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"Dynamics-aerosol-chemistry-cloud interactions in West Africa"

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D1.3 Detailed case studies

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1 Introduction

The major goals of DACCIWA project, an integrated study of boundary layer dynamics in the southern west Africa (SWA), were (a) to assess all relevant physical and chemical processes, (b) to improve the monitoring of climate and compositional parameters from space and (c) to develop the next generation of weather and climate models capable of representing coupled cloud-aerosol interactions, which will ultimately lead to reduced uncertainties in climate predictions (Knippertz et al., 2015). As part of the Work packages (WPs) to be undertaken within the DACCIWA project, an aspect is to report significant case studies (deliverable D1.3) arising from the following manifestations of the boundary layer: very persistent stratus decks, cloud free nights, strong low-level jets (LLJs), precipitation events, strong sea-breeze and convergence.

The cases were focussed on the field observations made in the Work package #1 (WP1) at the three supersites, Savè Benin ($8^0$00'03.6" N, $2^0$25'41.1" E, 166 m a.g.l.), Kumasi, Ghana ($6^0$40'48.6" N, $1^0$33'37.8" W, 266 m a.g.l.) and Ile-Ife, Nigeria ($7^0$33'11.5" N, $4^0$33'26.7" E, 274 m a.g.l.), particularly, data acquired within the designated Intensive Observation Periods (IOPs). The days selected for IOPs were based on the forecasts of advection of maritime air mass into the land areas. Fifteen (15) cases within the months of June and July, 2016 were studied. Concerted efforts were made to synchronise simultaneous measurements of the surface meteorological parameters, radiosonde (or tethersonde), ceilometer, cloud radar and sodar at the three sites, depending on available instrumentation (Kalthoff et al., 2018).

In this report, occurrences of the low-level clouds (LLCs) and LLJs within the boundary layer, and the impact of LLC on the surface energy budgets at the three supersites, together with monsoonal rainfall events that occurred during the DACCIWA campaign, particularly during the IOPs, have been discussed in detail below.

2 Investigations of Boundary Layer Dynamics and Low-Level Clouds during IOPs at DACCIWA Supersites; Kumasi, Savè and Ile-Ife

2.1 Characteristics of LLC and LLJ at Savè.

The relation between LLC and boundary layer conditions and the processes leading to LLC formation are investigated at Savè for 11 IOP nights, during which LLC are present. Based on ceilometer measurements and cloud radar data, the LLC characteristics (base, top, onset time, spatial extent and evolution) vary considerably (see Fig. 1). The average cloud base height is 250±120 m above ground level (a.g.l.) and the cloud top height 590±170 m a.g.l. The onset time estimated as the time when 60-min cloud-base fraction exceeded 95% ranges from 22:00 UTC until 04:45 UTC. The spatial distribution and evolution of LLC is studied from satellite images for night when no mid- or high-level clouds mask the LLC. During the four (4) available nights, the LLC showed large differences in respect to the location of first formation and to direction of subsequent growths. As the LLC grow towards the upstream side (i.e. towards the south-west), advection of LLC with the mean wind can be excluded as a mechanism for LLC growth.

In order to understand why LLC form, the relative humidity (RH) tendency and the contributions by moisture and temperature changes are studied between late afternoon and the formation of LLC. As nearly 100 % of the RH change is caused by cooling (Fig. 2, left). The different terms of the heat budget are investigated in detail (Fig. 2, right). Above 250 m a.g.l. horizontal cold air advection and cooling due to radiative flux divergence are responsible for the observed cooling at Savè. There is evidence that some of the cooling below this level can be adduced to sensible heat flux convergence that is attributed to shear-generated turbulent mixing below the LLJ axis.

Based on the dynamic and thermodynamic conditions, three phases can be identified during the nights. Mean profiles of thermodynamic properties in the boundary layer for the different phases normalized with the mean cloud-base height for each night are shown in Fig. 3. The stable phase forms just after sunset and is characterized by a surface inversion. With the arrival of the Atlantic inflow (cool maritime air mass) from the coast, an LLJ establishes (jet phase) and shear generated mixing and differential cold air advection destabilizes the nocturnal boundary layer and erodes the surface inversion. Once LLC exist at the site (stratus phase), the static stability in the sub-cloud layer and also in the clouds decreases and the LLJ axis shifts upwards compared to the jet phase.

