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Article

Boundary layer observations in West Africa using a novel microwave radiometer

BERNHARD POSPICHAL* and SUSANNE CREWELL

Institute for Geophysics and Meteorology, University of Cologne, Germany

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Abstract

Boundary layer measurements in Nangatchori, Benin were performed over the period of one full year (2006) using a novel ground-based microwave profiler and additional remote-sensing instruments. In this paper, the diurnal cycle of the ITD (Inter-Tropical Discontinuity) in the transition period between dry and wet season during the month of April is described in detail. Dry air masses from the north (Sahel) and moist air from the south (tropical Atlantic Ocean) cause very sharp temperature and humidity gradients in the low troposphere over West Africa. Continuous observations of these phenomena in terms of temperature and humidity profiles have been achieved for the first time with a high temporal resolution of less than 15 minutes. Especially the ability of the microwave radiometer to provide temperature profiles with high vertical resolution through multi-angle measurements gives detailed boundary layer information in conjunction with meteorological tower observations. Together with additional lidar ceilometer observations of aerosol backscatter the change of air masses can be seen very well. The high data availability of > 85 % allows a statistical analysis of the full month of April in which Nangatchori comes increasingly under the influence of tropical air. Thus the data set is well suited for an improved process understanding, model evaluation in a data sparse area, and possibly together with additional observations the development of improved boundary layer parameterizations for atmospheric models.

Zusammenfassung

Messungen in der atmosphärischen Grenzschicht mit einem neuartigen Mikrowellenprofiler und zusätzlichen Fernerkundungsinstrumenten wurden während des gesamten Jahres 2006 in Nangatchori, Benin durchgeführt. Dieser Artikel beschreibt im Detail den Tagesgang der ITD (Innertropischen Diskontinuität) in der Übergangsphase zwischen Trockenzeit und Regenzeit während des Monats April. Luftmassenwechsel bei Durchzug einer Front mit scharfen Temperatur- und Feuchtegradienten zwischen trockener Luft im Norden (Sahel) und feuchter Luft im Süden (tropischer Atlantik) konnten sehr gut erfasst werden. Erstmals gelang es, kontinuierliche Beobachtungen von Temperatur- und Feuchteprofilen mit einer zeitlichen Auflösung von weniger als 15 Minuten durchzuführen. Die Fähigkeit des Mikrowellenradiometers, Temperaturprofile in hoher vertikaler Auflösung zu liefern, erlaubt es, zusammen mit meteorologischen Messungen an einem Turm und Ceilometer-Beobachtungen, genaue Informationen über die Grenzschicht zu bekommen. Die hohe Datenverfügbarkeit (> 85 %), erlaubt eine statistische Analyse des gesamten Monats April, in dem Nangatchori fortschreitend immer mehr unter den Einfluss der tropischen Luftmassen gelangt. Weiters ist der Datensatz sehr gut geeignet, das Prozessverständnis zu verbessern, eine Evaluierung atmosphärischer Modelle in einer datenarmen Region durchzuführen und vielleicht in Verbindung mit zusätzlichen Beobachtungen verbesserte Modellparametrisierungen der atmosphärischen Grenzschicht zu entwickeln.

1 Introduction

The mechanisms that influence the strength of the West African Monsoon are still not well understood. The African Monsoon Multidisciplinary Analysis (AMMA) project has been launched to gain a deeper insight into this question by combining a wide variety of ground-based, maritime, airborne and satellite measurements. (REDELSPERGER et al., 2006). Atmospheric humidity plays a key role in those processes that determine the strength of the monsoon. A very significant part of the water - whether liquid or as water vapor – is located in the atmospheric boundary layer. For this reason, the observation of the lowest part of the atmosphere is essential to get a comprehensive view of the monsoon.

The diurnal cycle of atmospheric processes is recognized to be a key factor for the meridional transport of humidity in West Africa. A detailed overview of previous research is given by PARKER et al. (2005) which is briefly summarized in the following: During daytime a heat low develops over the Sahara with a pressure minimum in the afternoon. As the convective boundary layer grows during the day, vertical mixing prevails and the horizontal flow is rather weak. In the late afternoon when sensible heating diminishes turbulence stops rapidly, and the flow is able to respond to the heat-low pressure gradient force. The low level southerly flow intensifies over night and its edge moves northward. This nocturnal meridional flow is responsible for the advec-

*Corresponding author: Bernhard Pospichal, Institut für Geophysik und Meteorologie, Universität Köln, Zülpicher Str. 49a, 50923 Köln, Germany, e-mail: bpospich@meteo.uni-koeln.de

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tion of moist air in low levels further inland and forms the main moisture source for summertime convection in the Sahel. In higher regions around 700 hPa there is a dry return flow. By day the low level humidity falls, as dry air from above is mixed down in the developing convective boundary layer. Numerical investigation of heat lows over Northern Australia and the associated diurnal cycle have been performed by RÁCZ and SMITH (1999). They can show deep convective mixing during daytime, the development of a night-time low-level jet and nocturnal frontogenesis in the transition zone of the different air masses. Furthermore, they speculate that these features are likely to occur elsewhere under similar climatic conditions.

Observations are rather sparse in West Africa. The radiosounding network has been extended as part of AMMA, but even then, most of the stations performed soundings only two to four times a day at the main synoptic hours. In the past some campaigns, e.g. HAPEX-Sahel in 1992 (DOLMAN et al., 1997) and Jet 2000 (THORNCROFT et al., 2003) have provided more detailed observations by aircraft, enhanced radiosoundings, pilot balloons as well as in situ surface stations. A radiosonde campaign with twice daily ascents was performed at Parakou, Benin from April to October. The data have been used by SCHRAGE et al. (2006) to study nocturnal stratiform cloudiness during monsoon time. Since all these data are confined to limited time intervals PARKER et al. (2005) note the complete lack of measurements with high temporal resolution in that region. This deficit can also not be closed through satellite observations as those measurements do not resolve the atmospheric boundary layer adequately.

