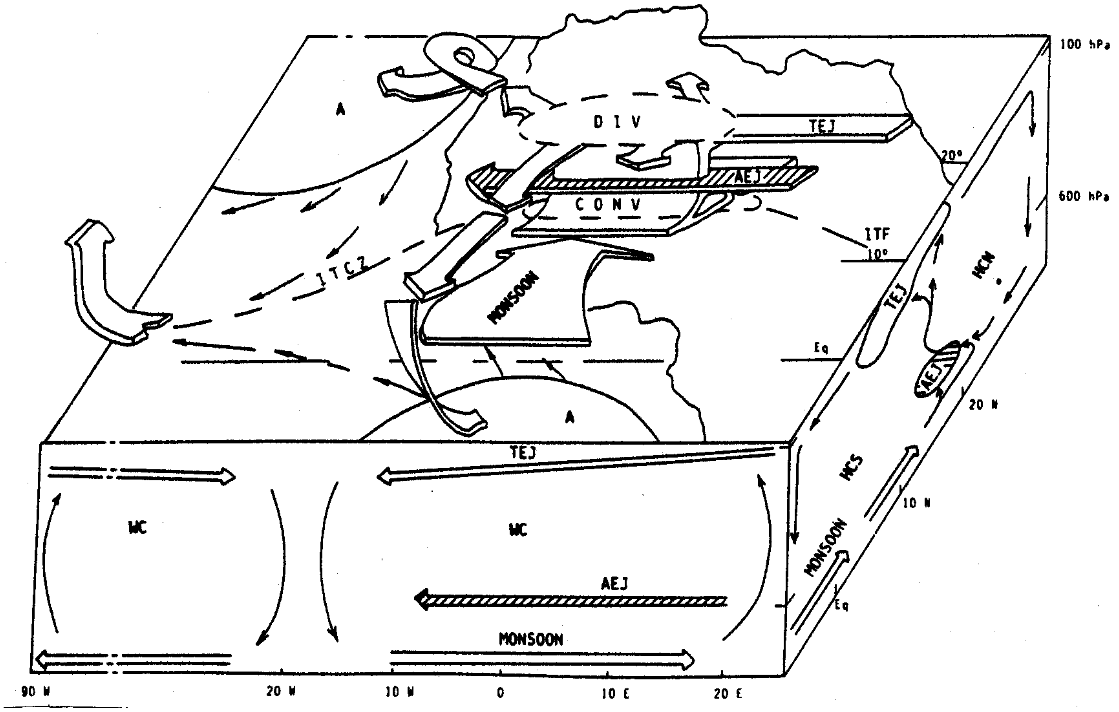


Figure 6: Schematic diagram illustrating the mean circulation of the West African monsoon

