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DACCIWA

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

Deliverable

D6.4 Precipitation case studies

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PP	Restricted to other programme participants (including the Commission Services)	
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R	Report	**x**
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Authors

Author	Beneficiary Short Name	E-Mail
Jean-Pierre Chaboureau	UPS	jean-pierre.chaboureau@aero.obs-mip.fr
Irene Reinares Martinez	UPS	irene.reinares@aero.obs-mip.fr
Andreas H. Fink	KIT	andreas.fink@kit.edu
Marlon Maranan	KIT	marlon.maranan@kit.edu

Changes with respect to the DoW

Issue	Comments
72-hour integrations with the WRF model have been conducted for the 2016 monsoon season. However, a strong drift in coastal SSTs was observed after the finalization of the runs. The error turned out to be severe such that the analysis of the WRF output had finally to be discontinued.	Efforts were undertaken to identify the cause of the drift, but it was not obvious.

Dissemination and uptake

Target group addressed	Project internal / external
Scientific community/Operational weather services	Internal and external

Document Control

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V0.1	24.10.2018	Template with basic structure
V0.2	29.11.2018	Version including KIT input to be approved by the General Assembly
V1.0	18.12.2018	Version including final correction approved by the General Assebly

Table of Contents

1 Introduction

Understanding the dynamical and physical processes responsible for rainfall is the main objective of this deliverable. One specific focus was on the processes that control the development of warm rain. It was planned to make some case studies of precipitation systems that occurred during the DACCIWA field campaign and to use a combination of observations and modelling

A first step has been to look into all the rainfall events that occurred during the DACCIWA aircraft campaign (Flamant et al. 2018) from 29 June to 14 July 2016. Each day, a 24-h simulation was performed with the Meso-NH meteorological model with two nests. The inner nest was run in convection-permitting mode using a horizontal grid mesh of 5 km. Its domain covers the aircraft range, typically over Togo and Benin. The simulations were performed with a prognostic dust scheme in case of any dust event over Benin. While dust was observed during one flight, the concentration of dust was however too low for having any impact on the cloud development. Note also that the aircraft missions were dedicated to pollution. As a consequence, no flight was of interest for any precipitation case study. Among the 16 days of the aircraft campaign, 13 were rainy. A preliminary analysis of rainfall events based on the simulations shows that three days had “orographic rain”, “afternoon convection” occurred on six days and four days were characterized by travelling storms.

Because no warm rain event was found during the aircraft campaign, this leads us to search for other rain cases before 29 June and after 14 July 2016. A total of nine cases were subjectively selected to have an as wide variety of rainfall types as possible with respect to the climatology of Maranan et al. (2018). For each case, the Meso-NH simulations were redone with one model only, and a finer mesh of 3 km. In the following, the performance of the model to represent seven cases is presented shortly. A deeper analysis is then shown for an orographic case.

Another rain event outside the aircraft campaign has attracted our interest. It is a coastal extreme event that occurred on 11-13 June 2016 with a daily rainfall amount of 224 mm/24 h in the town of Abakaliki (Nigeria) and more than 100 mm in Axim (Ghana) and Abidjan (Ivory Coast). A diagnostic study on this extreme event was performed. In the following, it will be shown that the event is a transition from a squall line to a coastal moist vortex, explained by novel dynamics concepts. The event went on at the coast with regenerating convection behind the leading major mesoscale convective system. Meso-NH simulations with different initial dates for this case were also conducated and will be discussed.

Outside the aircraft campaign, only one warm rain event was found on 24 July 2016 at the Savè supersite which was the only DACCIWA supersite instrumented with rainfall radar. This case was analyzed based on the rather limited rain radar information. The Meso-NH model was run in large-eddy simulation mode with a grid mesh of 200 m and compared with the radar observations. An assessment of the large-eddy simulation with other model simulations at coarser resolution has also been performed. Results from this warm rain event are presented in Deliverable 6.5.

The present report provides an overview of several precipitation case studies over south-western Africa. First, seven rain cases will be presented. Second, a diagnostic study on extreme precipitation along the Guinean coast will be described.

2 Precipitation case studies

Table 1 lists the events that occurred during the DACCIWA field campaign and that were selected. All of them have been simulated with the Meso-NH model using the configuration detailed in section 2.1. The performance of the model is described in section 2.2 for all the cases with the exception of the warm rain case. The latter is the subject of Deliverable D6.5.

Rainfall type	Date	Phase	Comments
Stationary convection	9 June	1	Accra: 184 mm, 143mm/6h
Orographic rainfall	6 July	2	
Abakaliki extreme event	11 June	2	Nigeria, MCS, > 200 mm/24h
Locally-induced convection	10 July	2	…. over Benin (in model)
NW rainfall	12 July	2	
Westward thunderstorm	13 July	2	31 mm in 6h, morning
Eastward squall line	20 July	2	
Night-time convection	23 July	3	
Warm rain	24 July	3	See Deliverable D6.5

Table 1: *List of precipitation events with the cases that occurred during the aircraft campaign in bold. The phases are the stages of three West African monsoon as defined in Knippertz et al. (2017).*

2.1 Model configuration and data

The simulations were run with the non-hydrostatic mesoscale atmospheric Meso-NH model (Lac et al. 2018), over a 384 × 432 km^2 domain centred over Togo and Benin (Figure 1). They were run with a 3-km horizontal grid that permits the convection to be represented explicitly. They started from ECMWF operational analysis at 00 UTC each day. The observational data sets used are the radiosounding from Savè at 05 UTC (available from 13 June onwards), the 24-h accumulated rainfall from rain gauges, the Tropical Rainfall Measuring Mission (TRMM) 3B42 product and the Integrated Multi-satellitE Retrievals for GPM (IMERG) product. The time and spatial resolution of TRMM and IMERG is 3 h and 0.25° and 30 min and 0.1°, respectively.

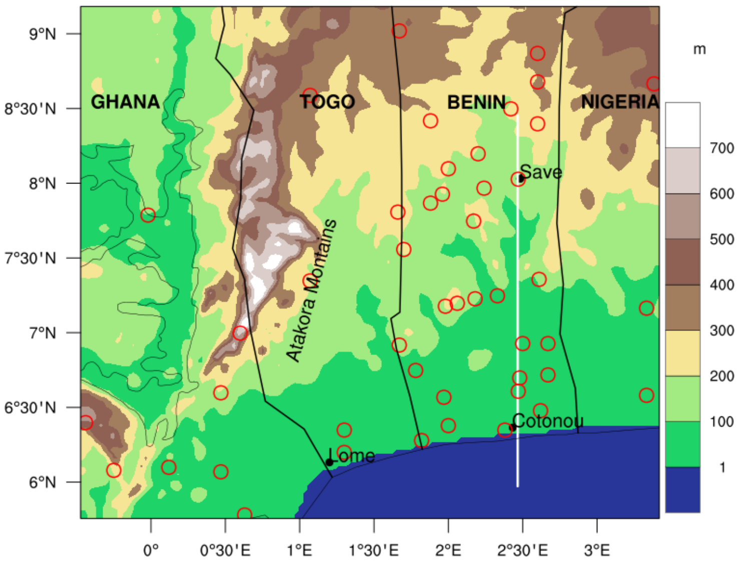

Figure 1: Meso-NH simulation domain. Colour-shaded is the terrain height. The location of the Savè supersite is indicated. The white line shows the location of the cross section in Figure.10. The locations of the rain gauges used in this study are shown with red circles.

2.2 Results

On 9 June 2016, stationary convection developed along the Guinean coast (Figure 2). Wind is southerly at low levels and north-easterly at mid-levels. The simulation predicted a storm too far east and inland.