In order to fill the gap of detailed observations in West Africa AMMA initiated the setup of the Nangatchori site in Benin where a variety of remote sensing and in-situ observations was installed. Continuous thermodynamic monitoring of the lower troposphere was performed in 2006 by a novel ground-based microwave radiometer, the Humidity And Temperature PROfiler HATPRO (ROSE et al., 2005), with high temporal resolution. Compared to other microwave radiometers HATPRO is able to observe temperature profiles with high vertical resolution in the atmospheric boundary layer (CREWELL and LÖHNERT, 2003) in addition to the standard products IWV (integrated water vapor), LWP (cloud liquid water path), and full troposphere temperature and humidity profiles. To our knowledge, this has been the first time that a microwave radiometer was used in West Africa for monitoring of the lower troposphere. Additional instruments at Nangatchori include a lidar ceilometer, vertical pointing Doppler rain radar, measurements of temperature, humidity and wind on a tower in 5 levels up to 6 m, detailed in situ aerosol observations, wind profiler and ozone lidar.

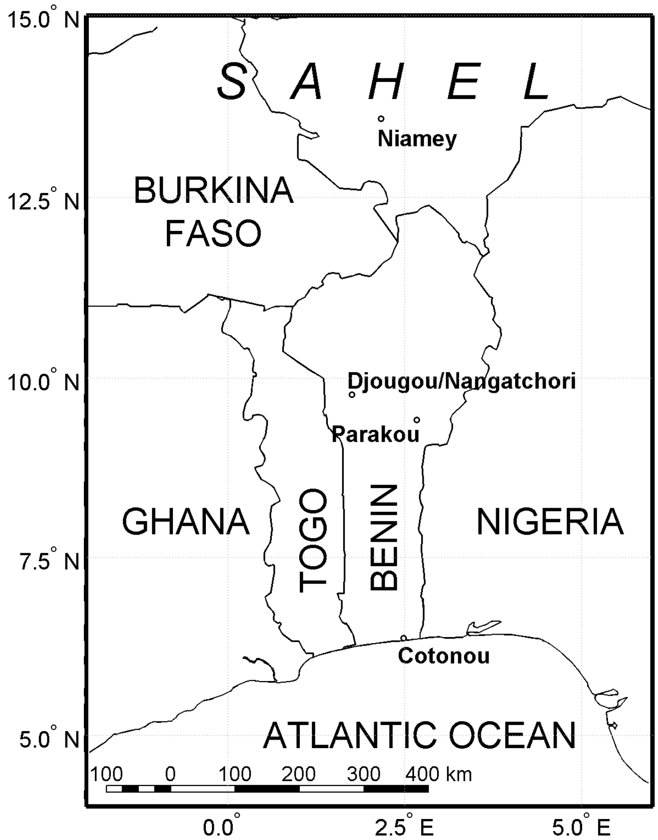

Figure 1: Map of Benin.

This paper presents first results obtained from the combination of ground-based instruments at Nangatchori with a special focus on the novel microwave radiometer (section 2). The observations are illustrated by a case study of the diurnal cycle of the ITD in April 2006 (section 3). A first glimpse of the expected long-term potential of the observations is given by a statistical analysis for the full month of April where the transition from dry to wet season occurred (section 4).

2 Observations

2.1 Measurement site

The site of Nangatchori (9.65° N, 1.73° E) is located 10 km south-east of Djougou at 415 m above mean sea level (Fig. 1). Djougou is the capital city of a province with the same name in central Benin about 300 km north of the Atlantic Ocean coast (Gulf of Guinea). This area lies in a tropical climate with a dry season between October and March and a wet season between April and September (also known as Savanna climate or tropical wet and dry climate). Temperatures rarely drop below 20°C; the extreme temperature range is 15 to 45°C. The measurement site is surrounded by manioc fields and some shrubbery in the east of the small village of Nangatchori. The site was established in early 2005 to serve as an AMMA measurement site and for security reasons

Figure 2: Setting of microwave radiometer HATPRO (right), lidar ceilometer (centre) and flux station (left) at the Nangatchori site in Benin.

the site is permanently guarded. The University of Bonn installed one microwave profiler (HATPRO), one lidar ceilometer and one Micro Rain Radar (Fig. 2) in January 2006. These three instruments operated in an autonomous mode over a full year until January 2007.

For a complete characterization of the atmosphere and the surface exchange processes many other instruments were located at this site. Measurements of chemical compounds of the atmosphere as well as aerosol particle observations have been performed. Besides the lidar ceilometer, two other instruments for optical remote sensing, one aerosol and one ozone lidar, were operating in Nangatchori. Wind profile information has been gathered by Very High Frequency (VHF) and Ultra High Frequency (UHF) radars since May 2006. Furthermore, a disdrometer and some pluviometers have been installed for precipitation studies. A six meter tower for eddy correlation measurements (water vapor and CO_2 fluxes) has been constructed. It was equipped with temperature and humidity sensors as well as anemometers in different levels. The temperature sensors which are used for the case study in section 3 are located 1.2 m, 2.5 m and 4 m above ground. Data is available with a 15 minute temporal resolution. Wind direction and speed measurements were performed at four levels, later only the wind at 6 m has been used. Wind data show large data gaps during the study period. Therefore observations from a wind sensor (RM Young 5103) at an automatic weather station in Djougou (10 km north-west of the measurement site) with a temporal resolution of 15 min are used in addition. Wind speed is averaged over the past 15 minutes.

Although the site is safe-guarded the infrastructure to operate the various instruments without skilled operators is quite problematic due to the unreliable power supply and missing phone and internet connection. Therefore much effort had to be put into preparing the instruments for the hot and partially humid climate as well as into installing unbreakable power supplies together with reliable procedures for automatic restarting in case the power cuts exceeded 3 hours. However, for the whole year of 2006 the data availability of the two main instruments which are described in detail below has been quite good (HATPRO 77 % and ceilometer 87 %).

