Variability of the atmospheric boundary layer over West Africa observed by ground-based remote sensing instruments

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ABSTRACT

In the framework of the "African Monsoon Multidisciplinary Analyses" (AMMA) project a variety of ground-based remote sensing instruments was deployed at two sites in West Africa during the entire year 2006. Amongst others, the instrumentation consisted of microwave radiometers, lidar ceilometers, wind profilers as well as weather radars. The instrument setup made it possible to monitor the planetary boundary layer (PBL) with a high temporal as well as vertical resolution over a full year's monsoon cycle.

In this presentation a statistical analysis of PBL parameters, such as temperature and humidity profiles, integrated water vapour, as well as cloud cover is performed with regard to both diurnal and annual variability. Furthermore, a comparison between measured profiles and the results of a mesoscale model for a case study is presented.

1. INTRODUCTION

In order to broaden the knowledge of the processes controlling the West African Monsoon, the international project "African Monsoon Multidisciplinary Analyses" (AMMA) [1] was launched. One of the main tasks was to enhance the ground-based observation network over this data sparse area. To reach this goal, three so-called supersites were established in different climate zones [2] where a comprehensive view of atmospheric, aerosol, hydrological and surface-exchange observations should be provided by a suitable set of instrumentation.

The climate in West Africa is mainly characterized by the strong contrasts between the moist monsoon flow to the south and the dry Harmattan air to the north. The interface between these two flows, called the Intertropical discontinuity (ITD), shows a distinct annual cycle (from 6°N in January to 20°N in July). Important factors for the onset of the monsoon season are temperature, humidity and wind conditions in the PBL. By using a combination of ground-based remote sensing observations it is possible to get a comprehensive and continuous view of these parameters, as satellites do not provide satisfactory information of the lowest atmospheric layers. The one-year deployment of many of the instruments at two supersites provides a very good overview of the annual cycle of various atmospheric parameters. In addition, the high temporal resolution of these measurements compared to radiosondes allowed the analysis of temporal PBL development and the passage of fronts.

2. MEASUREMENT SITES, INSTRUMENT SETUP

This paper will focus on the observations at two sites:

Nangatchori is situated in Northern Benin (9.7°N, 1.7°E) in the Sudano-Guinean zone with an annual mean rainfall of 1208 mm. Most of the precipitation falls between April and October (monsoon season). The dry season usually lasts from late October to early April, but is occasionally interrupted by moist air outbreaks from the south. At the site of Nangatchori, the atmospheric remote sensing setup consisted of a 14-channel microwave radiometer (HATPRO), a lidar ceilometer CT25K, two wind profilers (UHF, VHF), and a low-power vertical Doppler radar (Micro Rain Radar MRR). In addition, aerosol and rainfall as well as energy balance measurements were performed [3].

Niamey (13.5°N, 2.1°E) is the capital town of Niger and lies in the Sahelo-Sudanian climate zone with 495 mm rainfall per year. The wet season there is much shorter than in Djougou, considerable precipitation occurs only between June and September. At Niamey, the mobile facility of the Atmospheric Radiation Measurement (ARM) Program was deployed [4], with an instrumentation consisting of a cloud radar, a wind profiler, two microwave radiometers, two lidars, energy balance measurements as well as standard meteorological observations.

3. ANNUAL CYCLE

The most striking feature in the annual cycle is the variability of the atmospheric water vapor load. Several distinct features appear when regarding Fig. 1 which illustrates integrated water vapor (IWV) for Nangatchori and Niamey in 2006.

The dry season in the early year (January to April) was unusually moist over the region and characterized by several outbreaks of humid monsoon air from the south at both locations. The driest conditions were present in early April, particularly at Niamey with IWV values of 3 - 5 kgm^{-2}, which is typical for polar regions. Towards the end of April, the atmosphere was moistened quickly. From then on, the IWV remained rather constant throughout the whole rainy season in Djougou with