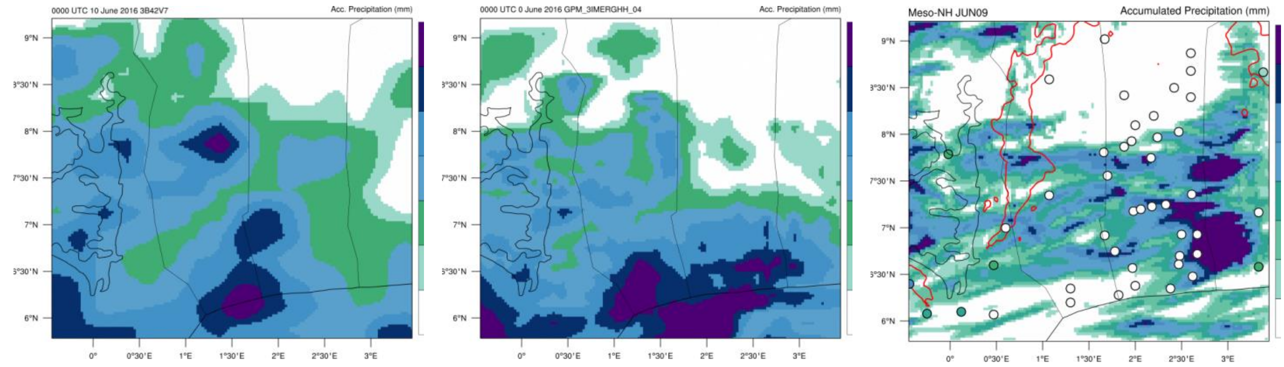

Figure 2: 24-h accumulated rain for (left) TRMM, (middle) IMERG and (right) Meso-NH on 9 June 2016. The red line shows the 400 m altitude. The rain-gauge values are reported within the coloured circles.

On 6 July 2016, rain fell over the Atacora Mountains as retrieved from TRMM and IMERG (Figure 3). This event occurred around 15 UTC. The low-level wind was south-westerly while at mid-levels, the wind blew from the east. The simulation shows good skill in predicting rain in the right place at the right time. This case is further investigated in Section 2.3.

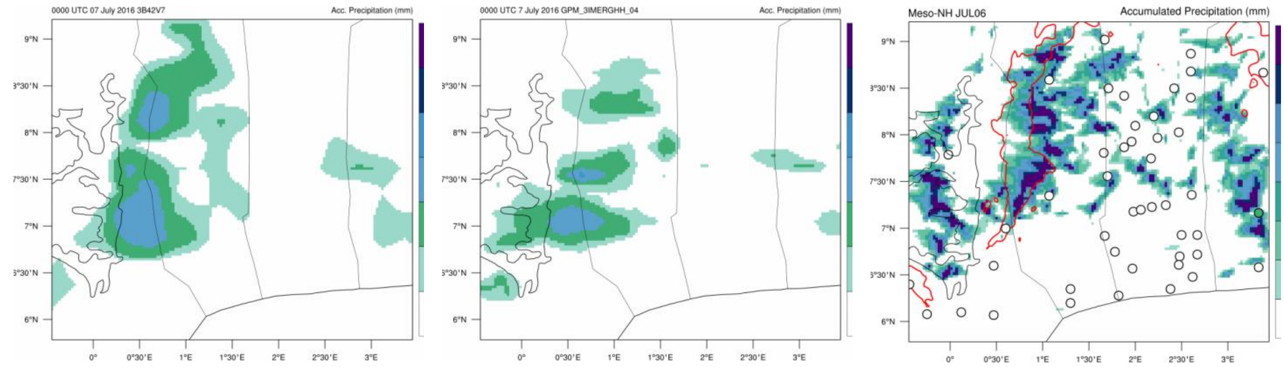

Figure 3: As in Fig. 2, but on 6 July 2016.

On 10 July 2016, locally-induced thunderstorm occurred over Benin around 18 UTC (Figure 4). The wind was south-westerly at low level and north-easterly at mid-levels. The simulation produced rainfall in the direction of the mid-level wind correctly, but too far south.

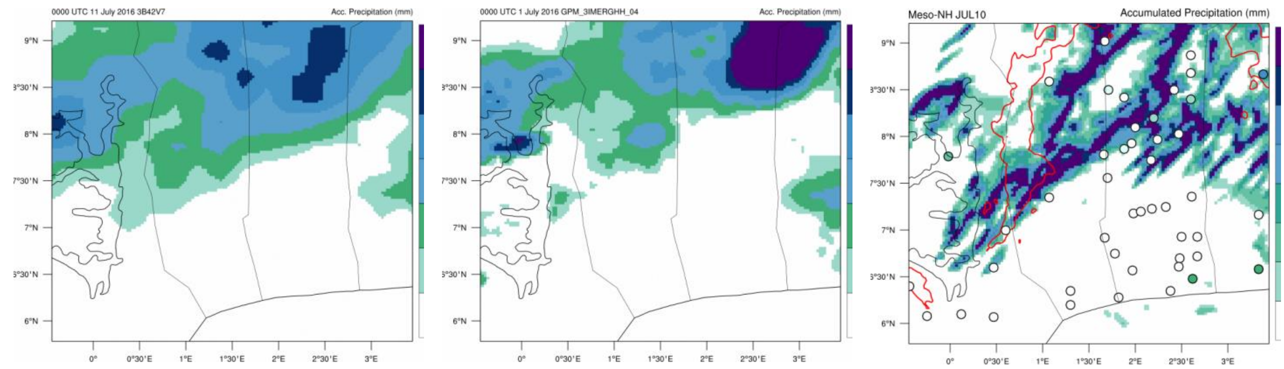

Figure 4: As in Fig. 2, but on 10 July 2016.

On 12 July 2016, rainfall was coming from the northwest (Figure 5). It is due to thunderstorms that developed in the afternoon and organized by low-level wind shear. The two satellite retrievals agree on the location and intensity of rain. They also found a spot of rain over the Atacora Mountains. The simulation produced precipitation with a larger intensity and too far west. It also missed the isolated storm over the mountains.

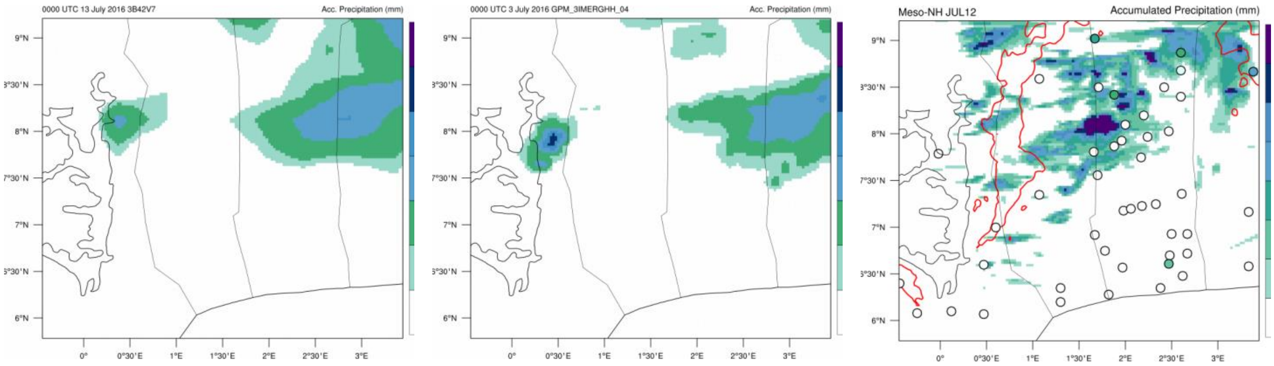

Figure 5: As in Fig. 2, but on 12 July 2016.