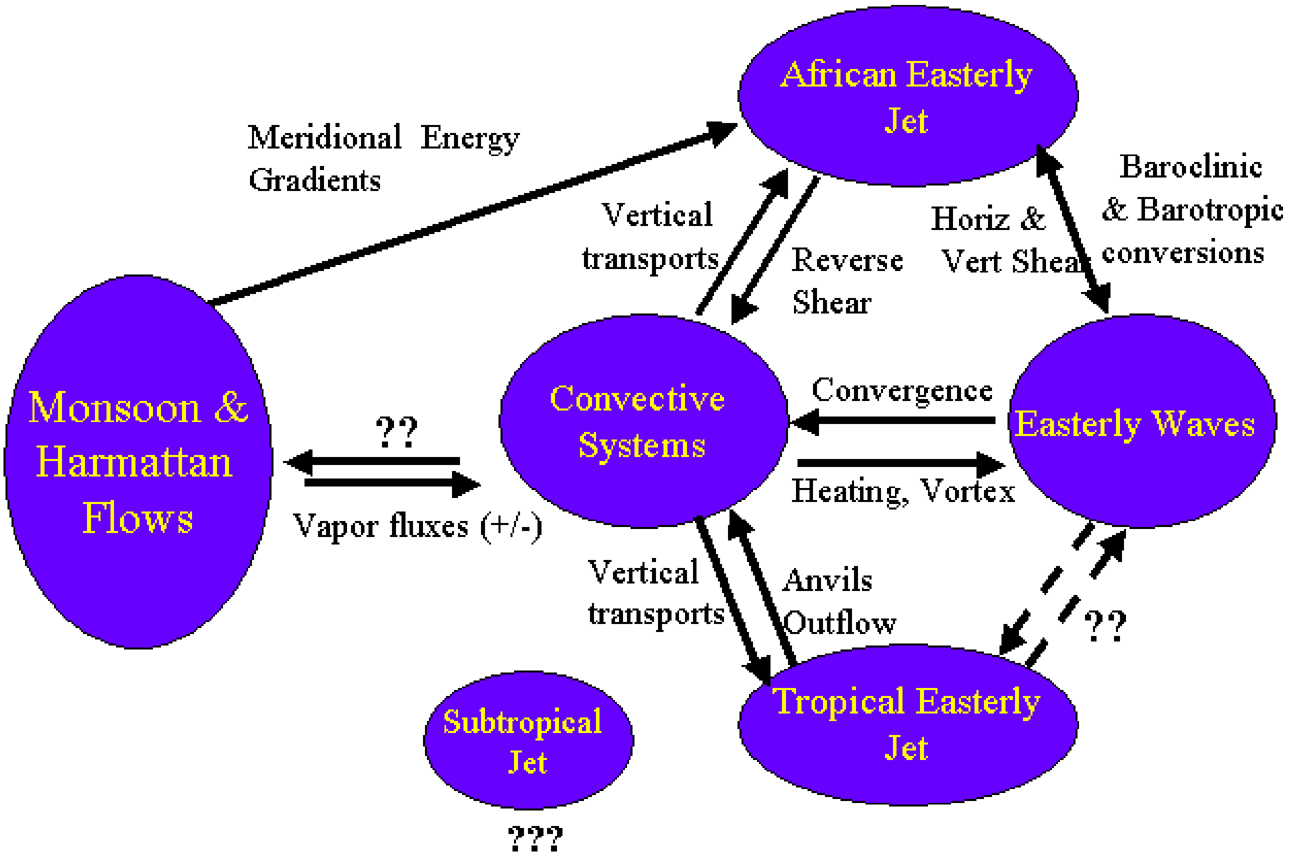


Figure 7: Main interactions between dynamical features of West African Monsoon.