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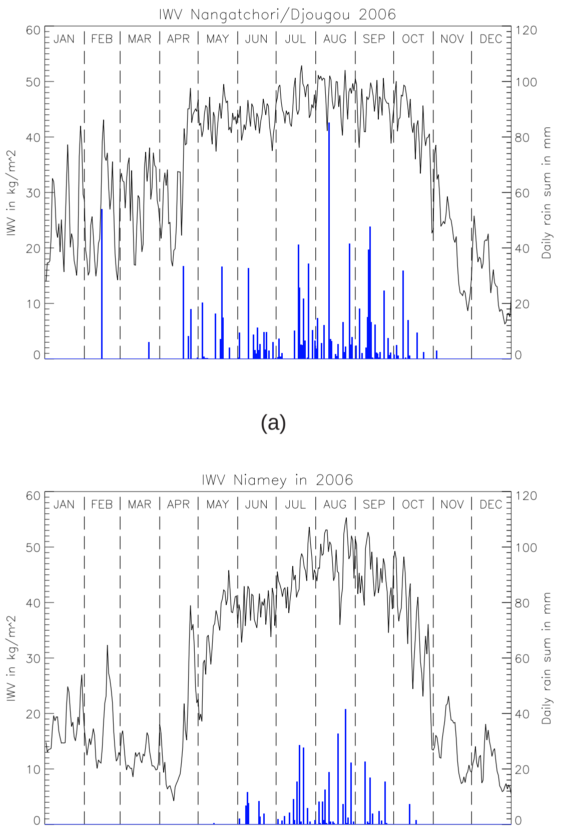
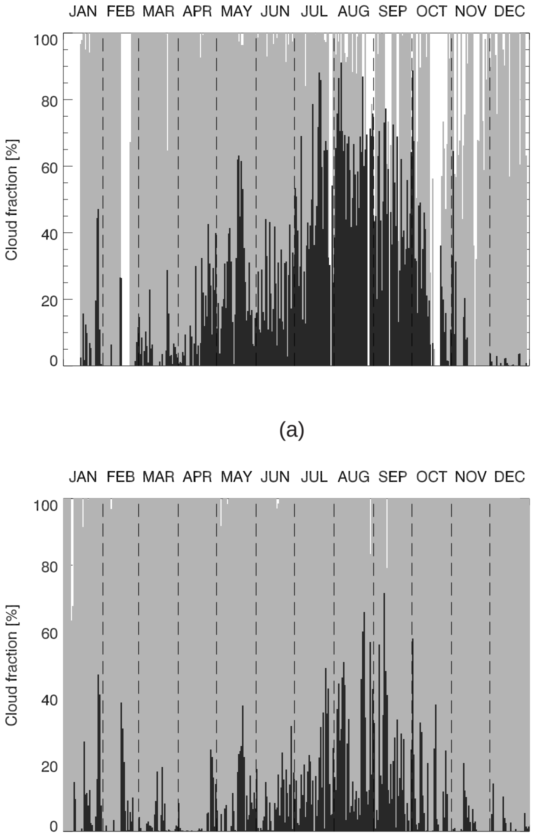


(a)

(b)

Figure 1. IWV annual cycle (black) and daily rain accumulations in 2006 (blue bars). IWV daily mean values derived from microwave radiometer measurements. a) Nangatchori/Djougou. b) Niamey



(a)

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Figure 2. Annual cycle of cloud occurrence in 2006. a) Nangatchori/Djougou. b) Niamey. Black: percentage of day with clouds detected by ceilometer, grey: percentage of day without clouds, white: no data.

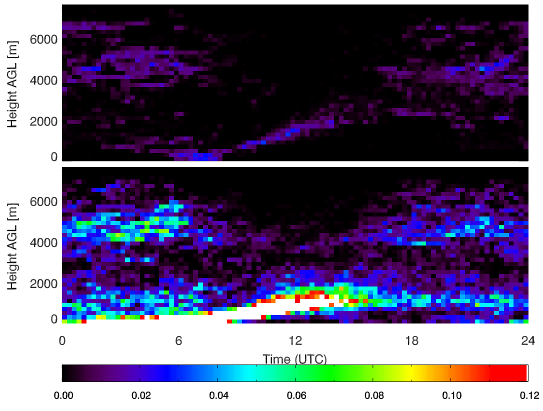
an average IWV of 44.0 ± 5.2 kg m^{-2}. However, the strongest precipitation activity which produced 62 % of the annual rainfall was connected to the monsoon peak from 15 July to 30 September when the atmosphere was slightly moister than before (IWV = 46.6 ± 3.9 kg m^{-2}).