On 13 July 2016, rainfall occurred in the morning due to a thunderstorm coming from Nigeria (Figure 6). This event was missed out by the simulation whose domain does not cover Nigeria. Further, the mid-level wind is very weak in the morning, which does not fit with the observed eastward propagation of the Nigerian thunderstorm.

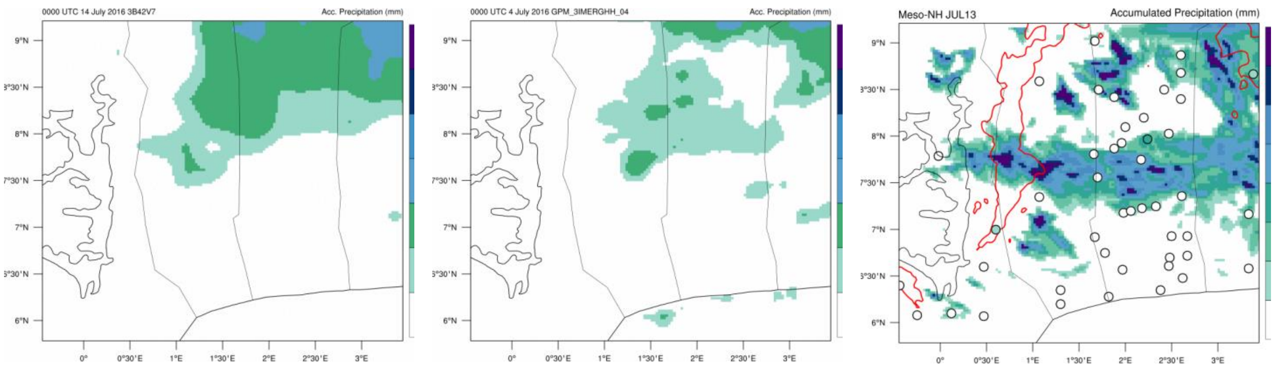

Figure 6: As in Fig. 2, but on 13 July 2016.

On 20 July 2016, an westward-propagating squall line led to intense rainfall (Figure 7). It developed in a typical south-westerly monsoon flow with a very weak mid-level wind. The two satellite retrievals differ in the location of the rainfall spots while the simulation run at higher resolution produced various rain structures at finer scale and partly much farther south.

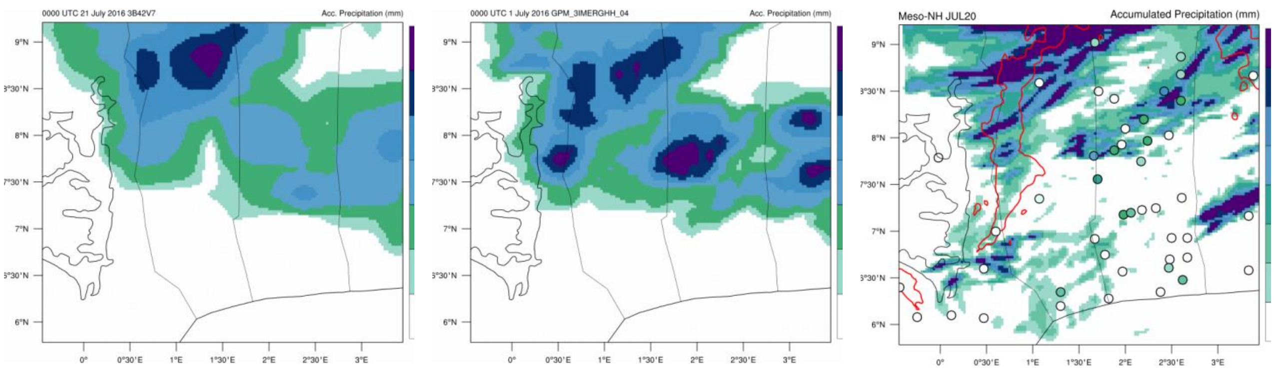

Figure 7: As in Fig. 2, but on 20 July 2016.

On 23 July 2016, convection developed during night time with large accumulated rain in northern Togo and Benin (Figure 8). The simulation missed this event completely. Indeed, convection was wrongly simulated along the border between Benin and Nigeria where the wind was weak both at low and mid levels.

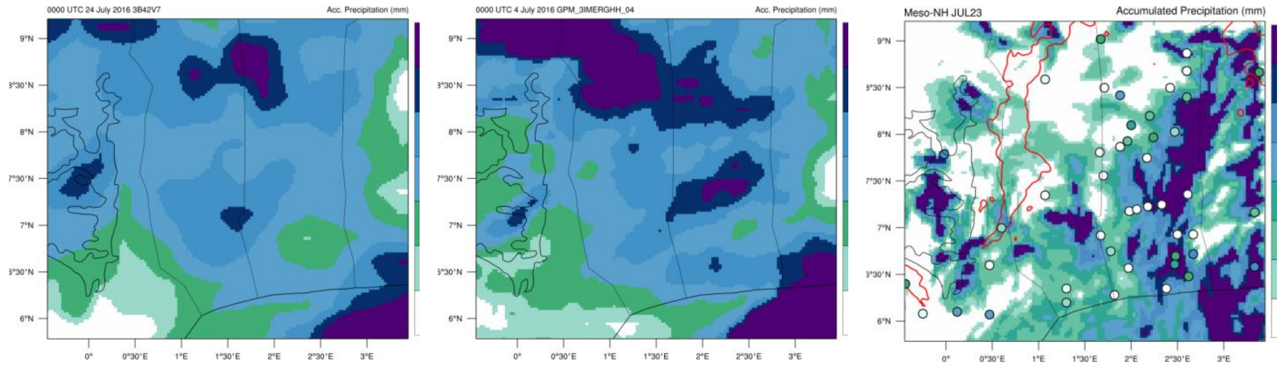

Figure 8: As in Fig. 2, but on 23 July 2016.

Overall, the precipitation events occurred in the presence of low-level moist monsoon flow (Figure 9). They differ in their environment mostly by the direction and intensity of the wind at mid-tropospheric levels, with a few cases showing a westerly flow. The latter synoptic-scale perturbations of the climatological easterly flow above 2 km have been described in Knippertz et al. (2017) and are not well represented by the model simulations (e.g. 12 and 13 July 2016 in Fig. 9). On these two days and on 23 July 2016, the model also show a too deep southwesterly monsoon flow. The two satellite products generally agree in the location and intensity of rain. They can however strongly differ in case of long duration of convection. Even though the 24-h accumulation period between the rain gauges (06 -06 UTC) do not exactly overlap with the model and satellite accumulation periods (00 – 00 UTC) and error in some gauges on certain days are likely, comparison to the rather dense surface gauge network suggest that both, the satellite rainfall estimations and the model do show to widespread rainfall. Yet, the simulations show a certain degree of realism. They can however miss the rain event, because of night-time development or propagation across the simulation domain, for example. Among the 7 cases, the orographic rain event of 6 July was selected for further investigation because of the ability of the model to reproduce the case with sufficient realism.