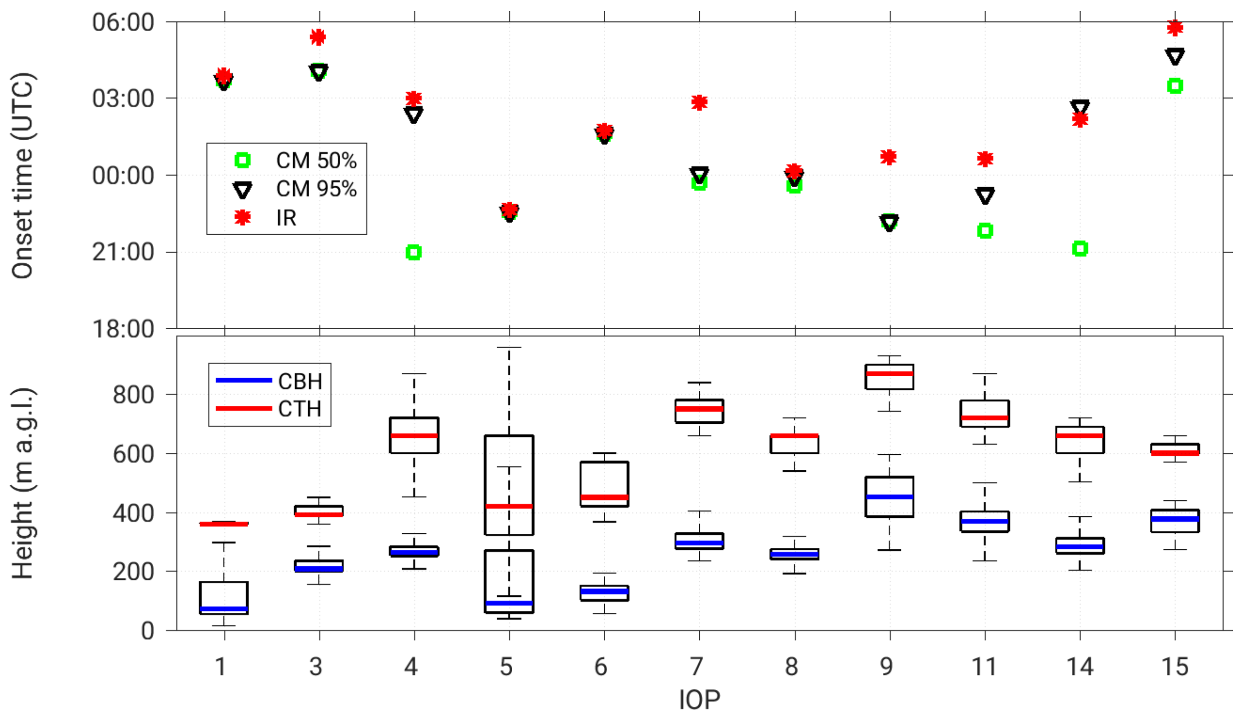

Figure 1: Onset time of LLC estimated from ceilometer cloud-base fraction using thresholds of 50 and 95 % and from infrared camera images (top), and cloud-base height (CBH) and cloud-top height (CTH) for the time period between the onset of LLC using 95 % threshold and 0700 UTC (bottom). The blue and red bars indicate median CBH and CTH, respectively, the top and bottom edges of the boxes indicate the 75th and 25th percentiles and the whiskers extreme values.

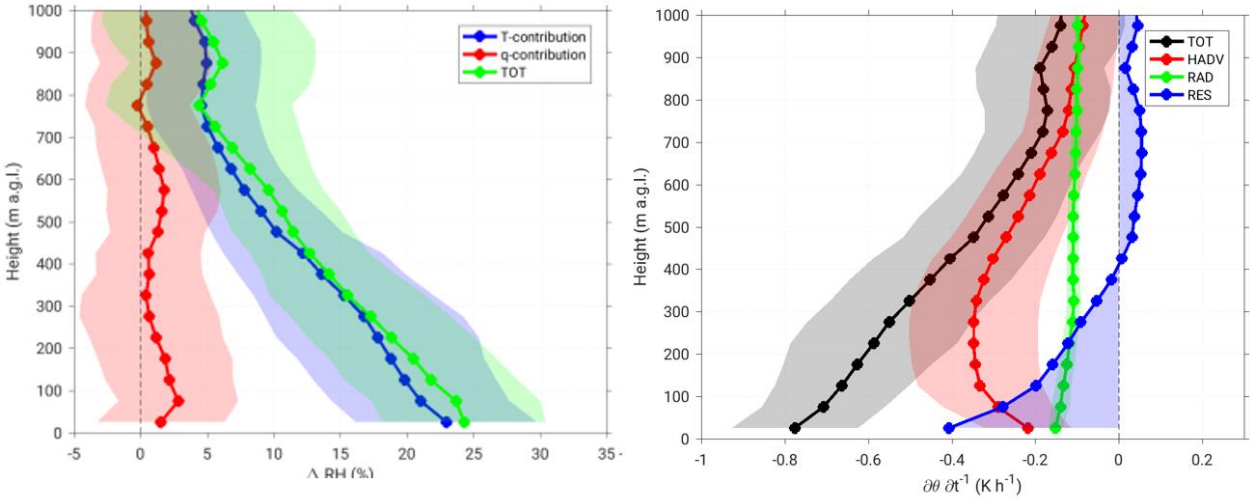

Figure 2: Mean profiles of relative humidity tendency and contributions by temperature and humidity change (left). Mean profiles of temperature tendency (TOT) and contributions by horizontal advection (HADV), radiative flux divergence (RAD) and residuum (RES) (right).

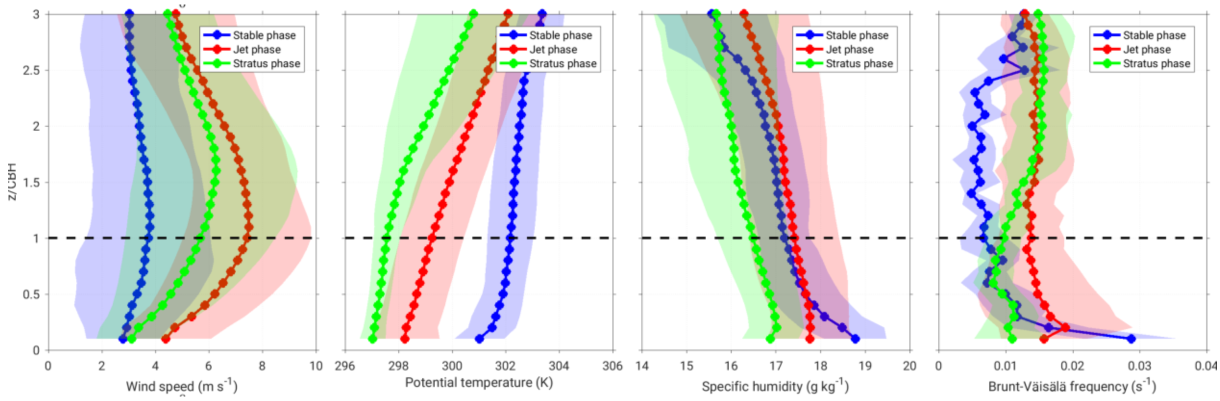

Figure 3: Mean profiles of horizontal wind speed, potential temperature, specific humidity and Brunt-Väisälä frequency during stable, jet and stratus phases. The profiles are averaged with the mean cloud-base height during individual IOPs.

2.2 Case Study (7 - 8 July 2016): The Diurnal Cycle of LLC and LLJ at Savè Supersite

Investigation of atmospheric conditions during IOP 8 (7 - 8 July 2016) was undertaken by inspecting the horizontal wind field (Fig. 4). During the afternoon and early evening, a moderate westerly and southwesterly flow of 3 m s-1 prevailed in the boundary layer. The onset of LLJ is observed at 20:30 UTC, with an abrupt increase of wind speed up to a maximum of 8 m s-1, at a height of 275 m a.g.l. The height of the LLJ maximum corresponds to the height at which LLC form roughly 3.5 h later. Once the clouds have formed, the jet axis shifted upwards to the height of around 450 m a.g.l. reaching the maximum speed of 10 m s-1. Weakening of the LLJ is seen after 04:00 UTC and the axis is lifted to around 600-700 m a.g.l. The period between the onset of LLJ and the formation of LLC is characterized with the strongest decrease of temperature. After the continuous stratus deck has formed around 02:30 UTC, the temperature was roughly constant below the cloud base as well as within the cloud layer.