Also at Niamey, two distinct phases of moistening can be distinguished (Fig. 1(b)). The first phase (pre-onset of the monsoon) starts about at the same time as in Djougou with a moist air surge at the end of April, but another dry spell followed in early May. In the end of May and in June, an IWV of 40 kgm^{-2} is reached. Some slight rainfall events already occurred in June, but the major moistening was only in the second half of July which is in accord with the findings of Janicot et al. [5]. The southward retreat of monsoon air started in early October and took place much faster than the onset. The last rainfall in Niamey was recorded on 19 October, and already two weeks later on 2 November Nangatchori received its last rainfall.

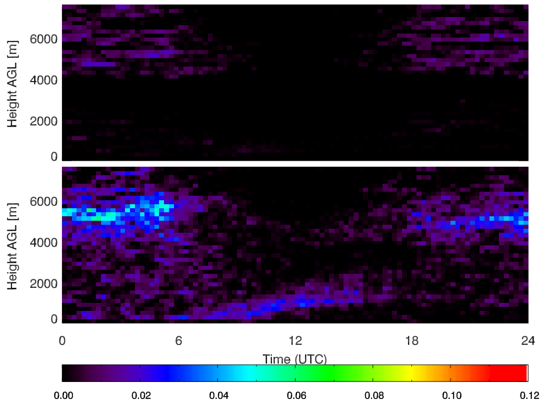
The annual cycle of cloud cover (Fig. 2) reflects the annual distribution of IWV and rainfall quite well. Cloud cover was observed by lidar ceilometers at Niamey and Nangatchori. At both locations, the cloud cover maximum can be found in July and August which is associated with the precipitation maximum. Clouds in dry season are mainly associated with mid-level humidity. For the whole year of 2006, 22.7 % of the time was cloudy in Nangatchori, and only 9.2 % in Niamey. During peak monsoon season (August), the difference is even more striking (64 % cloudy times in Djougou, only 26 % clouds in Niamey). For all these numbers it has to be kept in mind that high cirrus clouds (with bases higher than 7000 m AGL) were not detected by the ceilometer.

4. DIURNAL CYCLE

The diurnal cycle of atmospheric variables over this area does mainly depend on the position of the ITD. Before the ITD passes northward, the atmosphere is dry and strong nighttime cooling can be observed. When the ITD position is close to the station, a distinct diurnal cycle of water vapor combined with low-level jets that shift their direction during the night was observed [6]. During the wet season, high water vapor content and frequent nighttime clouds or fog dampen the diurnal cycle.



(a)



(b)

Figure 3. a) Cloud base height distribution for Nangatchori. Top: Dry season (January-April 2006), Bottom: Wet season (June-September 2006). b) Same as a), but for Niamey.

The diurnal distribution of cloud cover (Fig. 3) is an indicator for the humidity in the lower atmosphere. During both dry and wet seasons, a distinct diurnal cycle of cloud base heights can be recognized at Nangatchori (Fig. 3(a)). At Niamey (Fig. 3(b)) low clouds on top of the convective boundary layer (CBL) were mainly present only during wet season.

At Nangatchori, a few days with daytime convective clouds occurred during dry season between January and April. These days are connected with higher than average IWV values, i.e. moist air surges from the south (Fig. 1). As the soil is generally very dry without green vegetation at that time, evaporation is small and the CBL can grow fast, reaching a depth of about 2 km on these cloudy days. Note that during cloud-free days with lower IWV, a CBL depth of more than 3 km was observed. At the peak of the monsoon season (June-September), very low clouds (fog) were frequently observed during night, the bases were rising up to 800-1000 m in the afternoon. Because of the high water vapor content and the dense vegetation which changes the energy and moisture balance at the ground significantly (frequent nighttime fog and relatively low temperatures), the CBL does not grow deeper at that time of the year. In contrast, only few fog events and much less daytime convective clouds were observed in Niamey because of the generally drier conditions.

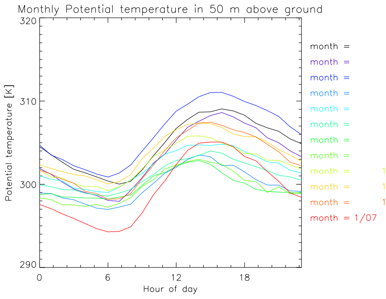


Figure 4. Potential temperature at 50 m above ground over Nangatchori

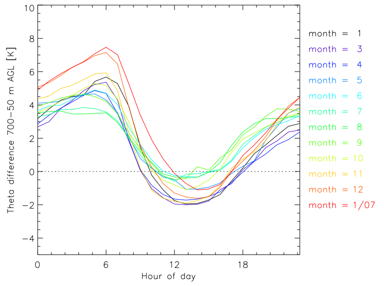


Figure 5. Potential temperature difference between 700 and 50 m above ground in Nangatchori