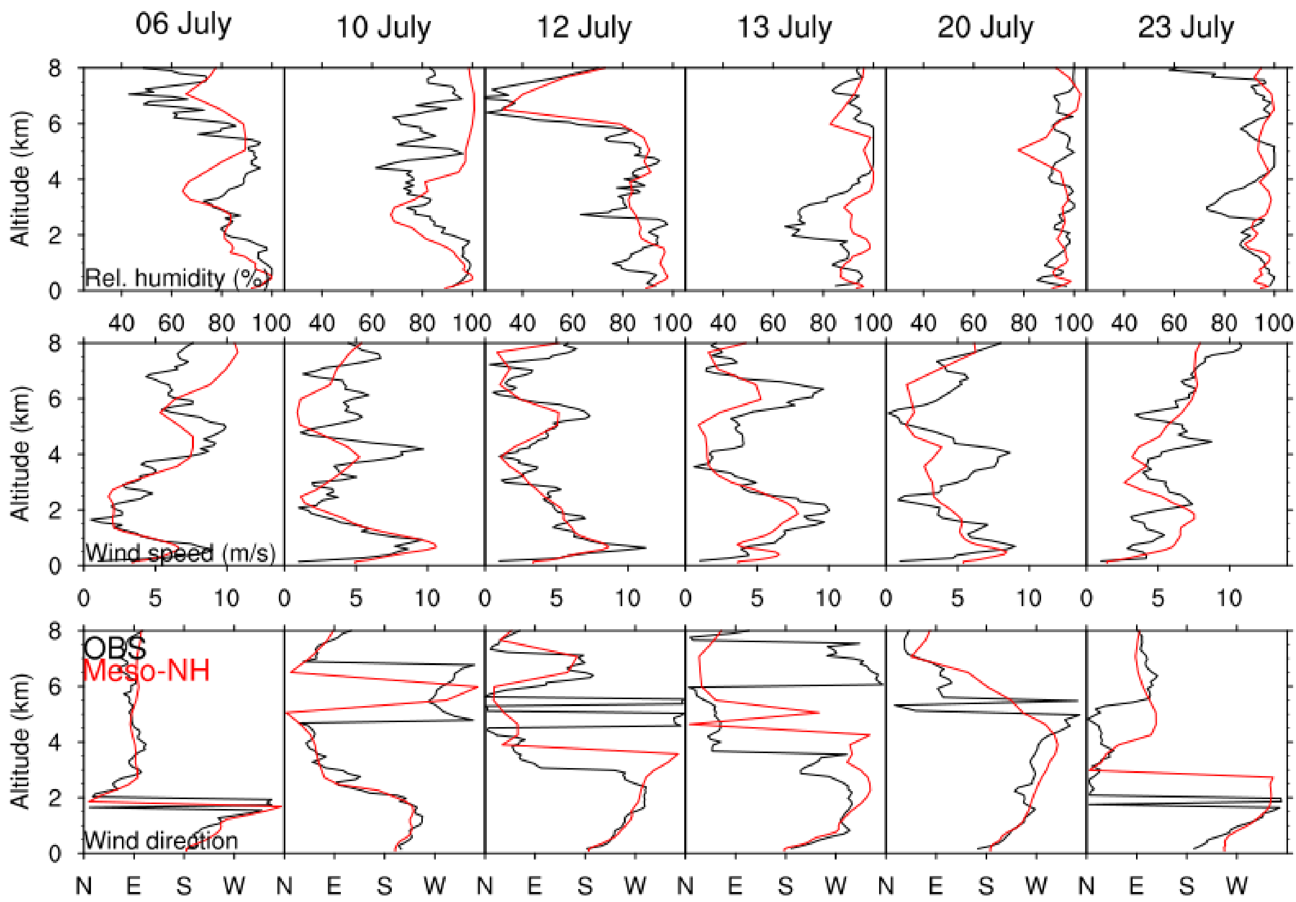

Figure 9: Vertical profile of relative humidity and wind speed and direction at Savè taken from (black) radiosondes and (red) Meso-NH simulations at 05 UTC for each event with the exception of 9 June.

2.3 Orographic rain event

Further investigation was done for one of the better simulated cases, the orographic rain on 6 July 2016. The development of the boundary layer can be summarized using the observations taken from the DACCIWA supersite of Savè (Figure 10). The horizontal wind speed measured by sodar in the first 500 m shows maximum values in excess of 10 m/s between 00 and 06 UTC and 18 and 00 UTC on the next day (Figure 9, left). These relatively high wind speeds are related to the night-time low-level jet (NLLJ). The end of the night is also characterized by the presence of low-level clouds (Figure 10, right). This is explained by the simultaneous radiative cooling of the continental air mass and the moisture transported from the sea by the NLLJ (Kalthoff et al. 2018, Adler et al. 2018, Babić et al. 2018). From 06 UTC onwards, the wind speed decreases with the gradual warming of land. This heating induces the vertical development of the atmospheric boundary layer, observable after 09 UTC when the base of the stratified clouds rises to about 1 km (Figure 10, right).

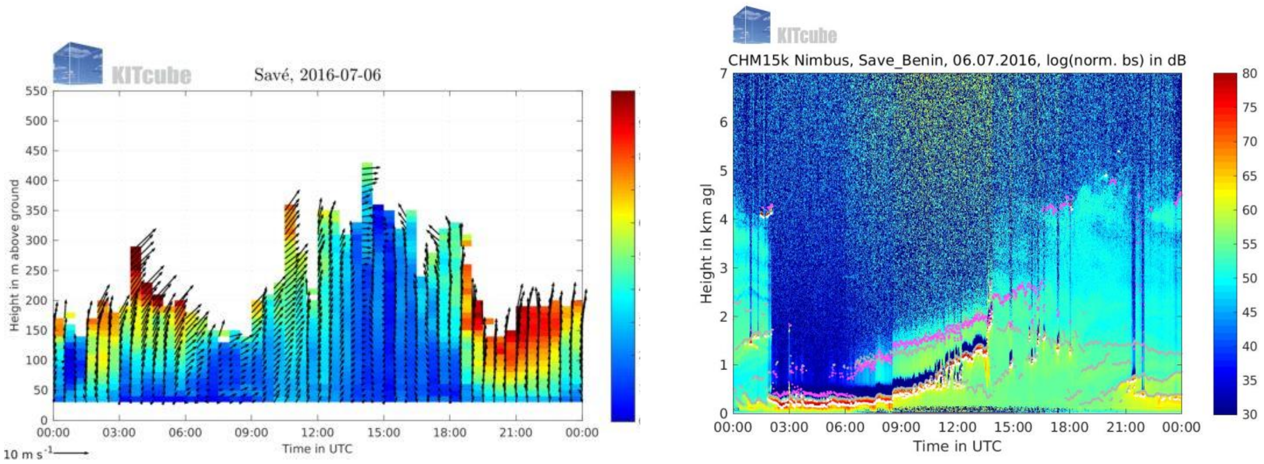

Figure 10: Time evolution of (left) horizontal wind speed from sodar and (right) cloud base height from ceilometer on 6 July 2016 at Savè.

The simulation fits the observations well. The NLLJ is set up in the early evening and enters the land up to 190 km. At 07 UTC, the NLLJ is at maximum with a speed of 12 m/s (Figure 11, left). It then decreases in intensity and is completely eroded at 13 UTC (Figure 11, right). The turbulent eddies associated with the development of the boundary layer set up the dry convection. From 11 UTC onwards, the difference between the air temperature at 2 m and the dew point temperature increases. This difference is on the order of 4°C; the air is thus not saturated (not shown) and the air becomes less humid. The development of dry convection rolls results in the decrease of relative humidity at low levels, from 98% in the morning to 70% in the afternoon (not shown). These rolls allow the destruction of the low-level jet and thus the dissipation of the stratified layer of clouds.