2.2 Microwave radiometer HATPRO

The microwave radiometer HATPRO (ROSE et al., 2005) continuously measures thermal emission by atmospheric components (water vapor, oxygen, liquid water) simultaneously in 14 channels distributed over two frequency bands. Seven channels are located along the high-frequency wing of the water vapor absorption line at 22.235 GHz (22.24 –31.4 GHz), and another 7 channels are located along the low-frequency wing of the 60 GHz oxygen absorption complex (51.26–58 GHz). HATPRO is operating in zenith pointing mode most of the time (except when performing elevation scans, see below) giving a set of 14 brightness temperatures every 2 seconds. Statistical algorithms are used in order to retrieve atmospheric parameters from brightness temperatures. These algorithms are developed on the basis of synthetic observations generated from a representative long-term data set (LÖHNERT and CREWELL, 2003). At Nangatchori, the zenith pointing mode was tilted by 20 degrees to the north to avoid direct sunlight. As a consequence, the optical path through the atmosphere is increased by 6.4 % which has been taken into account within the retrieval algorithms.

Coarse profiles of water vapor and temperature can be derived from the multi-spectral measurements when viewing in zenith direction. While the IWV can be obtained with a high accuracy of about 1 kg m^{-2} from the strength of the water vapor line, information on the vertical distribution is limited to about two independent layers with an RMS uncertainty of 1–2 gm^{-3} (LILJEGREN et al., 2005). The vertical resolution of the retrieved temperature profiles is slightly better with less than 2 km in the lowest 4 km (LILJEGREN et al., 2005) resulting in an RMS accuracy of 0.6 K near the surface and less than 1.6 K in the middle troposphere (GÜLDNER and SPÄNKUCH, 2001). The vertical resolution is limited through the weighting functions of the different frequency channels rather than through the radiometric noise. By observing the atmosphere under different angles additional information about the temperature of the lowest kilometer can be gained (see below). The thermal emission by clouds increases with frequency and therefore the liquid water path can be retrieved as well with an accuracy of about 25 g m^{-2} (LÖHNERT and CREWELL, 2003). It has to be noted that the retrieved parameters

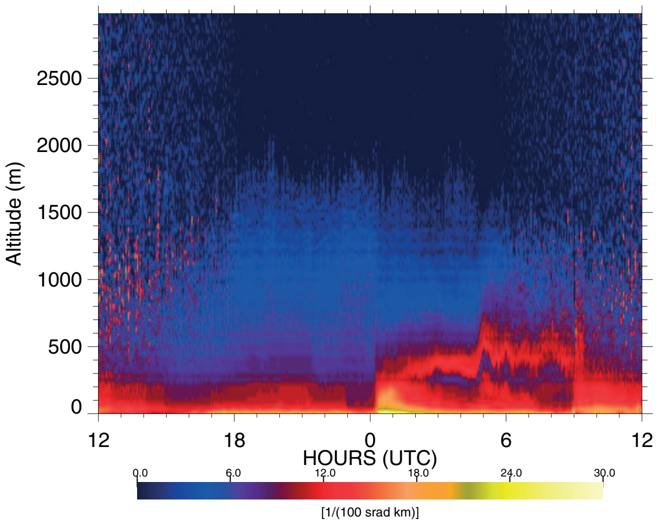

Figure 3: Temporal development of backscatter above the Nangatchori site derived from ceilometer observations from 10 April 2006 12 UTC to 11 April 2006 12 UTC. No clouds occurred during this time interval. Altitude is in meters above ground.

are available at the same temporal resolution as the raw data.

Statistical algorithms are limited for the range of atmospheric conditions for which they have been trained. Although radiosondes have been launched from April to October 2002 as well as during much of the year 2006 at Parakou, Benin (100 km east of Nangatchori), this dataset is by far not large enough for developing a robust retrieval algorithm. Due to the lack of reasonably good radiosonde data in Western Africa all retrieved HATPRO products used in this study were generated by applying a retrieval algorithm based on a 15-year dataset of about 10000 radiosoundings from Darwin, Australia. Climatic conditions in Northern Australia with marked dry and wet seasons are similar to those in central Benin. This was confirmed by comparing mean profiles and frequency distributions of the Parakou soundings with those from Benin. Because all atmospheric states observed in Parakou are included within the Darwin statistics we are confident about the retrieval quality.

The vertical resolution of the temperature profiles can be improved by performing elevation scans at relatively opaque frequencies. By assuming horizontal homogeneity of the atmosphere the observed radiation systematically originates from higher altitudes the higher the elevation angle. Since these brightness temperatures vary only slightly with elevation angle, the method requires a highly sensitive and stable radiometer. Crewell and Löhnert (in press) could demonstrate HATPRO's ability for that by comparisons with radiosondes and temperature measurements by a 100-m-mast. When using observations at six elevation angles between 5 and 90° the retrieval performance for the lowest 1500 m of the troposphere is significantly improved compared to zenith mode with an error of less than 0.5 K. Therefore boundary layer scans were performed about every 10 min in order to observe the evolution of night-time temperature inversions with high vertical as well as temporal resolution. The retrieval combines brightness temperatures measured at the four highest frequencies (54.94, 56.66, 57.30, and 58.00 GHz) under 5.4°, 10.2°, 19.2°, 30.2°, 42° and 90° elevation. The use of high (relatively opaque) frequencies limits the vertical information to about 1.5 km. The vertical distance of retrieved height levels is 50 m near the ground and gradually rising to 200 m in the highest levels. It should be noted that the true resolution might be worse especially for the higher levels depending on the actual situation, e.g. in case of multiple temperature inversion layers. The resulting vertical resolution is best within a couple of 10 m close to the surface and gradually decreases to about 300 m at 400 m height (WESTWATER et al., 1999).

Observations are possible during nearly all weather conditions. Only when precipitation causes wet antennas or radomes no useful measurements can be performed. A high power dew blower is installed to remove water droplets on the radome. Auxiliary measurements of air pressure, temperature and humidity are automatically performed by HATPRO. A rain detector is used to flag periods of rain, and a GPS clock is used for exact time synchronization of the measurements.