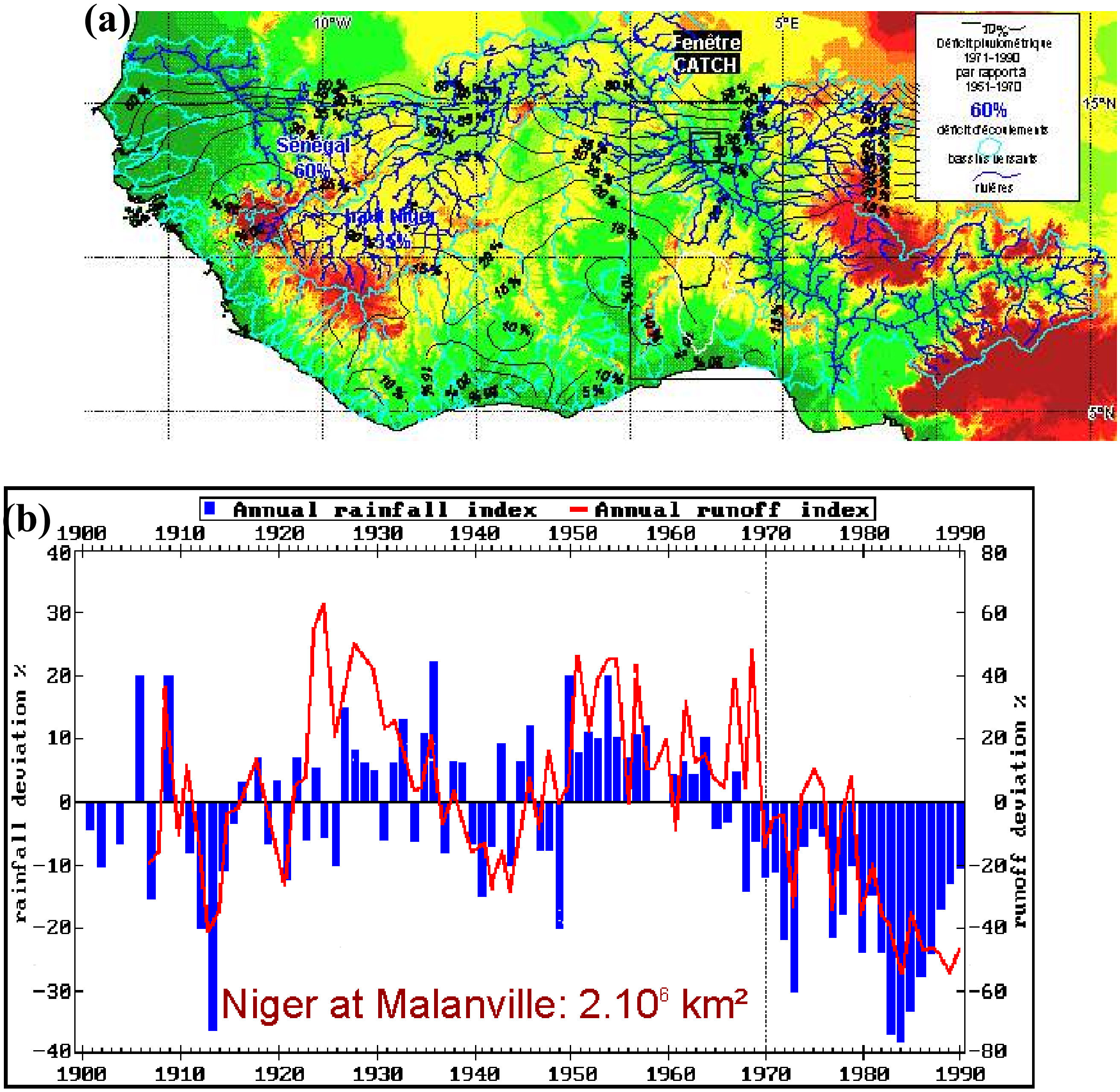


Figure 8: **a)** Rainfall and basin deficits (in %) for West Africa between wet period (1951-1970) and dry period (1971-1990) and **b)** Time series of annual rainfall deficit and annual runoff deficit for the Niger river at Malanville.