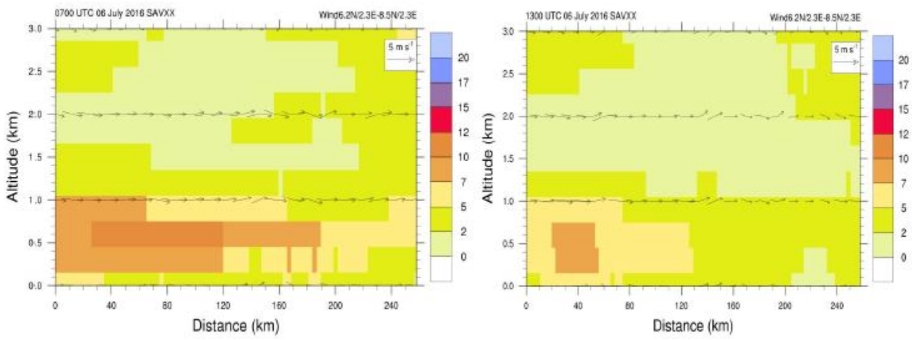

Figure 11: Vertical section of the wind speed along 2°30 E across Savè at (left) 07 and (right) 13 UTC. The location of the cross section is shown in Figure 1.

The mountain range of Atacora in Togo plays a key role in the formation of clouds and precipitation. The relief channels the wind and associated moisture supply and triggers convection. When the south-westerly monsoon flow arrives at the Atakora low mountain range, the air parcels are forced to rise. They undergo cooling and eventually saturate. The relative humidity at 950 hPa rises from about 80% at 12 UTC to 95% - 100% at 15 UTC (not shown). When the air is brought to its level of free convection, it condenses and an orographic cloud forms. As a result, at 11 UTC, cumulus clouds form with cloud tops up to an altitude of 2 km. At 13 UTC, cumulonimbus clouds develop with tops at 12 km altitude which yield precipitation (Figure 12). Once arrived at the downwind side of the mountain, they dissipate at 17 UTC.

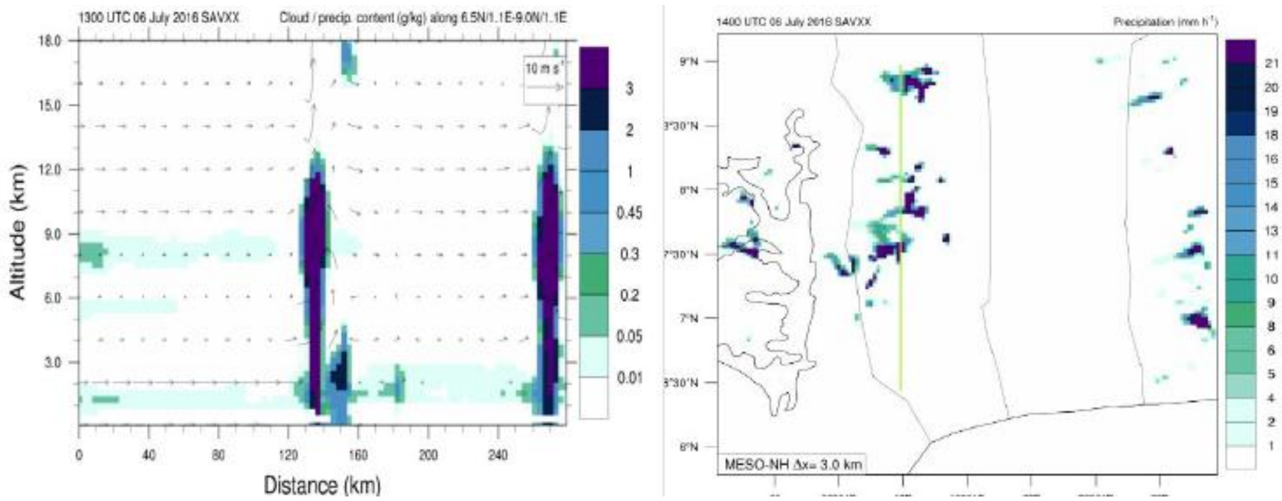

Figure 12: (left) cloud content and (right) instantaneous rainfall on 6 July at (14 UTC. The vertical section is across 1°E.

Rain appears over the lowlands of Togo and Benin later on. From 11 UTC, stable stratiform clouds dissipate and scattered convective clouds develop. The stable layer is then disturbed by the development of the atmospheric boundary layer. At 17 UTC, a convective cell is formed about fifty kilometres south of Savè. At 18 UTC, it evolves into a deep convective cell (Figure 13, left) and is associated with heavy rainfall (Figure 13, right).

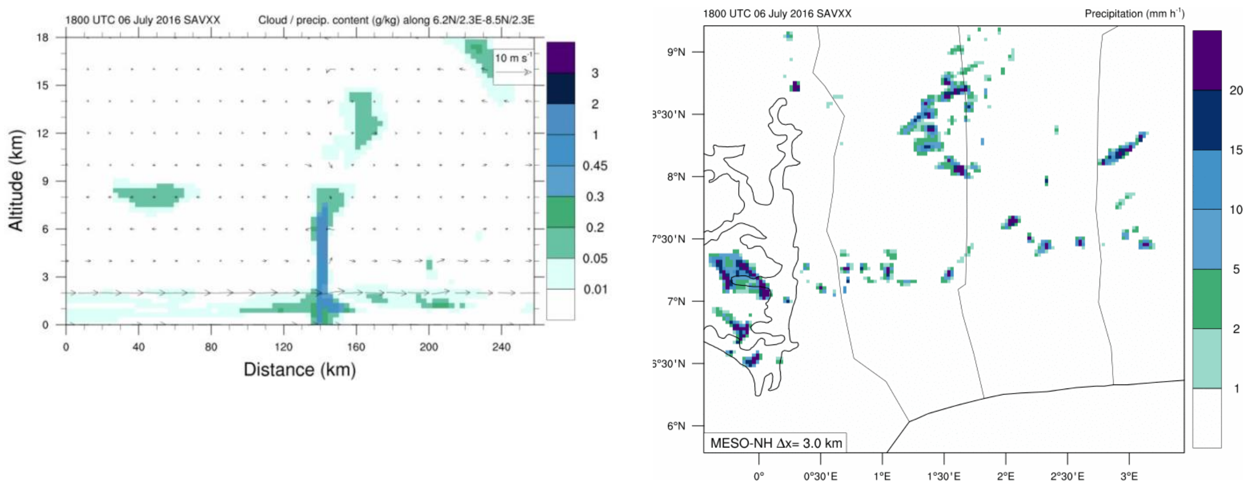

Figure 13: As in Fig. 5, but at 18 UTC and across 2°30 E for the vertical section. The location of the cross section is shown in Figure 1.

3 Extreme precipitation along the Guinea Coast

3.1 Overview of the case

Between 11 and 13 June 2016, the Guinea Coast region was affected by a series of intense convective systems. One of these was a long-lived and intense mesoscale convective system (MCS) and caused one of the highest recorded daily rainfall amounts over all near-coastal stations with 223.5 mm on 12 June 2016 at the southern Nigerian station Abakaliki. On the following day, the stations in Axim (Ghana) and Abidjan (Ivory Coast) each reported more than 100 mm. Overall, the abovementioned period marked the wettest spell along the Guinea Coast during the DACCIWA field campaign in June and July 2016 (Knippertz, et al., 2017).