2.3 Lidar ceilometer

The Vaisala CT25K Lidar Ceilometer (ROGERS et al., 1997) continuously operated in Nangatchori from January 2006 to January 2007. It sends out laser pulses at 905 nm and measures atmospheric backscatter with a temporal resolution of 15 seconds and a vertical resolution of 30 m (100 ft) in 250 range gates up to 7500 m (25000 ft) distance. To avoid direct sunlight during daytime the ceilometer was tilted by 20 deg to the north. This enabled us to observe through the whole year with the same angle even at June solstice when the sun is 15 deg north of Nangatchori and in the same direction as HATPRO. The basic purpose of this ceilometer is to detect cloud base heights. This is internally done by the Vaisala software using first a conversion of backscatter to extinction by Klett inversion (KLETT, 1981) and a successive threshold to detect up to three cloud layers simultaneously. As a further application, the backscatter profiles can indicate layers of enhanced aerosol content. This is especially true during nighttime when no solar backscatter reduces receiver sensitivity and the low vertical mixing in the boundary layer leads to distinct layers of different aerosol content. An example for this gives Fig. 3 where the change of air masses at 0015 UTC can be clearly seen. Furthermore, between 01 and 09 UTC wave disturbances can be identified from the temporal oscillations of high backscatter in about 500 m above ground.

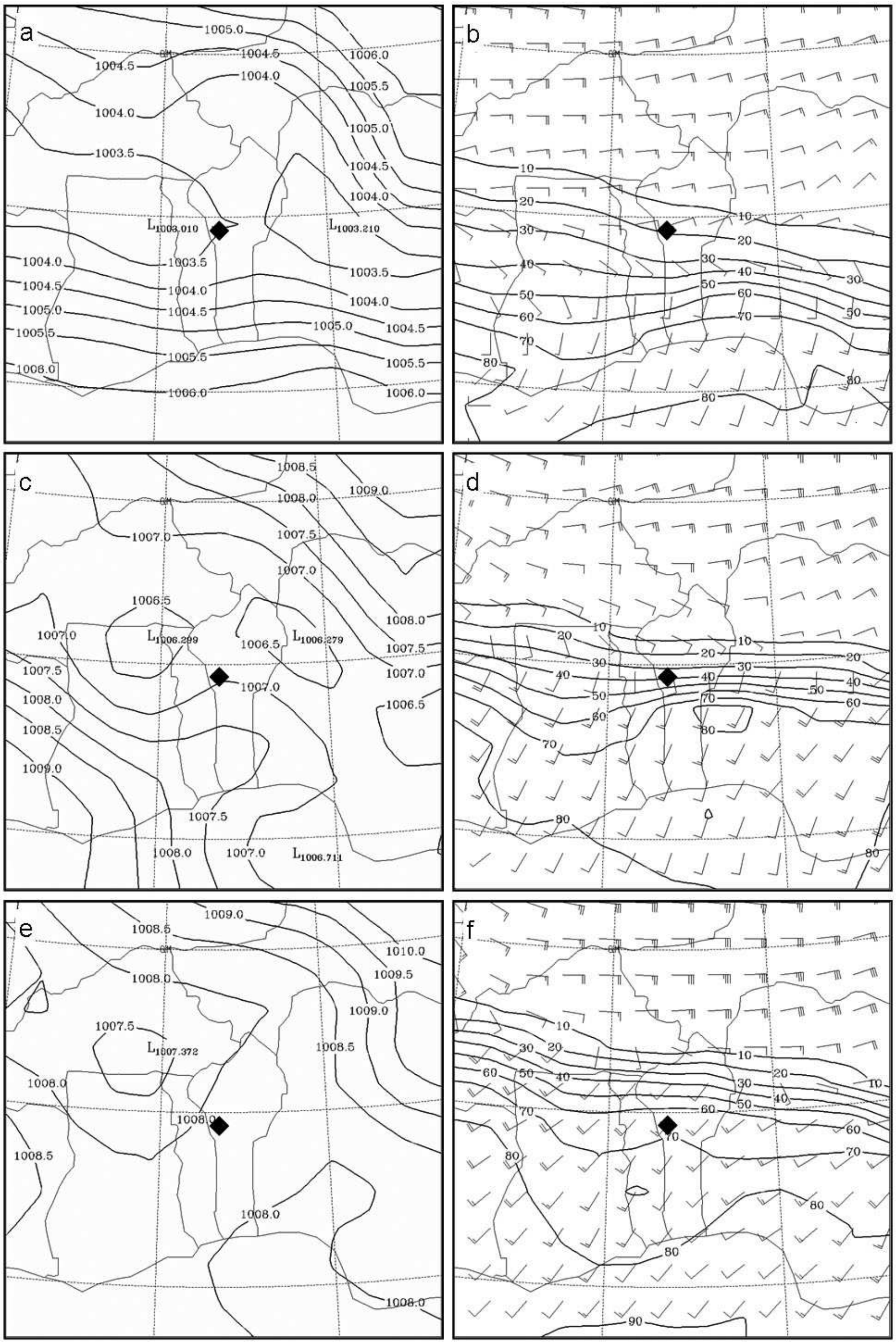

Figure 4: (a), (c), and (e) show the analyzed mean sea-level pressure on 10 April 2006 18 UTC, 11 April 2006 00 UTC and 11 April 2006 06 UTC, respectively. (b), (d), and (f) show wind vectors and relative humidity (in %) in 925 hPa for the same dates. These analyses are based on operational ground-based and upper-air observations. The black diamonds in all sub-plots represent Djougou. Source: NOAA Air Resources Laboratory, FNL-Archive.

3 Case study of diurnal cycle of the ITD over Nangatchori

The ITD (Inter-Tropical discontinuity) marks the confluence line between the moist southwesterly Monsoon flow and the dry Harmattan winds from the north-east. The average position of the ITD in January and February is just north of the Guinean coast at about 7°N (Fig. 1) although single precipitation events can occur in Central and Northern Benin even at that time. Around spring