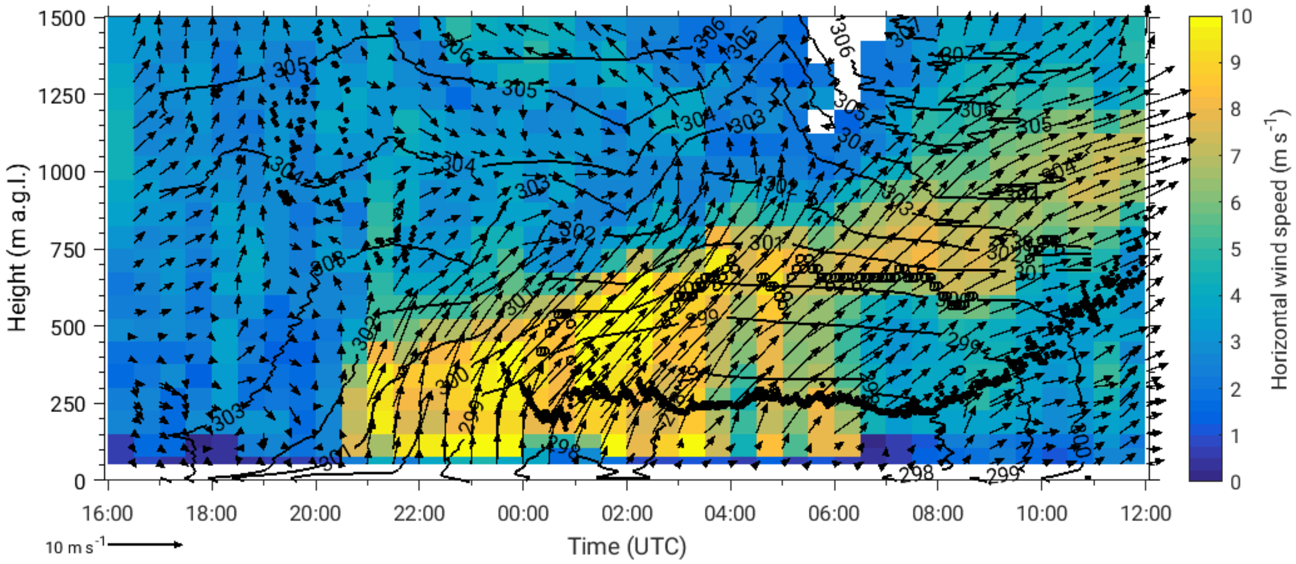

Figure 4: Temporal evolution of the wind speed is shown in color, while arrows show wind direction obtained from UHF profiler. Black contours show linearly interpolated potential temperature measured every 1.5 h by radiosondes. The black dots show CBH and cloud top height (CTH) is shown with black circles.

A drop of temperature by 3 degrees was observed in the period between 20:00 and 00:00 UTC (Fig. 4), while simultaneously RH increases by 10 % in the layer below 700 m (Fig. 5). The onset period of LLJ was associated with an increase of moisture, after which specific humidity starts to decrease. Due to the observed varying atmospheric conditions, the investigated period can be divided into five different phases. The first phase identified is the period between the sunset and the onset of the LLJ, and this phase is denoted as stable phase. This phase is followed by the jet phase, a time period between the onset time of LLJ and the formation of LLC. The period of roughly 2.5 h after LLC formation is identified as the transition phase, since non-stationary atmospheric conditions were observed. This is followed by a stratus phase, which corresponds to the period between 02:30 and 06:30 UTC, with a persistent stratus deck and almost constant atmospheric conditions. The final convective phase is associated with growing convective boundary layer (CBL) and is characterized with lifting of the cloud base, increased surface heating and consequently increased vertical mixing.

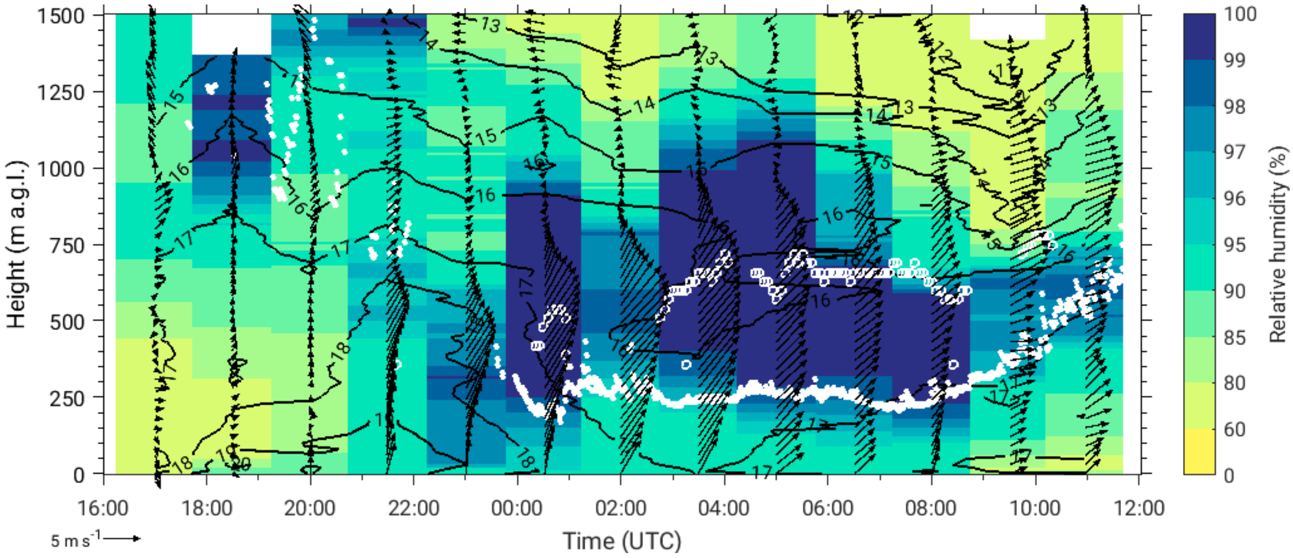

Figure 5: Temporal evolution of relative humidity (color) and specific humidity in g kg^{-1} (black isolines) in the lowest 1.5 km obtained from radiosonde profiles performed every 1.5 h. The arrows show the horizontal wind vector from radiosondes. The CBH is indicated with white dots and the CTH with open white circles.