The following description of this case is based on the study by Maranan et al. (2019, submitted to Monthly Weather Review). Figure 14 illustrates six key stages in the development of the MCS, which eventually caused the extreme rainfall amount over Abakaliki, Axim and Abidjan. It formed in the afternoon of 10 June over the Sudanese Darfur Mountains (stage 1; 13°N, 24°E) as a consequence of diurnal heating and quickly moved south-westward over southern Chad until it reached the eastern border of Nigeria around noon on 11 June. During this period, the MCS gradually grew in area and intensity (stage 2) and ultimately developed into classical West African squall line (stage 3), as indicated by its sharp western flank and an elongated band of cold cloud-top temperatures, which mark the convective region of the squall line. Over Nigeria (stage 4), the squall line started to deform and intensify and featured three distinct convective cores. Here, the extreme rainfall at the Abakaliki station in the late evening of 11 June was caused by the southernmost core (black circle), which remained stationary over the region for several hours (not shown). The proposed reasons for the deformation and stationarity of the squall line are given in Section 3.3. Eventually, the MCS moved over open waters in the morning of 12 June (stage 5), where a more pronounced bending of the cloud system is visible. In the early morning of 13 June (stage 6), the MCS fragmented and started to dissipate. At the same time, new convective cells developed in the vicinity of the decaying MCS, which further intensified as they moved farther westward and caused the high rainfall amount at Abidjan. Eventually, this newly generated convective system went on to move towards the eastern Atlantic Ocean in the course of 13 June.

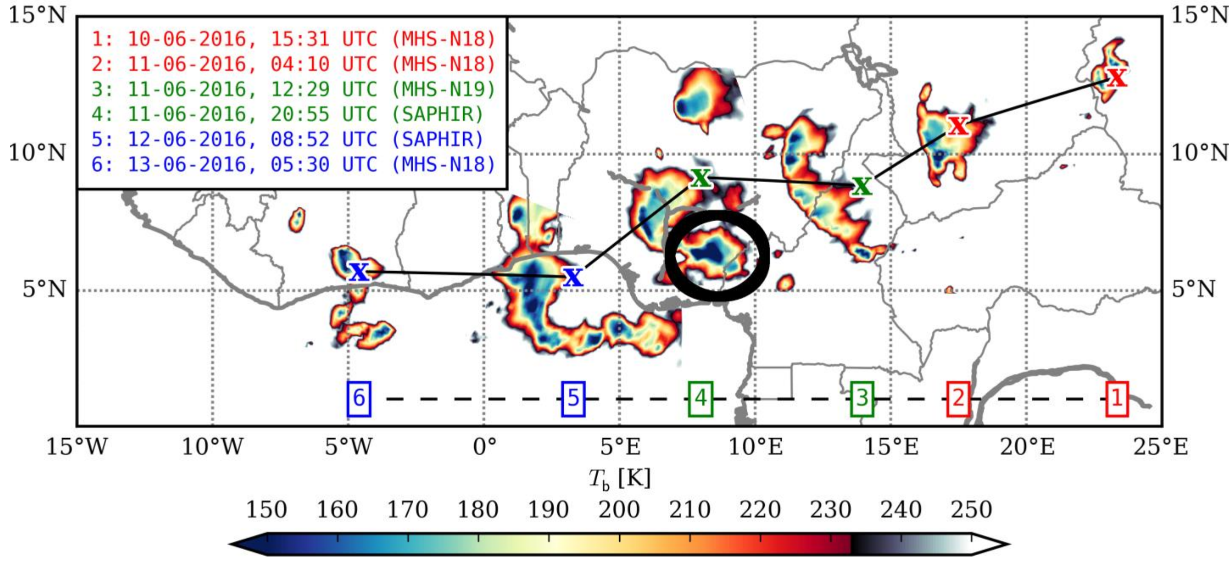

Figure 14: Spaceborne, microwave-based cloud brightness temperatures (colour-shaded) at successive stages of the MCS, measured by the Microwave humidity sounder (MHS) and the Sounder for Probing Vertical Profiles of Humidity (SAPHIR). The legend refers to the stage numbers at the bottom of the panel and indicates the day and time of overpass of MHS and SAPHIR, respectively. The black circle indicates the Abakaliki region centred on the Abakaliki rain gauge station.

3.2 Rainfall distribution

Because of the intensity and longevity of the MCS, paired with its distance travelled, the region-wide wettest spell during the DACCIWA field campaign can largely be attributed to this single event. In Figure 15, the total rainfall amount along the MCS path is shown. Here, both spaceborne rainfall estimates from the Integrated Multi-Satellite Retrievals for GPM (IMERG) and daily rain gauge information collected by the DACCIWA project from several national weather services. Several streaks of higher rainfall amounts clearly visualise the south-westward movement of the MCS (or at these stages of the squall line) at the beginning of its lifetime. Particularly because of the high translation velocity as a squall line, local rainfall accumulations between the stages 1 and 3 were not as high as closer to the coast during later stages, where the translation velocity is significantly reduced (not shown). Over southern Nigeria, an area of close to 200 mm in IMERG is visible, which agrees relatively well with the 223.5 mm measured at Abakaliki. Recalling stage 4 in Figure 14, this area of high precipitation coincides with the position of the intense southernmost convective core. Based on the substantially lower rain gauge values at surrounding stations, it becomes apparent how localised this extreme event in the Abakaliki region was. After stage 4, further high rainfall amounts over land are comprised to the immediate coastal area due to the fact that the MCS was most active over ocean. As mentioned in the previous section, it culminated in more than 100 mm at Axim and Abidjan.

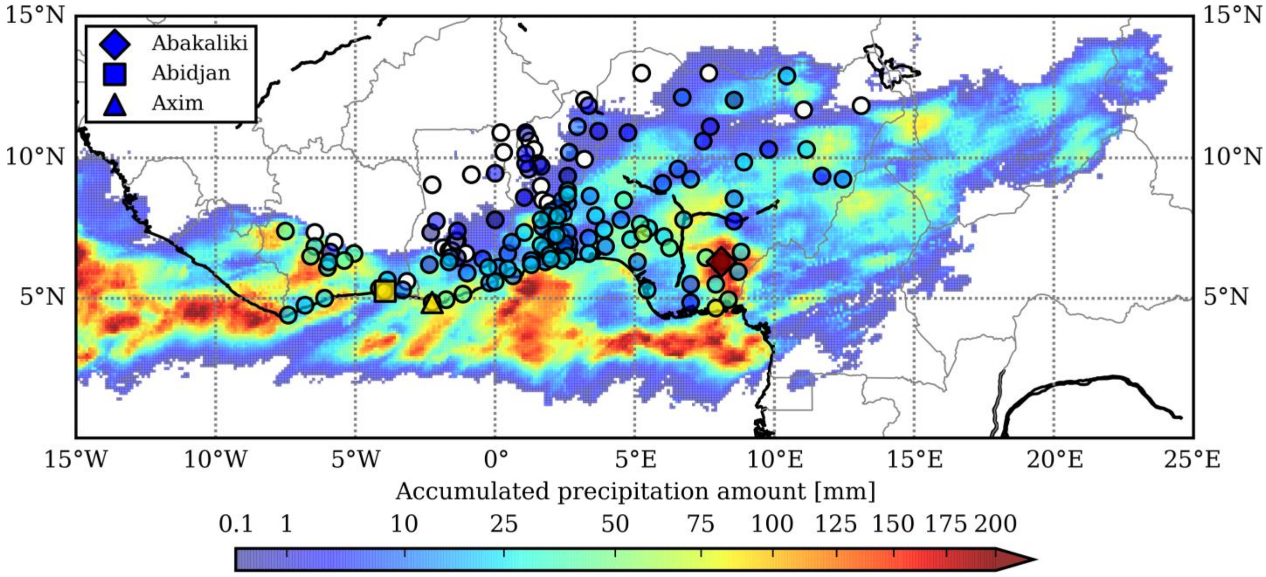

Figure 15: Comparison of total rainfall along the MCS path between IMERG (colour-shaded) and a collection of daily rain gauge data (scatters) from several national weather services. The stations Abakaliki, Abidjan and Axim are highlighted with individual markers indicated in the legend.