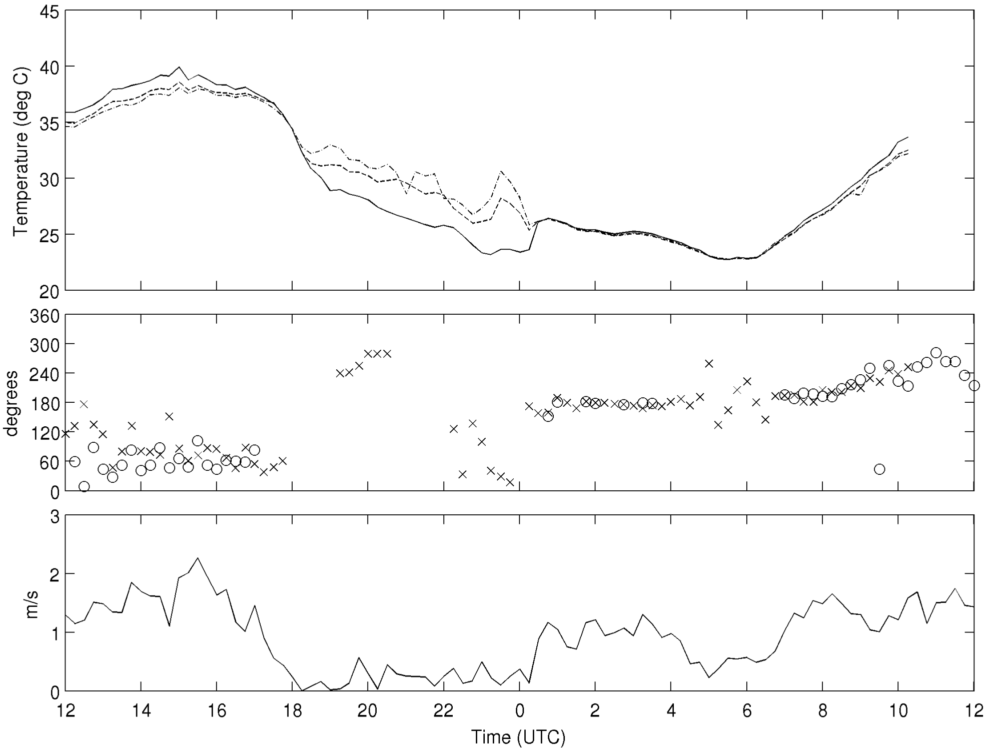

Figure 5: (a) Time series of air temperature at the Nangatchori site derived close to the ground from tower observations at three different height levels (solid line 1.2, dashed line 2.5 and dash-dotted line 4 m agl) from 10 April 2006 12 UTC to 11 April 2006 12 UTC. (b) Time series of wind direction for the same period. Crosses represent Nangatchori measurements in 4 m agl, circles mark Djougou measurements in 2.4 m agl. (c) Time series of 15-min average wind speed (2.4 m agl) at Djougou.

equinox when the sun path crosses the equator, the ITD already lies further north caused by increasing convection in the southern part and the higher solar radiation over the Sahel area. As a consequence of the larger solar input in the Sahel region, the afternoon heat low over the Sahel area strengthens and the temperature gradient between the hot and dry air and the humid and relatively cool air masses over the ocean becomes sharper. Along the West African coast between Nigeria and Ivory Coast the thunderstorm activity increases significantly, whereas in the Sahel zone the highest temperatures of the year can be observed. However, the ITD does not proceed continuously to the north; it is rather associated with abrupt shifts of the convergence zone and shows also strong diurnal variability. SULTAN and JANICOT (2003) describe the mechanisms of that northward move in detail.

A pronounced diurnal cycle of the ITD position with low-level moisture transport is known to play an important role for the monsoon circulation (PARKER et al., 2005). STENSRUD (1996) gives an overview over earlier works on low-level jets and their importance to regional climate. WHITEMAN et al. (1997) performed a study in the US (Southern Great Plains) where they state the importance of low-level jet moisture transport from the Gulf of Mexico to the north. Likewise, this seems to be true for the West African region. This cycle of the ITD is influenced by a large diurnal temperature range in the dry air to the north of the ITD and the nearly constant temperature at the ocean shore. As an example, analyses of mean sea-level pressure for 10/11 April (Fig. 4) show that the meridional position of the pressure minimum varies significantly over the day. It is at its southernmost point at 18 UTC and moves north during night-time. This northward retreat of the heat low is associated with an abrupt change in temperature and humidity at a given site which will be illustrated with the help of Nangatchori observations.

In the year of 2006 the northward propagation of the ITD was delayed by several weeks. Between 0 and 5°E the mean position of the ITD during the first (10.25°N) and second (11.60°N) ten-day-period of April 2006 showed an anomaly of 1.65° and 1.3° to the south (180 and 140 km), respectively[1] . Associated with this feature, the region experienced unseasonably dry conditions. Towards the end of April the ITD moved north of this area and dry air masses did not extend any longer as far south as Nangatchori.

As one example we describe in this section the 24-hour period from 10 April 2006 12 UTC to 11 April 2006 12 UTC. Sunset and sunrise time for the night 10/11 April are 1803 UTC and 0545 UTC, respectively.

[1]http://www.cpc.ncep.noaa.gov/products/fews/ITCZ/itcz.shtml

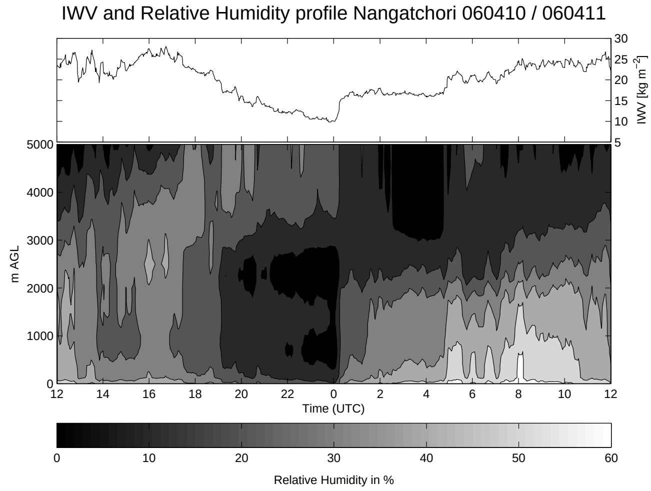

Figure 6: Temporal development of humidity above the Nangatchori site derived from HATPRO observations from 10 April 2006 12 UTC to 11 April 2006 12 UTC. The vertical integral, e.g. the integrated water vapor (top), reveals strong jumps at 0015 UTC and 0445 UTC. When interpreting humidity profiles (bottom) the limitation to 1–2 independent layers has to be kept in mind (see section 2.2).