In order to quantify whether the specific humidity (q) or temperature (T) change has a stronger influence on the RH tendency and consequently on LLC formation, we determined their respective contributions using consecutive radiosonde measurements. In Fig. 6, the term (I) is the observed RH tendency, term (II) represents the contribution from q change and term (III) is the contribution from T change. During the early evening, in the stable phase, RH increases in the layer below 350 m, with the maximum of about 4 % per hour (Fig. 6a). Above this level up to roughly 700 m, RH is almost constant, while above 700 m, RH decreases. The decrease in the value of the temperature is mostly responsible for the increase of RH below 350 m, while on average there is a small positive moisture contribution. The median wind speed profile in this phase is less than 3 m s^{-1} in the lowest 1 km. During the next phase, the layer with significant increase of RH deepens to about 700 m a.g.l., with the maximum rate of 6 % per hour (Fig. 6b). The main bulk of this change is caused by cooling, while moisture change is negligible during the jet phase. The layer of the maximum change corresponds to the level of the LLJ axis. During the transition phase, which is characterized with almost no change of RH within the cloud layer, while below the cloud base a small decrease of RH of -1 % per hour is recorded. In stratus phase, a small positive RH tendency exists below the LLJ axis (about 0.5 % per hour), mostly due to positive q tendency. In the convective phase, the temperature continues to increase below 700 m, and has a stronger contribution to negative RH tendency, while specific humidity tendency is small.

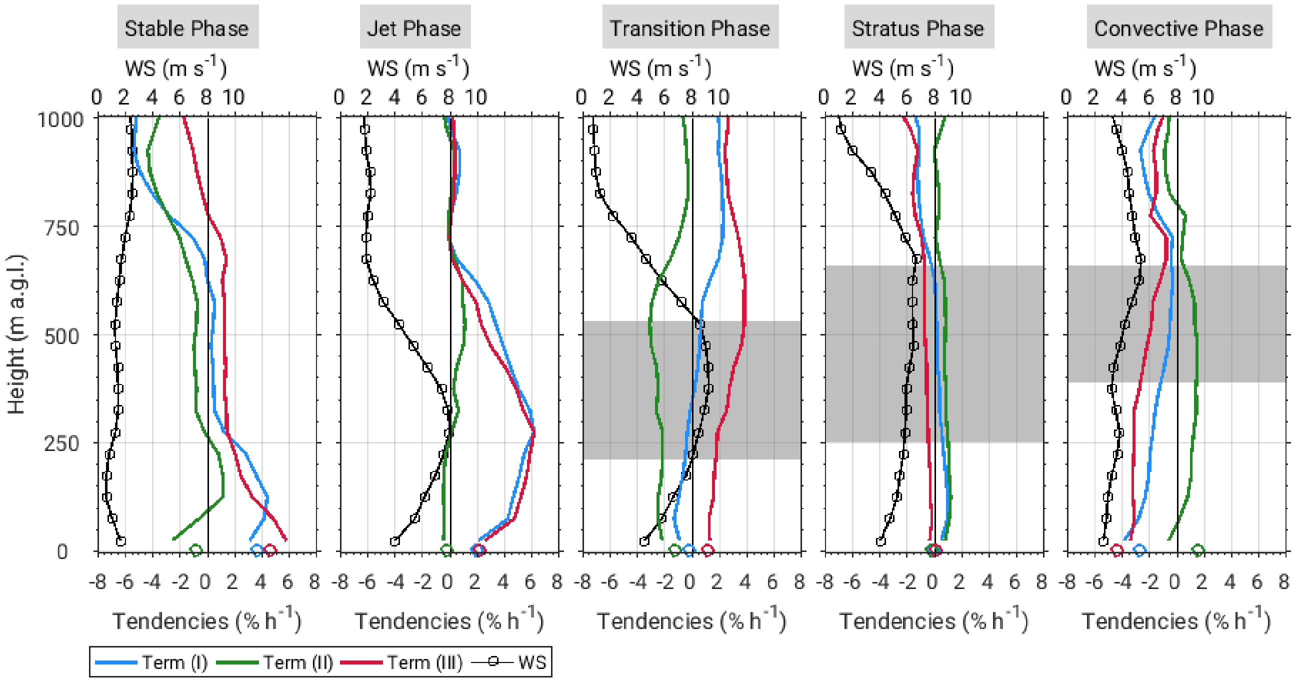

Figure 6: The observed RH tendency profiles obtained from radiosonde measurements for different phases during IOP 8 is shown in blue, while contributions from the temperature change term and specific humidity term are shown in red and green color, respectively. The circles show values of different terms of RH tendency obtained from surface measurements. The black circles denote the median horizontal wind profile for each phase. Shaded gray areas denote the mean cloud layer.

2.3 Observational study of occurrences of LLJ and LLC at Savè Supersite

Observational study of the low-level atmospheric dynamics and LLC (stratus/stratocumulus) over the Southern West Africa in the framework of the DACCIWA project is done using in-situ and remote sensing measurements at Savè in Benin from 20 June to 30 July 2016. The characteristics of the LLCs are analyzed using data from a ceilometer, an infrared cloud camera and a cloud radar: onset, evolution and dissipation time, base height and thickness. The ultra-high frequency (UHF) wind profiler and energy balance station data were used to estimate the characteristics of the LLJ as well as the monsoon flow depth and strength. The microwave radiometer is also used to investigate the lower troposphere thermodynamic conditions.

Based on 41 nights of observations, the thickness of the monsoon flow is on average 2 km and the strength varies between 2 m s^{-1} in the afternoon and 4 m s^{-1} at night with the occurrence of the LLJ. Except during rain events, LLJ forms every night at Savè between late afternoon and sunrise (Fig. 7). It is associated with 65% LLC occurrence. Characteristics of the LLJ and LLC show a strong variability from day-to-day. They both indicate significant variability of their onset and breakup time (Fig. 7). Figure 8 shows that LLCs form at the jet core height about 3 hours after onset of the latter. The cloud base height decreases during night and remains below the jet core. The cloud top height is observed above the jet core. Furthermore, LLC reduced the strength of the jet by turbulence mixing within.