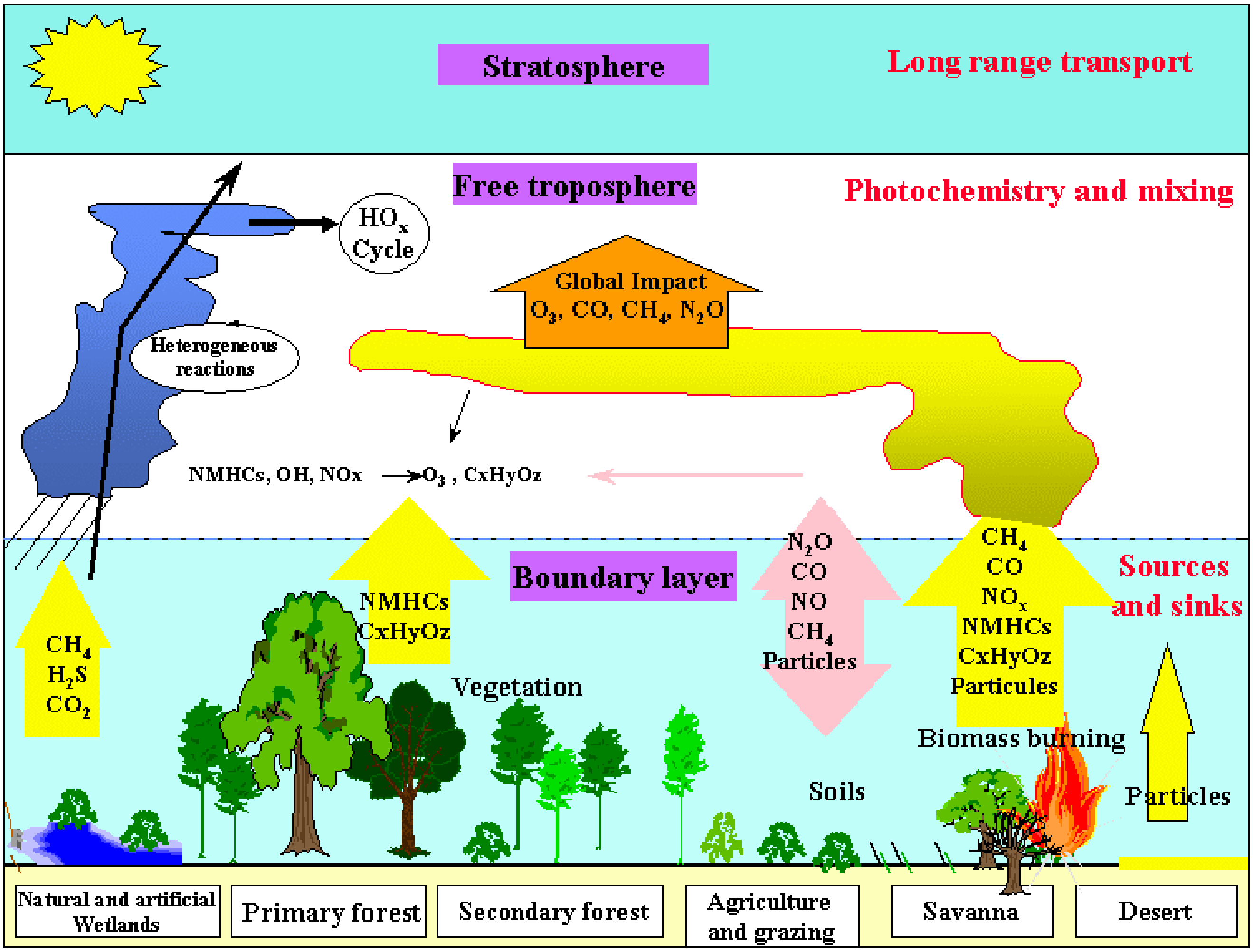


Figure 9: Schematic diagram showing the main chemical species relevant for West Africa region.