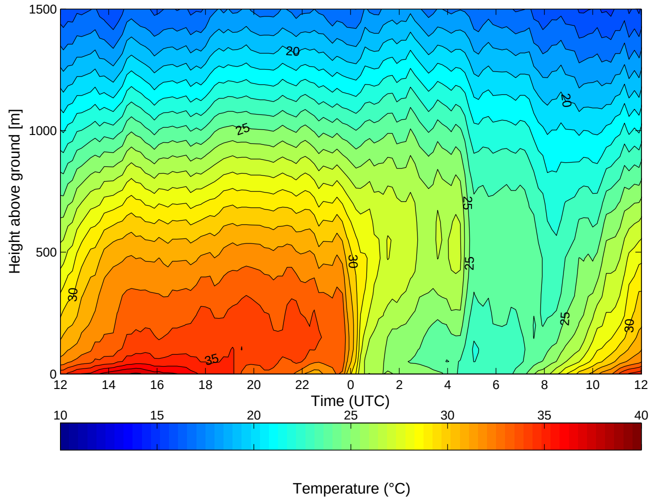

Figure 7: Temporal development of atmospheric temperature as boundary layer profile from HATPRO observations between 10 April 2006 12 UTC and 11 April 2006 12 UTC.

It has to be noted that during this period no single cloud was detected over Nangatchori. The meteorological situation is described by analyses of the Global Data Assimilation System (GDAS) at NOAA Air Resources Laboratory. Although these analyses suffer from the sparse data availability over the region they give an overview over the synoptic conditions and agree with the observations of surface weather stations (not shown).

During daytime on 10 April a heat low at about 10°N (Fig. 4a) occurs. The dry and cloudless atmosphere is heated by the sun and temperatures in the region rise over 40°C, the maximum temperature in Niamey (Niger) being 43°C. Further south, at the coastline large convective cells are formed with afternoon rainfall, thunderstorms were observed at 17 UTC in Cotonou.

Density differences cause the cold air masses over the sea (land-sea wind system) and the outflow of convective systems to propagate inland. At daytime, the northward extent of this moist air mass is not very large because of the turbulent vertical mixing in the convective boundary layer (CBL) inland. In Nangatchori, north-easterly winds which carry dry air from southern Niger and northern Nigeria could be observed between 1400 and 1800 UTC (Fig. 5b). The deep convective boundary layer over the study area allows moisture to ascend to higher levels by vertical mixing. For that reason, relative humidity at levels between 3 and 4 kilometers above ground increases during the afternoon towards sunset (Fig. 6). The lowest atmospheric pressure at 1800 UTC over West Africa can be found to the west of Djougou from southern Mauretania over southern Mali to Burkina Faso (Fig. 4a). The observations and the analyses show that the ITD was situated south of Djougou at this time of day.

At sunset, the north-easterly wind at the ground declines (Fig. 5c). The lower troposphere remains very dry and a sharp and shallow temperature inversion is formed over the lowest meters above the ground through strong radiative cooling. The temperature gradient measured at the tower between 1.2 and 4 meters above ground is up to 4 K (Fig. 5a), but only the very lowest part of the boundary layer is stably stratified. Already 50 meters above ground, the temperature does not change compared to afternoon values (Fig. 7). The analyzed wind field (Fig. 4b, d, f) shows that at higher levels (925 hPa, about 300 m agl) the wind speed in the free atmosphere remains high after sunset.

Further south, the moist and relatively cool air from the ocean and the coastal region south of the ITD starts to move north. The northward propagation of the humid air starts because the turbulence diminishes rapidly in near-surface levels due to the missing sensible heating. Therefore the flow is able to respond to the pressure gradient force.

The front of cool and humid air reaches Djougou on its way north at 0015 UTC on 11 April 2006. The arrival immediately caused a removal of the shallow temperature inversion (Fig. 5a) and a sudden rise of surface pressure by 1 hPa (not shown). However, the most striking features can be seen when looking on the wind direction which changes from 17° (north) to 172° (south) from one 15 min measurement to the other (Fig. 5b). The temperature and humidity profiles measured by HATPRO reveal a moist and more or less isothermally layered air mass up to 800 meters agl (Fig. 6 and 7) which reveals air from the south replacing the well-mixed dry air. This rather shallow layer has quite a strong effect on the ver-