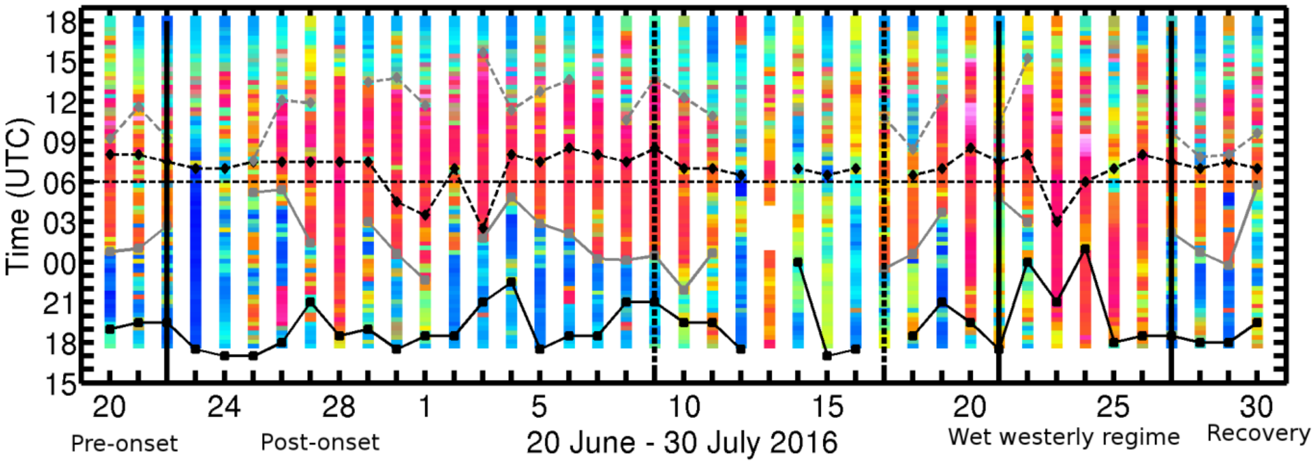

Figure 7: Time series of the onset (dot lines) and breakup time (dashed lines) of LLJ and LLC respectively in black and gray. In color, temporal evolution (from 18:00 UTC the day before to 18:00 the current day) of the mean color of the infrared cloud camera image.

A large occurrence of density currents is observed during the study period. These phenomena contributed to the cooling of the lowest atmosphere before the LLJ onset. Figure 9b shows a sudden cooling of the lowest atmospheric layer at the arrival of Atlantic inflow or the LLJ onset. This means that these two phenomena are associated with an advection of cold air coming from the coast or vertical transport of surface radiative cooling (Figure 9a) by turbulence.

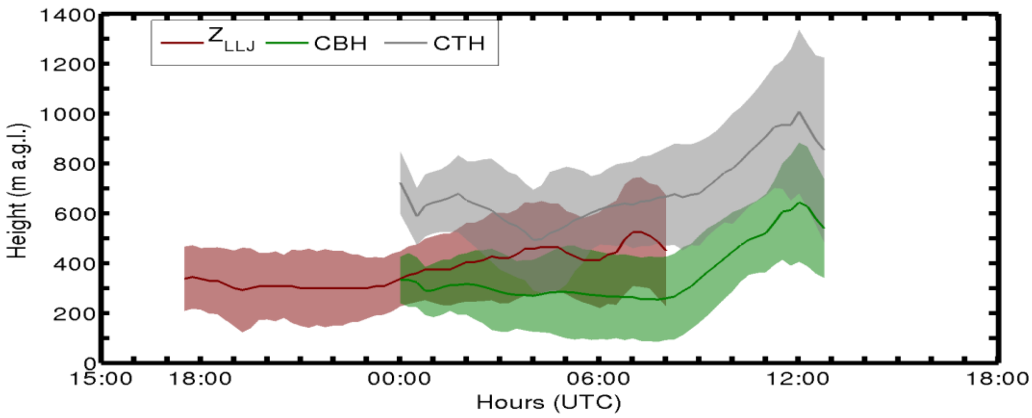

Figure 8: Diurnal cycle of the median of the low-level jet (LLJ) core height, cloud base height (CBH) and cloud top height (CTH). All the time, the median is computed using at least four values. Shaded areas indicate the variability. The LLJ core heights are estimated from the UHF wind profiler, CBHs from the Ceilometer and CTHs from the cloud radar.

Based on the Richardson number, turbulent kinetic energy and surface stability parameter, we classified all nights in terms of the main processes associated with the LLJ. The results show a large number of nights in which LLC is sustained by advection of cold air from the sea due to prominence of LLJ.

This study also gives a quantification of the characteristics of both Monsoon flow, LLJ and LLC, which is important for numerical weather and climate models.

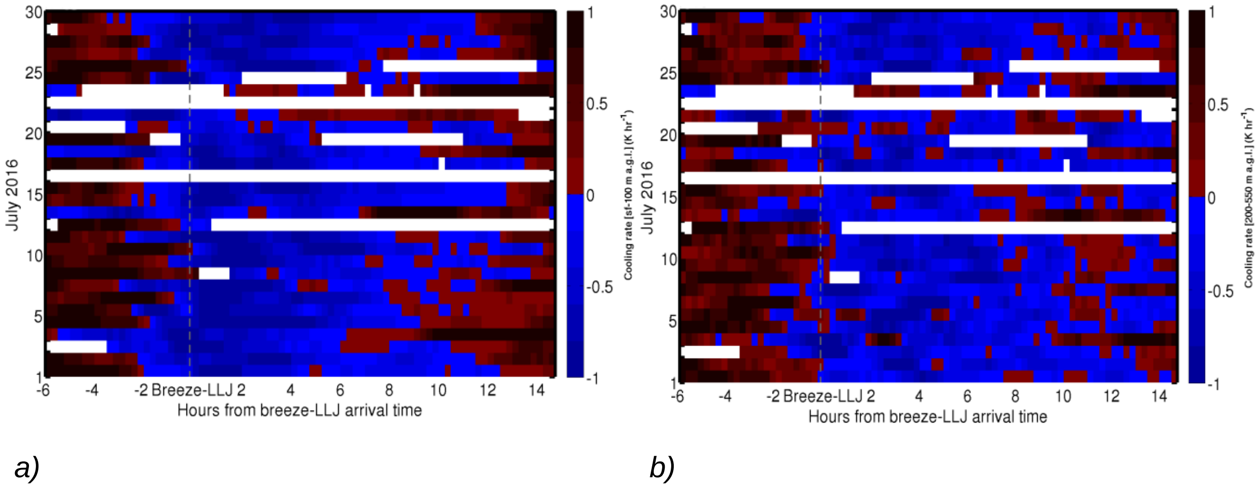

Figure 9: Time series of the temperature tendency in the lowest layers: a) in the layer up to 100 m and b) in the layer 200 - 550 m. The abscissa are centered at the arrival of the Atlantic inflow or LLJ at Savè.

2.4 Observations of nocturnal LLJ and surface energy budget at Ile-Ife (OAU) Supersite.

At Ile-Ife supersite observations of LLJs in the boundary layer have been discussed with occurrences of the LLCs and monsoonal rainfall events during the DACCIWA campaign, particularly for the IOPs. The combined influences of LLCs and rainfall on the surface energy budgets were presented as case studies at the supersite. At the project location, there were no instrumentations available for direct measurements of cloud structure and genera such as, cloud-base-height, cloud-top-height, onset time and spatial extent. The cloud base temperature was determined simply by the use of a hand-held infrared thermometer. Only visual identification of the cloud type and amount were made. Additionally, the cloud amount during the daytime period was determined using a scheme proposed by Jegede et al. (2006). The cloud base height was estimated from tethered radiosonde data. A METEK acoustic sounder was deployed to obtain 10-min averaged profiles of the boundary layer winds (probing heights up to 510 m) to determine occurrences of LLJs. To measure surface energy fluxes (net radiation, soil heat, sensible and latent heat) at the location, an eddy covariance system together with a four-component net radiometer and soil heat flux plate were set up. The measurement complex was continuously maintained in operation throughout period of the DACCIWA campaign (June and July 2016).