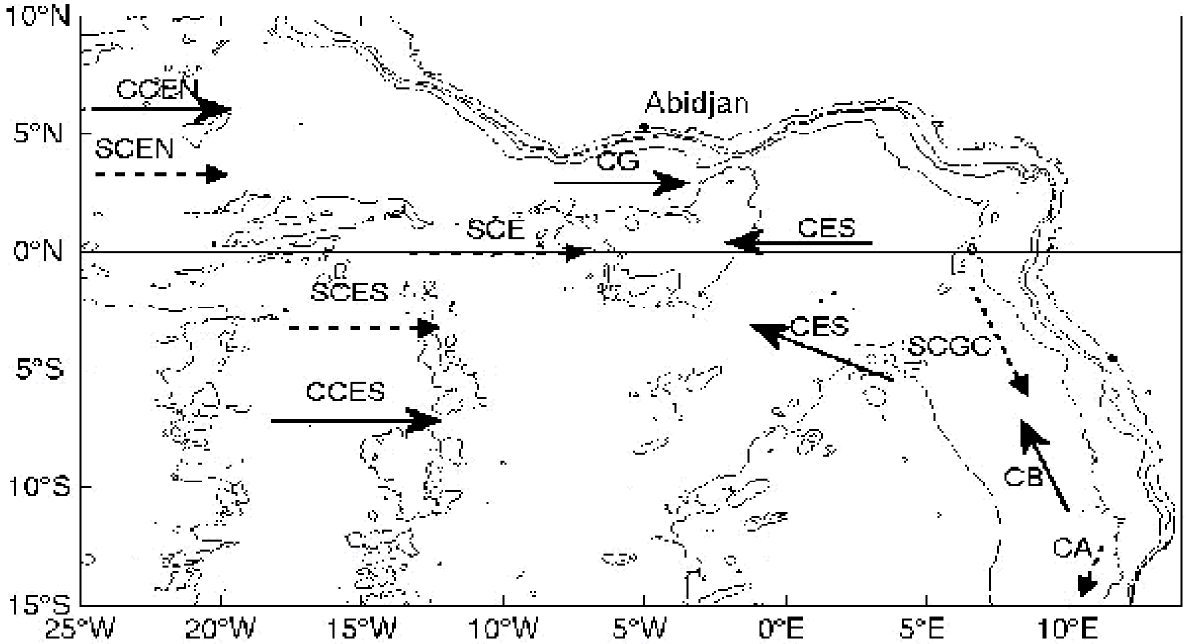
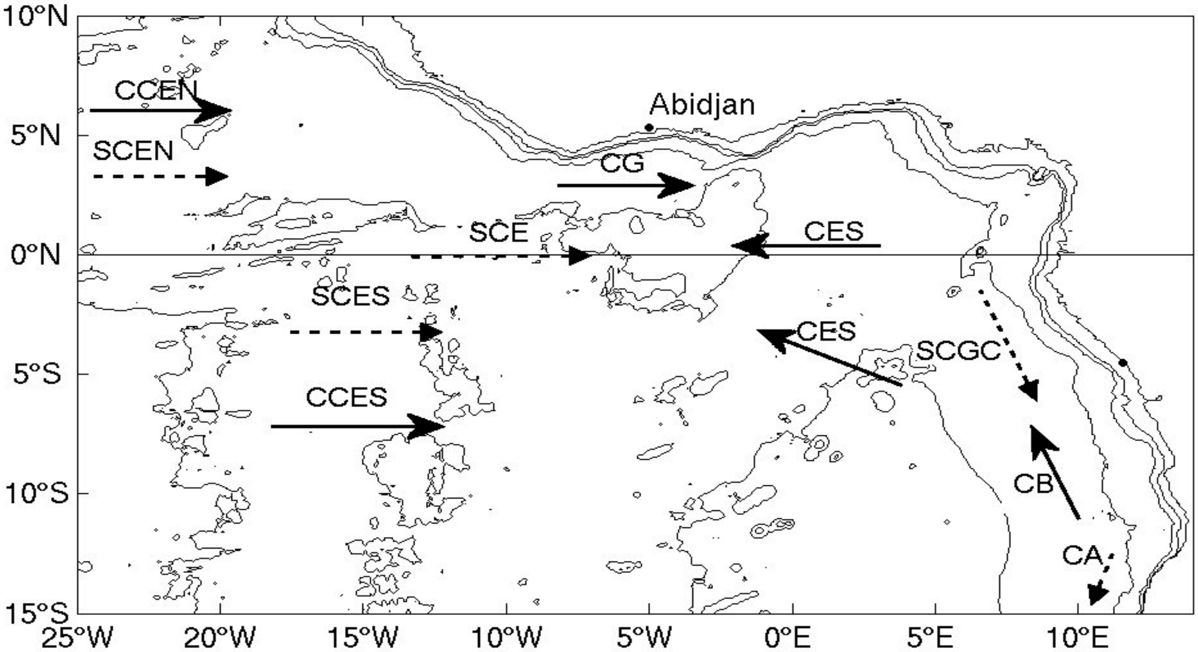


Figure 10: Mean surface and subsurface Currents in the eastern tropical Atlantic. *<u>Surface currents</u> -full arrows- : North Equatorial CounterCurrent (CCEN) ; Guinea Current (CG) ; South Equatorial CounterCurrent (CCES) ; South Equatorial Current (CES) ; Benguela Current(CB). <u>Subsurface currents</u> -dashed arrows- : North Equatorial UnderCurrent (CSEN) ; Equatorial UnderCurrent(SCE) ; South Equatorial UnderCurrent (SCES) ; Gabon-Congo UnderCurrent (SCGC) ; Angola Current*