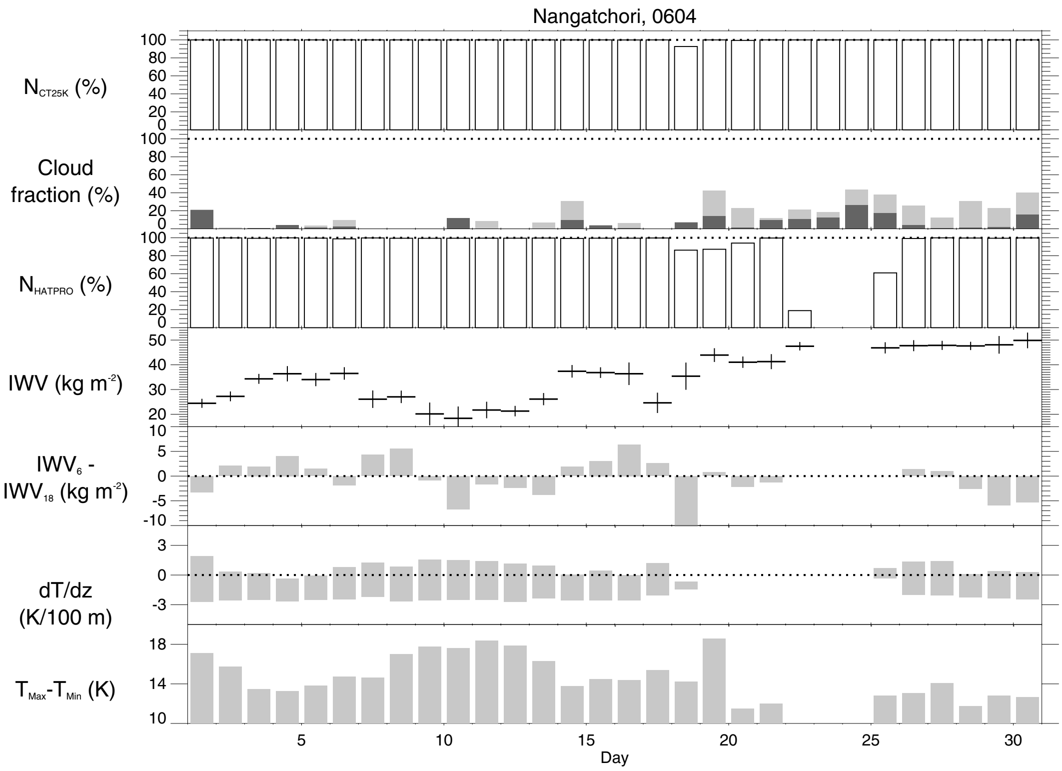

Figure 8: Statistical overview of Nangatchori measurements in April 2006. (a) Data availability of ceilometer measurements per day (in %). (b) Fraction of the day with clouds detected by ceilometer (in %). In black lowest cloud base $<$ 3 km agl. Note: Cloud bases higher than 7 km agl are not detected (e.g. Cirrus clouds) (c) Data availability of HATPRO zenith observations per day (in %). (d) 24-hour mean of IWV plus standard deviation. (e) Difference between IWV at 06 UTC and IWV at 18 UTC. (f) Temperature difference between ground level and 200 m above ground. Bars show extremum values in 24-hour periods. Extremum values are mean of highest and lowest 10 % of measurements (g) Diurnal temperature range measured at the ground.

tically integrated water vapor which rises from 10 to 16 kg m^{-2} within 20 min (Fig. 6). Fig. 3 shows that the air from the south contains more aerosols in the lowest levels. This is probably caused by the stronger winds which raise the dust from the completely dry soil. The meridional extent of this phenomenon cannot be determined exactly because of the lack of data from this region. However, the surface analyses (Fig. 4) allow the conclusion that the northernmost parts of Benin are not influenced by the cycle of the ITD on that day.

Shortly before sunrise, another drop in boundary layer temperature by 2 K at 0500 UTC in connection with a rising IWV value from 17 to 21 kg m^{-2} occurred. Starting around 5 UTC until 8 UTC the passage of wave disturbances can be identified well by the correlated oscillations of the relative humidity (Fig. 6) and the backscatter (Fig. 3). However, the origin of these disturbances remains unknown. About two hours after sunrise the start of convective boundary layer formation can be seen well in the temperature profiles (Fig. 7). It takes until noon until the whole lower troposphere is well-mixed. Humidity profiles show that relative humidity below 1 km above ground reaches the highest values between 0700 and 1000 UTC. Later, the maximum of relative humidity moves higher up. The onset of dry air inflow from the north-east around 1200 UTC removes the moist air in low levels and closes the diurnal cycle. The main features of this cycle are summarized in Tab. 1.

Though being a well-known phenomenon the diurnal cycle of the ITD could be documented through a combination of different instruments with much detail. The time around 10/11 April 2006 was characterized by relatively low IWV values and a rather southern position of the ITD for this time of the year. The MSL pressure gradient on 10 April 2006 12 UTC east of Benin between the heat low at 10°N (Nigeria, Chad) and a surface high pressure over Libya has become larger compared to previous days. This resulted in a strengthening of the northeasterly winds between 10 and 15°N allowing to carry dry Saharian air further south. However, this feature can also be observed in other nights with higher IWV values. The representativeness of this particular day can only be investigated by a long-term statistical analysis, first results are given in Section 4.

4 Statistical analysis of data

While the previous section focused on a one-day case study, we now want to demonstrate the potential of the observations for statistical analysis. As an example we

Table 1: From the Gulf of Guinea to the Sahel.

Time	Coast (6°N)	Djougou (9.7°N)	Sahel (13-15°N)
12–18 UTC	Deep convection, large thundery cells with rain, moist air remains in coastal area	dry convection, deep convective boundary layer water vapor of last night is lifted from the ground to higher levels	Heat low with its center to the northwest of Benin (Mali, northern Ghana, Burkina Faso). Dry and hot northeasterly flow
18–00 UTC	“dying” convective cells, moist air starts to flow northwards	Dry Sahelian air in low levels. Boundary layer remains well-mixed except for the lowest < 100 m with a shallow temperature inversion	Pressure minimum remains over the area. At 00 UTC on 11 April it can be found over northwest Nigeria.
00–06 UTC	Southerly flow	Around midnight a quick jump from dry and warm air (easterly flow) to moist and relatively cool air (south-westerly flow). Stable stratification (dT/dz~0 up to 800 m)	Pressure gradients weaken. Moist air penetrates into southern Sahel. Lowest pressure further north than at dawn.
06–12 UTC	Initiation of convection	Moisture supply from south continues, gradually onset of convection and rising convective boundary layer	Start of heat low formation. Dry air flow from north-east due to stronger pressure gradients

chose the month of April 2006 which encompasses the transition period from dry to wet conditions at Nangatchori. During that month data availability of HATPRO temperature profiles is 83 % with 3169 boundary layer scans performed. This results in one profile every 11.3 minutes when averaging the number of scans over all available periods. Zenith observations providing IWV, LWP and humidity profiles are available for about 85 % of the month. For the ceilometer the data availability is even better with about 99 %. The reason for this difference in the data availability is the failure of the HATPRO instrument to restart after one specific power break which occurred on 22 April (Fig. 8a, c)

The month of April is characterized by largely clear skies, i.e. only in 11.6 % of all measurements clouds below 7 km agl were detected by the ceilometer (Fig. 8b). It has to be noted that clouds higher than this altitude or optical thin cirrus clouds (at altitudes above the freezing level at 4000 m) cannot be detected with this instrument. In the first period from 1–18 April, the cloud fraction was very low, which is typical for the dry season, only towards the end of the month the cloud amount increased, reaching up to 40 % on some days. Clouds below 3000 m (black bars in Fig. 8b) were mainly detected during the second part of the month.