We have presented two case studies (June 15 and 27, 2016) during the DACCIWA campaign at the supersite in Ile-Ife detailing the prevailing boundary layer conditions (winds and cloudiness) and thermodynamic structure. On both days considerable amount of low-level clouds were manifest and correspondingly, lowering of daytime values for surface energy fluxes was observed.

In the first case study that is, June 15, it can be observed just after the sunrise that low-level cumulus clouds begin to form in the boundary layer at Ile-Ife. This is a result of considerable evaporation from the wet surfaces after precipitation event of the previous day. The sodar echogram of the horizontal wind speed profile is shown in the topmost panel (Fig. 10a). The blank areas shown in the plot represent missing data when sodar echo returns fail plausibility tests. The red circled area is indicative of wind speed maximum (above 10 m/s) around 350 m height a.g.l. The high wind speed noticed at about 16:00 UTC is indicative of a gust front of a Mesoscale convective system (MCS) passing Ile-Ife. The duration of jet was sustained until about 22:00 UTC on the same day. At about midday, low-level clouds aggregate in amounts ranging between 70 % and 85 %, which developed into stratocumulus in the late afternoon. The considerable cloudiness (low-level) on this particular day shown in Fig. 10(b) was responsible for the relatively low values of net radiation (< 350 Wm^{-2}) recorded during the afternoon. Heavy precipitation at the location began at about 15:00 UTC and continued steadily until the evening, around 20:30 UTC. The rainfall amount recorded within that period of five and a half hours was 89.15 mm. The time of commencement of rainstorm at the location coincided with arrival of the MCS observed. The surface energy budget plotted in Fig. 10(c) showed partitioning of the available energy as 60 % and 40 % for latent and sensible heat respectively (Bowen ratio, 0.4 – 0.6) in the daytime. The turbulent fluxes flattened out to negligible values as the rain water quenched surface heating in the late afternoons.

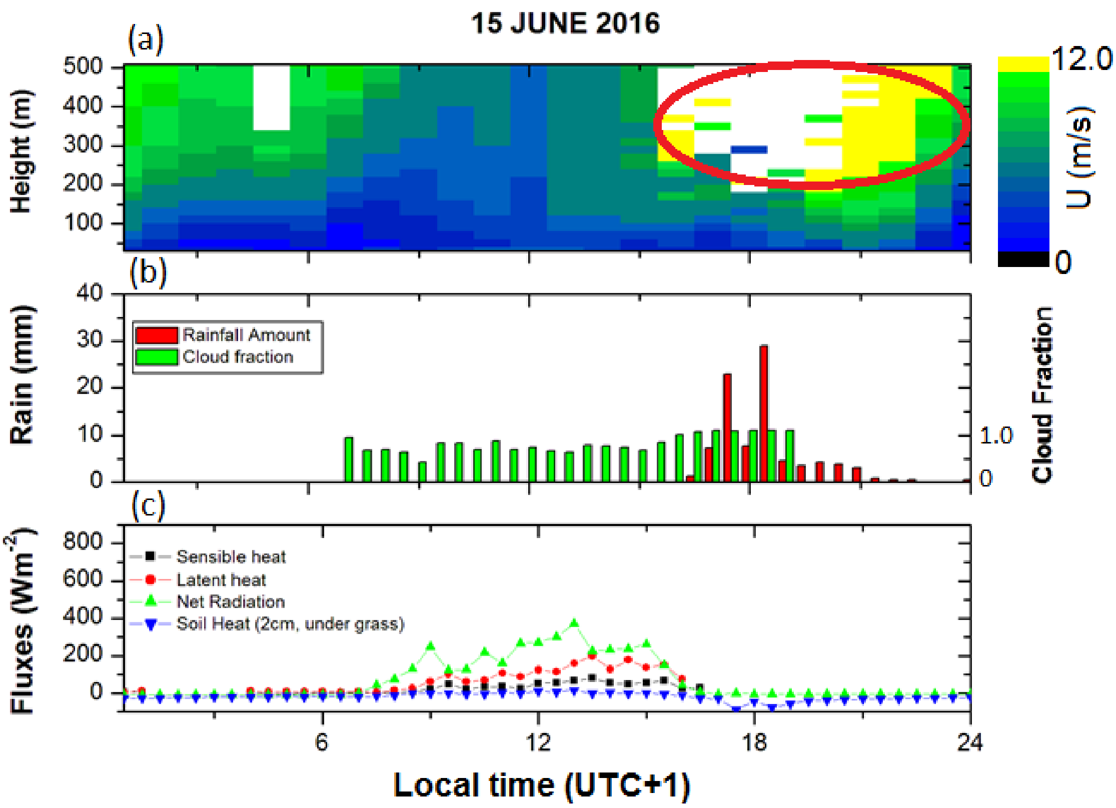

Figure 10: Observations of (a) low-levels winds, (b) cloudiness and rainfall amount, and (c). surface energy fluxes in the boundary layer at OAU Supersite on June 15, 2016.

For the second case study, which was 27 June, 2016, the wind field obtained from the sodar echogram (Fig. 11 (a)), indicated occurrence of a LLJ which was in the early morning at 02:00 UTC. The jet axis was located about 400 height a.g.l. Another wind maximum (indicated by the circled areas in red in the Fig.11(a)) was observed 19:00 UTC at about 360 m a.g.l. The clouds in the boundary layer which formed as a result of early morning convective activities broke up at about 13:00 UTC (Fig. 11(b)). The reduction in cloud amount is attributed to the drier air coming from the northeasterly flow. The clouds thereby were dissipated allowing considerable heating to occur at the surface. The net radiation thus increased considerably reaching up to 600 Wm^{-2} at about 13:00 UTC and consequently, the convective heat fluxes on this day. Later on, as the moist southwesterly flow returned, the cloud amounts increased to about 85 %, thus shutting off the surface heating by incoming solar radiation and the net radiation values dropped to about 220 Wm^{-2} (Fig. 11(c)). Attendant to the diminished convective heating at the surface, there was a rainstorm at about 15:30 UTC which was associated with increased wind speed observed in the boundary layer. This was found to match the appearance of a wind maximum (see Fig. 11(a)). There was quenching of surface heating by the rain-shower beginning 16:00 UTC. Correspondingly, the surface fluxes fell sharply to negligible values (< 10 Wm^{-2}).