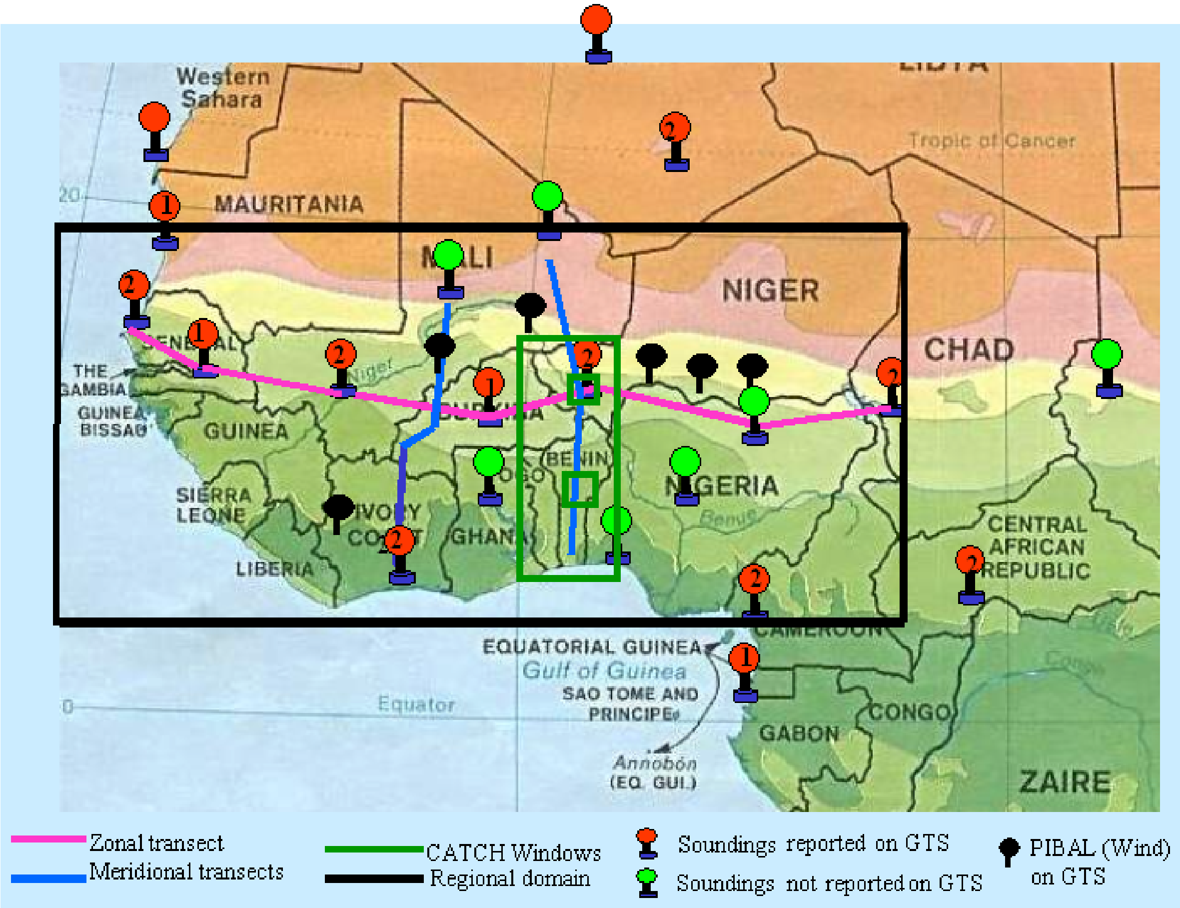


Figure 11: The three experimental transects and CATCH windows. Soundings received at ECMWF through the GTS for July 2000 and other soundings existing or notified by WMO are also represented. The number of soundings by day is indicated. PIBALs (winds deduced from balloon tracking) received at ECMWF are also given.