The transition to a wetter climate is even more evident in IWV (Fig. 8d) whose mean value for the whole month is 34.6 kg m^{-2}. Dry air was present in the beginning of the month which was replaced by quite humid conditions towards the end. The lowest 24-hour-mean occurred on 10 April with 18 kg m^{-2}, whereas on 30 April a mean value of 50 kg m^{-2}, i.e. more than a doubling of IWV, could be observed.

Under the dominant clear sky conditions atmospheric stability is expected to show pronounced variations between very stable (nighttime) and unstable (daytime) conditions. Therefore the presence of temperature inversions was investigated using the following definition: For a given profile, at least one level between 50 and 1500 m agl has to show a higher temperature than the lowest retrieved value at the ground. This criterion was met by 883 HATPRO temperature profiles (27.9 %). The maximum inversion strength during this period was 5.6 K/200 m which occurred on 7 April, 2330 UTC. (28.1° C at the ground, 33.7° C in 200 m above ground). This was shortly before the arrival of the moist air flow from the south which reached Nangatchori less than half an hour later. Generally, every night temperature inversions could be observed with highest values very often between 2100 and 0000 UTC. The absence of strong inversions in the early morning hours before sunrise where typically the strongest radiative cooling occurs can be explained by the following mechanism: The presence of dry air before midnight allows together with weak winds a more effective radiative cooling of the near surface air layer. Stronger winds and increased moisture prevent shallow temperature inversions to be formed after the passage of the nocturnal front.

With the nocturnal passage of the ITD, sharp drops in temperature associated with increasing atmospheric humidity were observed in many nights during the transition period. To quantify these jumps, a threshold of a 3 K temperature decrease within one hour at 200 m agl was introduced. With this criterion, between 1 and 18 April, in 16 out of 18 nights this feature could be observed. The highest temperature changes (7.1 K within one hour) were detected in the nights 9/10 and 10/11 April, the mean value of temperature jumps over all 16 nights being 5 K. The mean front arrival was at 2319 UTC, the extremum values are 2034 UTC and 0220 UTC, respectively.

Examining more closely the Figs. 8d, e, f, and g, a five day period of moister conditions (3–7 April) is replaced by drier air masses (8–12 April). The daily mean water vapor content (Fig. 8d) correlates well with observed stability and diurnal temperature range. During the drier periods the vertical temperature gradient and the diurnal temperature range (Figs. 8f and 8g) is more pronounced. The time of arrival of the nocturnal front is also related to the mean daily IWV content. In the period 3–7 April, the mean front passage at Nangatchori was at 2200 UTC, whereas from 8-12 April the front arrived at 0020 UTC (not shown). One can assume that the ITD position in the evening was further south during the drier period, causing a later arrival of the front in Nangatchori. Fig. 8e gives another interesting result: In the moister period, at 18 UTC the IWV content was mostly higher than at 06 UTC whereas on the drier days, this diurnal variation is reversed. If daytime dry air inflow occurs IWV values at 18 UTC are lower than at 06 UTC. In contrast, if humid air is prevalent the IWV values tend to be higher in the evening due to daytime evaporation and possibly further advection of moist air from the south. It can be seen that the case study from 10/11 April in section 3 corresponds to the driest phase of the month. It should be noted that on moister days in the study period the low-level inflow of dry air (as seen in Fig. 6) is not as strong as on 10/11 April or even completely missing. The southward propagation of the dry air depends on the position of the ITD.

5 Conclusions and outlook

A first investigation of the comprehensive boundary layer observations conducted in West Africa during the AMMA campaign in 2006 has been performed. The diurnal cycle of the ITD in the transition period between dry and wet season over Nangatchori (Benin) has been analyzed in detail using a combination of ground-based remote sensing instruments operating at high temporal resolution. This diurnal cycle of the inter-tropical discontinuity (or front) can be summarized as a moisture transport mechanism in northern direction which comprises the following features: As soon as the atmospheric boundary layer stabilizes after sunset the humid (and comparatively cold) air to the south of the ITD starts moving north due to the pressure gradient over the area (which is caused by the previous day's heat low). In the course of the night this gradient weakens and the southerly winds calm down towards sunrise. With increasing solar heating convection is initiated and the moisture which was carried north during the night is lifted to higher levels. Around noon, the heat low starts deepening again and the dry air inflow from the north resumes.

The microwave profiler HATPRO turns out to be an excellent means to determine boundary layer temperature profiles as well as humidity measurements. In the future we will further improve HATPRO's retrieval products. Following CREWELL and LÖHNERT (in press) composite temperature profiles from boundary layer scans and zenith observations will be derived. These composite profiles will combine the advantages of both observation modes and give a consistent temperature profile from 50 m above ground to the upper troposphere. No significant differences are to be expected in the lowest kilometer which is dominated by the boundary layer scans and above 2 km where all information stems from zenith observations.

Because of limited information available on the atmospheric state over Africa the statistical retrieval algorithms used in this study rely on tropical observations in Australia. The enhancement of the radiosonde network in Africa as part of AMMA will enable us to further improve the retrievals. However, it should be noted that the expected improvement will be of minor nature and no significant changes to the results presented here are expected.

Further analysis will be done in particular for the wet seasons, to describe in detail the evolution of meteorological parameters in association with squall lines and thunderstorms. Additional information of vertical wind distribution will be obtained by including data from an UHF wind profiler which has operated in Nangatchori since May 2006. Whether the sea-breeze circulation or the outflow of large convective cells in the coastal area has an influence on the strength of the southerly low-level jet cannot be determined by only looking on measurements at one location. Therefore, future work will comprise gathering all available observations for 2006 and look for related phenomena at other places. This is planned especially for Niamey, Niger (13.5°N) where the diurnal cycle of the ITD is likely to happen later in the season. A large set of atmospheric remote sensing instruments was deployed in 2006 at the Atmospheric Radiation Measurement (ARM) mobile facility of the US Department of Energy in Niamey including similar instruments to those used for this study.

The comprehensive data set over a full year cycle will enable us to investigate atmospheric processes via detailed case studies but also on a statistical basis. Both approaches can also be used to evaluate the performance of atmospheric models in a data sparse region. While case studies might be more suitable to analyze whether mesoscale models are able to reproduce the small-scale variabilities observed, the statistical analysis enables a long-term evaluation of global weather forecast models.

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