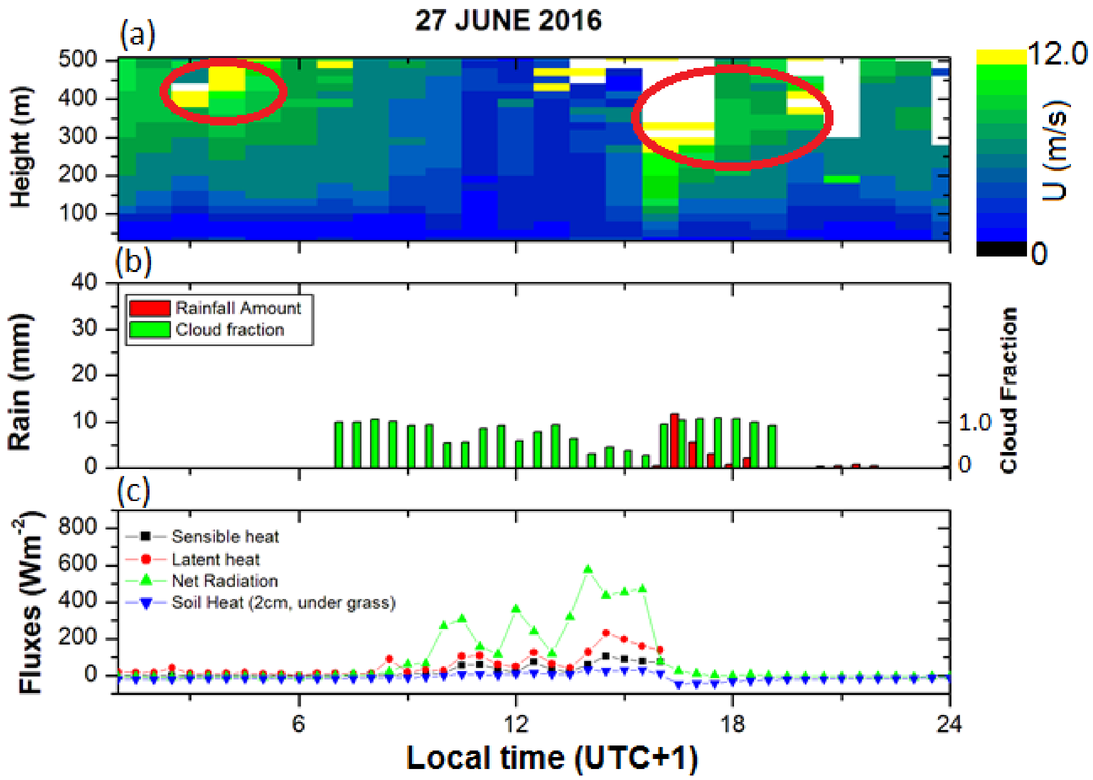

Figure 11: Observations of (a) low-levels winds, (b) cloudiness and rainfall amount, and (c). surface energy fluxes in the boundary layer at OAU Supersite on June 27, 2016.

2.5 Rainfall patterns over Ghana on IOP days from network of observing stations

As part of the DACCIWA field campaign, a network of optical rain gauges was deployed in the Ashanti Region of Ghana. These optical gauges were situated at varying distances from the Kumasi supersite to assess the spatio-temporal distribution of rainfall, particularly in the study domain. These optical gauges also served a secondary purpose of augmenting pre-existing rain gauge network of the Ghana Meteorological Agency (GMet), which have daily time resolution. Contrarily, the optical rain gauge has a temporal resolution of 1 minute and therefore allows for sub-daily rainfall assessments. Here, the GMet rain gauge network over the country, coupled with the DACCIWA optical gauges, were used to provide information on the spatial rainfall patterns over the entire country for the months of June - July 2016, as shown in the Figure 12, which encompass the DACCIWA field campaign period.

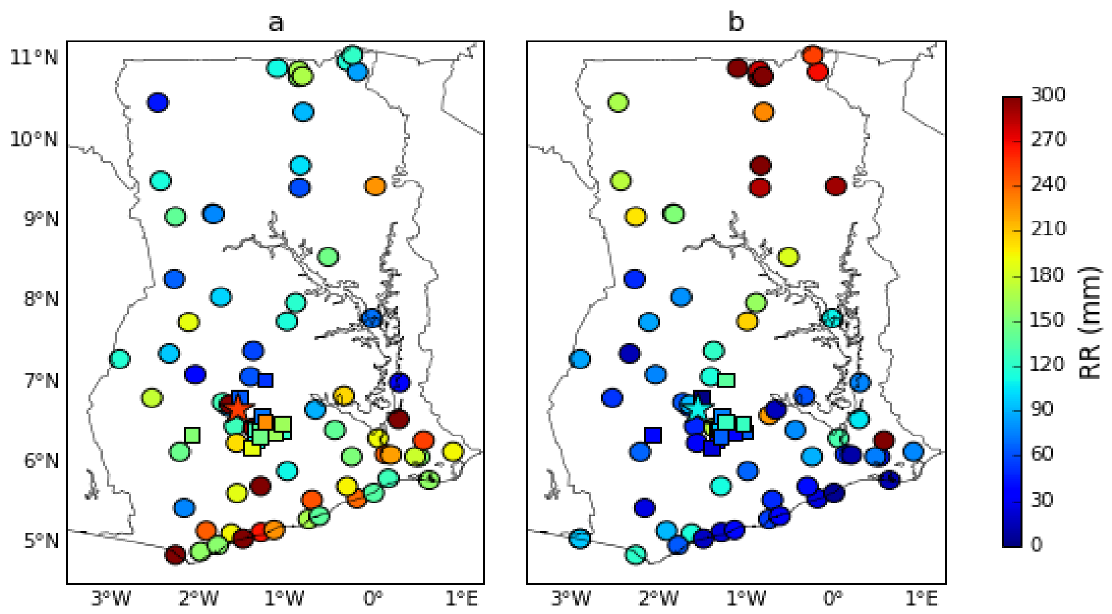

Figure 12: Spatial distribution of monthly accumulated rainfall over Ghana for (a) June and (b) July 2016. The circles represent GMet rain gauge network over the country, the squares represent the DACCIWA optical rain gauge network and the star denotes the AWS rain gauge deployed at the supersite.