3.3 Important dynamical aspects

From initiation to dissipation, the MCS underwent several changes with respect to shape, intensity and its overall character. The development into a squall line is a typical feature during the rainy season of the West African monsoon from April to October. Favourable environmental conditions leading to it, such as strong vertical wind shear, mid-tropospheric dryness and midlevel disturbances, are relatively well known (e.g. Fink and Reiner, 2003; Laing et al., 2008) and were also present in this case study. However, the intensification of the MCS, resulting in the extreme rainfall amount at Abakaliki, involves dynamical aspects that have never been investigated in detail for this part of the world and are summarised in this section.

Prior to the arrival of the squall line in the afternoon of 11 June, the Abakaliki region experienced a strong local increase in precipitable water (PW, Figure 16a), a measure for the liquid water in the atmospheric column if all water were collected as rain. Maranan et al. (2019) describe the proposed dynamical mechanisms leading to this increase in more detail. In brief, this PW increase resulted from the formation of a local and short-lived heat low in the Abakaliki region. Its development was primarily driven by insolation and column subsidence due to upper-level convergence forced by the upper-level outflow of the MCS, which overall led to a warming of the tropospheric column and thus a net surface pressure fall. The Abakaliki region was in the center of low-level convergent motions, leading to the aforementioned high PW values. In Figure 16a, regions of high PW are indicated in greenish colours. Furthermore, red contours denote areas of moisture flux convergence larger than 100 mm/day, which eventually resulted to a further increase of PW. Both factors were present over the Abakaliki region and ensured favourable conditions for MCS intensification. This intensification is reflected in the development of the intense convective core, which was presented in Figure 14 at stage 4. Figure 16b illustrates the situation during the overpass of the MCS on early 12 June. The further increase in ambient PW as well as constant moisture flux convergence in the Abakaliki region becomes apparent, which in turn led to a constant moisture supply for the MCS. This environmental setting was strongly supported by the development of a mid- to low-tropospheric vortex, as suggested by the rotational signature in the blue streamlines. Aside from trapping moisture, the emergence of the vortex also led to an overall deceleration of the MCS, allowing for locally higher rainfall accumulations during its movement along the coast. Again, this deceleration of the MCS was a key ingredient for extreme rainfall over Abakaliki.

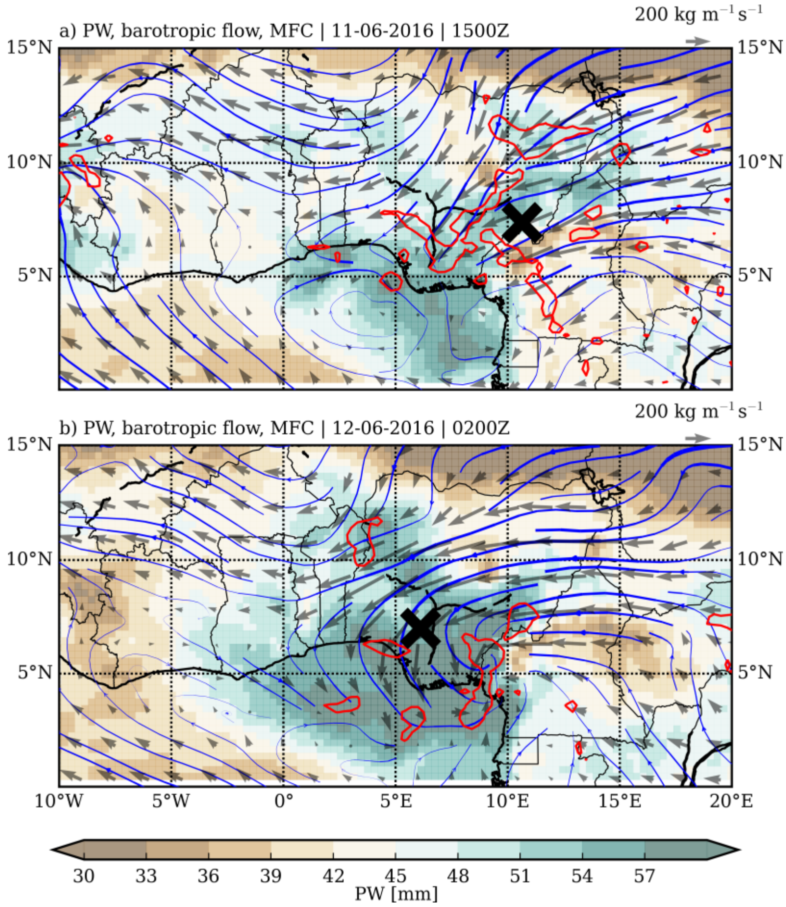

Figure 16: Precipitable water (PW, colour-shaded), moisture flux convergence (MFC) > 100 mm/day (red contours), the mass-weighted wind in the 600-950 hPa layer (barotropic flow, blue streamlines) and moisture flux (grey vectors) on (a) 11 June 2016, 15 UTC prior to MCS arrival, and on (b) 12 June 2016, 02 UTC, during the MCS passage. The black x-mark indicates the center of mass of the MCS at the respective timesteps.

During its subsequent westward movement along the West African coast on 12 June onwards, the MCS was further accompanied by a lower-tropospheric vortex structure, which developed out of the aforementioned main vortex. This is highlighted in the Hovmoeller diagram in *Figure 17*, showing the meridional wind (colour-shaded), the MCS track (solid black line) and the positive portion of relative vorticity (black contours) and zonal windspeed (green contours). While the main vortex remained east of 5°E over the course of 12 June, a separate vortex structure almost parallel to the MCS track is visible during 12 and 13 June. This structure likely ensured the sustainment of the MCS by maintaining low-level convergence and thus the supply of moisture. It is also suggested that the vortex structure led to the development of new convective systems in the vicinity of the decaying MCS on early 13 June, which eventually resulted in the high rainfall amount over Abidjan (not shown).

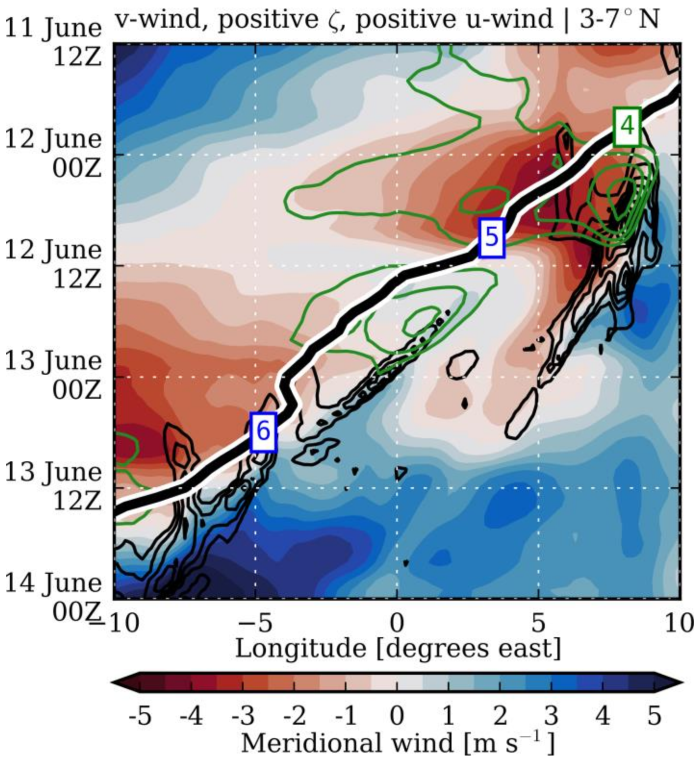

Figure 17: Hovmoller diagram showing the meridional wind (colour-shaded), the MCS track (solid black line) and the positive portion of relative vorticity (black contours) and zonal windspeed (green contours). The numbers refer to the MCS stages, which are also presented in Figure 14..