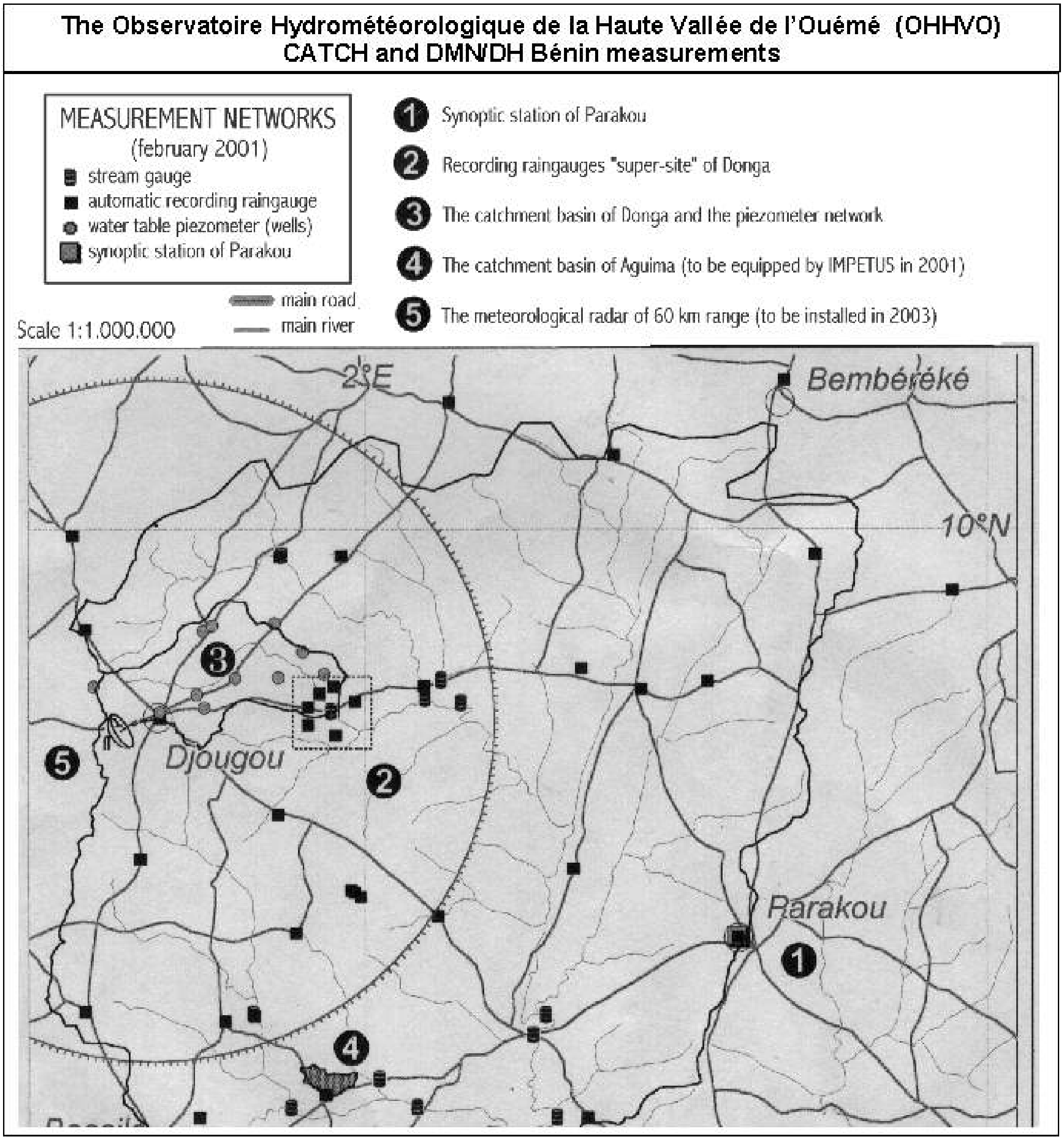


Figure 12: The CATCH and DMN.DH Benin measurements. The IMPETUS site under development is also indicated.