From microwave radiometer observations under different elevation angles, the temperature within the PBL below 1000 m above ground level (AGL) can be retrieved with an RMS error of less than 1 K [7]. Fig. 4 presents the potential temperature in 50 m AGL over Nangatchori for all months of 2006. In the annual range it can be seen that the highest daytime PBL temperatures occur in April. The sun has reached its zenith position over Nangatchori, but the moist air masses have not yet reached the area. Therefore, a large portion of the incoming solar radiation is used to heat the PBL. The lowest daytime temperatures within the PBL were observed in the wet season (June-September). Frequent cloud cover prevents the sun to heat the ground and the PBL. Note that sunrise is at about 06 UTC and sunset at about 18 UTC all year round.

The potential temperature difference between 700 m and 50 m AGL (Fig. 5) gives an impression on the stability within the PBL. Positive values correspond to a (dry) stable atmosphere and negative values can be observed under unstable conditions. During dry season, strong nighttime inversions are frequent, therefore the mean monthly inversion strength at sunrise at 0600 UTC is up to 7 K (December 06, January 07). On the other hand, negative values are seen during daytime. These super-adiabatic conditions show the significant instability in lower levels during dry season. The monsoon season is characterized by less strong nighttime inversions and neutral conditions during daytime.

4.1. Comparison with Meso-NH model

The validation of atmospheric models over this data sparse region was another goal of the atmospheric measurements within AMMA. Therefore, the mesoscale model Meso-NH (10 km horizontal resolution, driven by ECMWF analyses) was run [6] for a case study in April 2006.

During this period at the monsoon onset, Nangatchori was both influenced by dry and wet air masses in a diurnal change. Around midnight, the moist air from the south arrived at the site with a sudden change in temperature, humidity and wind (Fig. 6). Microwave radiometer as well as wind profiler measurements show this diurnal cycle with sharp air mass changes. These contrasts were captured well by the mesoscale model despite the poor data availability for the model initialization.

5. SUMMARY

The ability of a setup of ground-based remote sensing observations to capture diurnal and annual cycles of atmospheric variables was shown. For the first time such an instrument setup was deployed in West Africa during the AMMA campaign, presenting a new insight into processes within the atmospheric boundary layer.

ACKNOWLEDGMENTS

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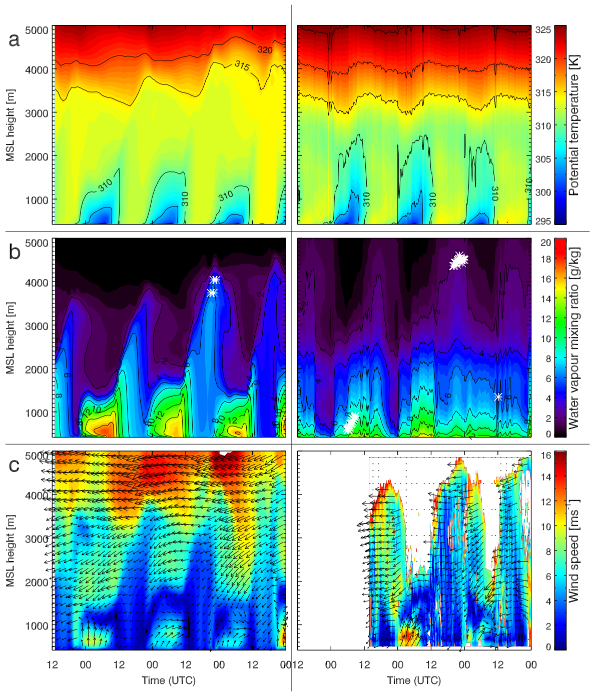

Figure 6. a): Time-height potential temperature cross-sections over Nangatchori from 9 April 2006, 12 UTC to 13 April 2006, 00 UTC. Left: Meso-NH calculations. Right: HATPRO microwave profiler observations. b) Same as a), but for water vapour mixing ratio. White asterisks show 100 % relative humidity (calculated by model, left) and cloud base height detected by the ceilometer (right). c) Same as a), but for horizontal wind speed (left: Meso-NH results, right: UHF wind profiler). Arrows depict horizontal wind.

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