3.4 Summary

A manuscript investigating the (thermo-) dynamical aspects of this extreme rainfall event at the Guinea Coast has been submitted (Maranan et al. 2019). The documented formation of a mid- to low-level vortex associated with the passage of a MCS and an extreme rainfall event has never been investigated for southern West Africa to the best of our knowledge. It provides new insights into MCS maintenance in the Guinea Coast region, where the classical model of self-sustainable squall lines is considered to be less effective due to a much moister environment compared to the Savannah or Sahelian region. In general, such vortices are known to produce long-lasting rainfall (Fink, et al., 2006) due to continuous low-level convergence (e.g. Buckle, 1996). However, they have rarely been reported in association with extreme rainfall events in the Guinea Coast region, if at all. Although favourable environmental conditions for the extreme nature of rainfall over Abakaliki and the MCS maintenance are strongly proposed to be achieved by the vortex structures, the exact mechanisms remain uncertain. Further insights may be gained through high-resolution model runs, which are capable of capturing the physical processes that lead to the extreme event.

3.5 Meso-NH simulations of the Abakaliki case

The Meso-NH model was run over a large domain covering the entire path of the thunderstorm (Figure 18). This was done in a convection-permitting mode using a horizontal grid spacing of 2.5 km. The model was initialized with ECMWF operational analysis and assessed against satellite Meteosat Second Generation (MSG) images in the thermal infrared.

The first simulation was started at 00 UTC 10 June 2016. It is not able to produce the extreme event. Convection forms correctly in the afternoon of 10 June over the Sudanese Darfur Mountains and survives into the night. At 12 UTC 11 June 2016, the simulated convection however remains scattered without developing into squall line as observed at the eastern border of Nigeria.

The second simulation was started at 00 UTC 11 June 2016. After the spin-up time, it produces intense convection with mid-tropospheric cyclonic circulation in the afternoon of 11 June over southern Chad. At 04 UTC 12 June 2016, a squall line is simulated, but over central Nigeria instead of western Nigeria (Figure 18, top). It presents strong vorticity of equal intensity for both the northernmost and the southernmost convective cores (Figure 18, bottom left). This differs from the observed squall line that starts to deform and intensify and features three distinct convective cores. As a consequence, the simulated southernmost core does not remains stationary over southern Nigeria and misses the extreme rainfall recorded at the Abakaliki station in the late evening of 11 June. In the simulation, the accumulated rain over the 2-day period is large, above 180 mm, but located too far south (Figure 18, bottom right).

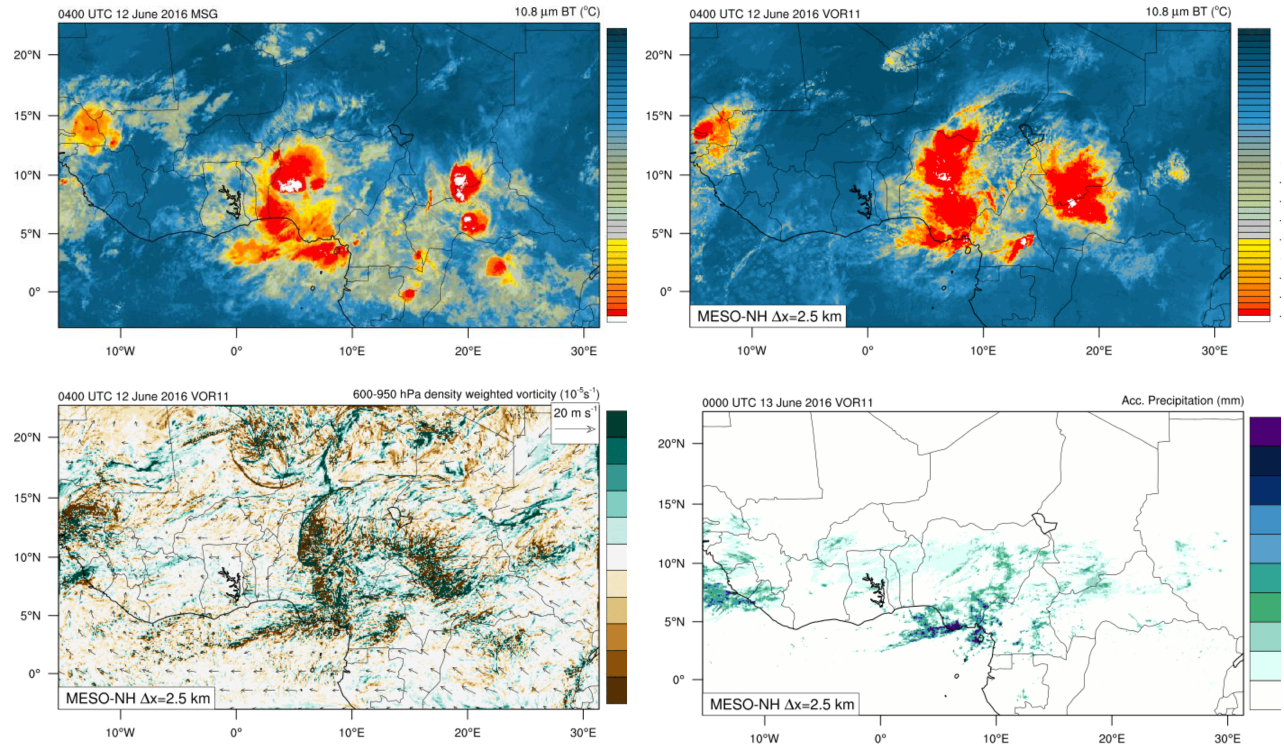

Figure 18: snapshot at 0400 UTC 12 June 2016 showing (top) simulated and observed satellite infrared image from (left) the Meso-NH simulation and (right)MSG observation and (bottom left) 600-950 density-weighted vorticity; (bottom right) accumulated rainfall since 00 UTC 11 June.

4 Conclusion

Nine precipitation cases were investigated. The selected cases show various characteristic in space and time. None of them developed in the presence of dust in contrast to the AMMA case studied in the course of the DACCIWA project (Reinares Martínez and Chaboureau 2018a, b). Among them, only one was a case of rainfall of warm processes during the field campaign in Savè (see Deliverable 6.5). The role of shear is seen to be important, as the biggest systems were those for which the wind shear is important. For the extreme case along the Guinean Coast region, further ingredients implying novel dynamics concepts are needed for transforming a squall line into a coastal moist vortex.

Model skill in rainfall and cloud prediction is overall low. This is consistent with results presented in Kniffka et al. (2019, in preparation). Even if a convection-permitting simulation can capture the degree of organization better than parameterized convection and improves the diurnal cycle of precipitation, it fails to represent the triggering of MCSs over SWA (Reinares Martínez and Chaboureau 2018a). This failure was attributed to the initial conditions because of a mid-level wet bias in the model in the study by Reinares Martínez and Chaboureau (2018a). This could also be the case for some rainfall events investigated here for which the wind direction at mid-levels greatly differs from radiosondes at Savè. The representation of the convective organization is also thought to be sensitive to the subgrid scale turbulence scheme (e.g., Machado and Chaboureau 2015).Overall, simulations of rainfall events over West Africa remain a challenge.

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