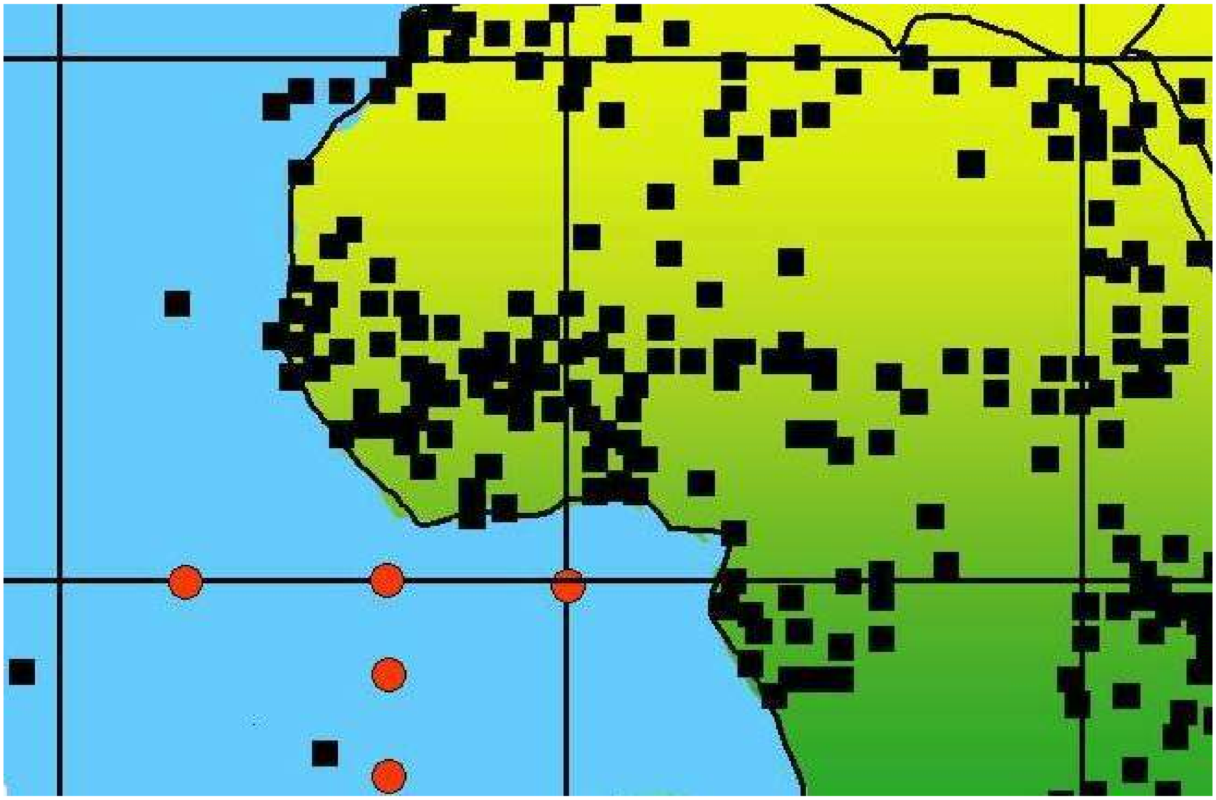


Figure 13: Example of meteorological surface stations received at ECMWF. Red dots represent operational PIRATA-ATLAS moorings received a swell at ECMWF.

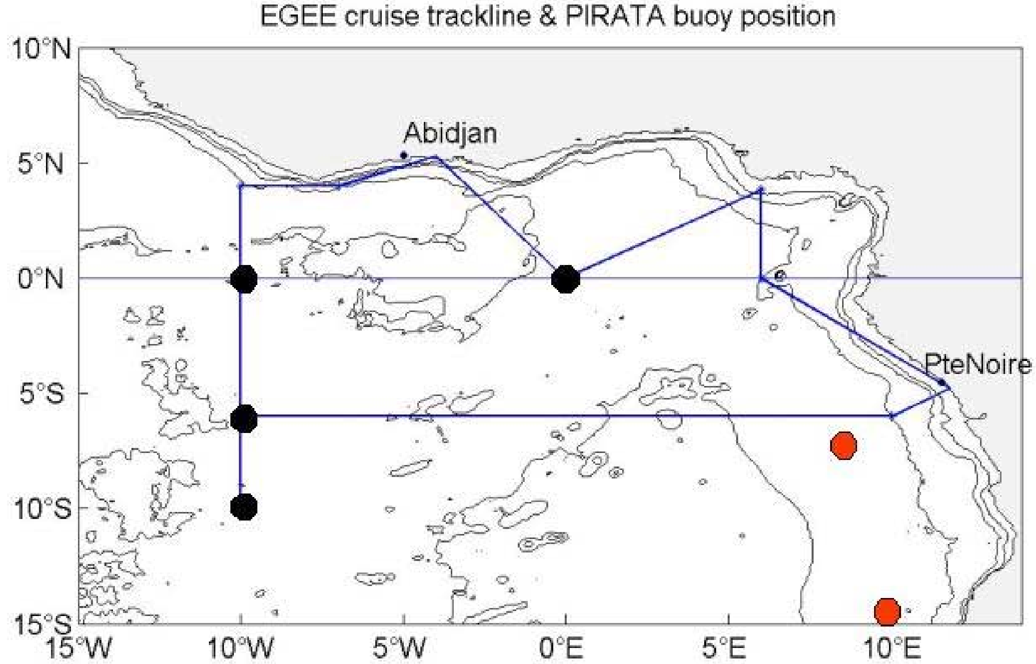


Figure 14: Possible tracks of cruises and PIRATA ATLAS moorings location (black dots: currently operational; red dots: scheduled).