A general observation made is the dominance of the tropical rainbelt in the lower half of the country, especially, the southern to south-western portions of the country in June. These rainbelts, migrated further northwards to higher latitudes (particularly, north-eastern parts of the country) in the month of July, are attributable to the ascent of the Inter-Tropical Convergence Zone (ITCZ) - which is linked with convective activities over the regions that it traverses or the regions that lie in its vicinity. Monthly values of rainfall totals ranged between 25 mm and 300 mm. Furthermore, the optical gauges from the DACCIWA gauge network and the Automated Weather Station (AWS) rain gauge mounted at the Kumasi supersite were used to assess temporal patterns of rainfall over the study domain. As shown in Figure 13, the rainfall events were generally convective, occurring mostly beyond peak net radiation hours, precisely from 1500 UTC to 2300 UTC. These convective rainfall patterns are observed in all the DACCIWA gauge network stations and the supersite as well.

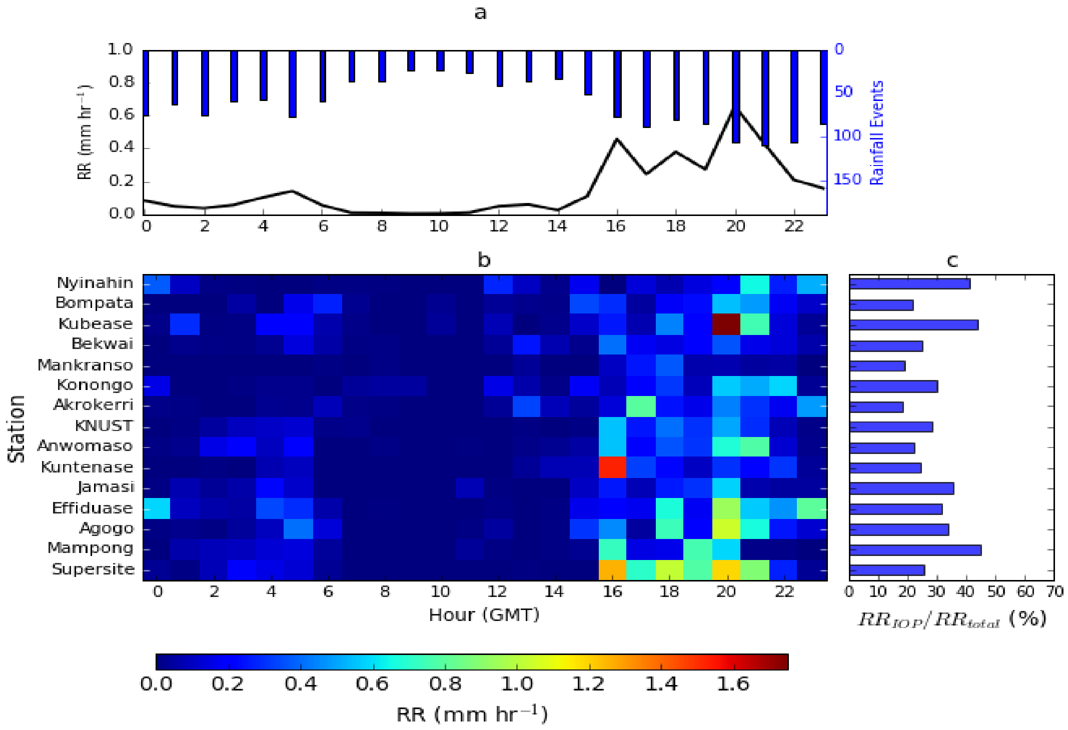

Figure 13: Diurnal profiles of average rain rate from **(a)** all the gauge network and **(b)** individual gauge station, deployed during the DACCIWA field campaign. The proportions of accumulated rainfall on IOP days to the entire June-July 2016 period (expressed in %) is shown in (**c**).

As a measure of the contribution of rains on IOP days to the total rainfall for the June - July 2016 period, the ratio of rainfall accumulated on IOPs to the rainfall accumulated within the two months were expressed in percentages, as shown in Figure 13c. In general, the contributions of rains on IOP days were less than half of the accumulated rainfall within the June - July 2016 period.

3 Conclusions

The boundary layer data acquired from the three supersites; Kumasi, Savè and Ile-Ife, have been used copiously in this study to extend understanding of processes responsible for occurrences of LLC and LLJ in SWA. Five stages of LLC development can be identified: stable, jet, transition, stratus and convective, which accompany LLJ formation at the same height, roughly 350 m a.g.l. some 3 hours later. It turned out that nearly 100 % of the RH increase, finally resulting in LLC formation, is caused by cooling. The main process contributing to cooling is cold air advection accompanied with the arrival of the Atlantic inflow.

As a case study, spatial rainfall patterns over Ghana captured the northward migration of the tropical rainbelt. Within the observation period (June – July, 2016), more rains was recorded in the southern half of the country in June. A shift of rainbelt was observed in the northern areas for July. The north-eastern part of the country received more rains in July. Also, rainfall was observed to be typically convective over the spatial domain of the DACCIWA rain gauge network, with major events occurring between 1500 GMT and 2300 GMT. Moreover, the contributions of rains on IOP days to the rainfall accumulations for the two-month observation period were below 50 %. Detailed discussions on the precipitation processes over Ghana have been provided in the DACCIWA Work Package 6 (WP6). The combined influences of LLCs and rainfall on the surface energy budgets were also established.

4 References

Jegede, O. O., E. O. Ogolo and T. O. Aregbesola, 2006. Estimating net radiation using routine meteorological data at a tropical location in Nigeria. *International Journal of Sustainable Energy*, 25, 107 - 115.

Kalthoff, N.; Lohou, F.; Brooks, B.; Jegede, G.; Adler, B.; Babić, K.; Dione, C.; Ajao, A.; Amekudzi, L. K.; Aryee, J. N. A.; Ayoola, M.; Bessardon, G.; Danuor, S. K.; Handwerker, J.; Kohler, M.; Lothon, M.; Pedruzo-Bagazgoitia, X.; Smith, V.; Sunmonu, L.; Wieser, A.; Fink, A. H.; Knippertz, P., 2018. An overview of the diurnal cycle of the atmospheric boundary layer during the West African monsoon season: Results from the 2016 observational campaign. *Atmospheric Chemistry and Physics*, 18, 2913 - 2928. doi:10.5194/acp-18-2913-2018.

Knippertz, Peter., Hugh Coe, Christine Chiu, Mat J Evans, Andreas H Fink, Norbert Kalthoff, Catherine Liousse, Celine Mari, Richard Allan, Barbara Brooks, Sylvester Danour, Cyrille Flamant, Oluwagbemiga O Jegede, Fabienne Lohou, John H Marsham. The DACCIWA project: dynamics-aerosol-chemistry-cloud interactions in West Africa, *Bulletin of the American Meteorological Society*, 96, 1451 - 1460. doi:10.1175/BAMS-D-14-00108.1