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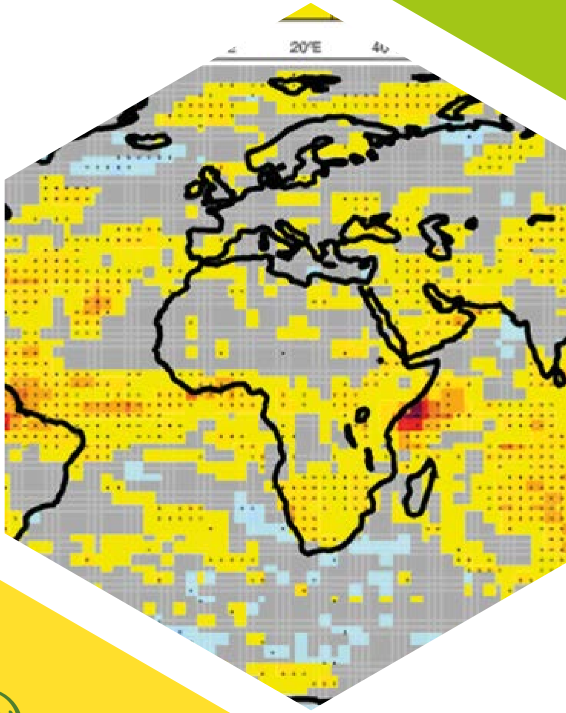
DACCIWA
Dynamics-aerosol-chemistry-cloud
interactions in West Africa



Key lessons from the **DACCIWA project** for operational meteorological services

funded by the
European Union

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

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Key Findings

Improved atmospheric predictions across time-scales are important for the development of greater resilience of the West African population to hazardous weather and climate change. The EU-funded project Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa (DACCIWA) produced the most comprehensive observational dataset of the atmosphere over densely populated southern West Africa to date. Using this dataset to foster our understanding of atmospheric processes, and to evaluate dynamical models and satellite data, the following conclusions are highlighted as directly relevant to operational meteorological services:

Meteorological observations for southern West Africa

- The meteorological station network in West Africa is sparse and existing data are not always available for research and operations, limiting evaluation of model and satellite products.
- Standard satellite cloud retrievals underestimate the frequency of low clouds during boreal summer by 30%, leading to errors in surface shortwave radiation.
- Inconsistent retrievals of shortwave absorption lead to uncertainty in estimating the total aerosol radiative effect.
- Satellite-based rainfall datasets tend to overestimate the number and length of weak rainfall events while underestimating the intensity of strong events.

Emission data for southern West Africa

- DACCIWA compiled a new inventory of human emissions for Africa that compares better with observations than standard emissions datasets.
- Emissions of particles and organic gases from vehicles in southern West African cities are higher than those in other locations.
- Burning seemingly similar materials may lead to very different emissions.

Quality of operational forecasts

- Numerical Weather Prediction (NWP) skill in rainfall and cloud prediction is overall low with some skill evident on the regional level when synoptic-scale vortices are present.
- Forecasts tend to be too cold and dry at the immediate Guinea Coast during the summer monsoon, possibly due to problems with the Maritime Inflow phenomenon.
- Low clouds tend to be underestimated in many weather and climate models, leading to too much incoming solar radiation at the surface.
- A more realistic representation of convection in West Africa can improve medium-range forecasts in the extratropics including Europe.

Impact of additional radiosonde observations on analyses and forecasts

- The assimilation of an unprecedented radiosonde dataset into the ECMWF model shows a lower-tropospheric dry bias in parts of southern West Africa during the wet summer monsoon.
- The same ECMWF model also shows a general cold bias, possibly due to too strong cold advection from the Gulf of Guinea during the night.
- Forecast improvements due to better observations are moderate at best, pointing to model and data assimilation deficits being a substantial obstacle to better forecasts.

Importance of aerosol

- Aerosol influences the atmosphere mostly through radiative and less through cloud microphysical effects with an important role for water uptake by aerosol particles.
- The radiative effect of aerosol likely delays the daytime stratus-to-cumulus transition, the advancement of the coastal front and convective triggering, leading to more intense storms but less rainfall overall.
- An interactive representation of dust and biomass burning aerosol from central Africa can improve subseasonal predictions.

Critical processes suspected to cause model error

- DACCIWA's new observations-based conceptual model for the formation and dissolution of the extensive low cloud decks of southern West Africa can be used as a benchmark for models.
- Warm rain and drizzle frequently occur in southern West Africa during the summer monsoon season impacting on cloud lifetime and the vertical distribution of moisture.
- Convective organisation is a key element of the meteorology of southern West Africa, creating large sensitivities to model resolution.
- African easterly waves and Kelvin waves considerably modulate rainfall and need to be better represented in models.

Recommendations

Based on five years of intensive research using field observations, multi-satellite datasets, targeted modelling experiments and operational forecast products, the DACCIWA project makes the following recommendations in order to guide future activities and developments of operational services in Africa itself and in other regions providing products for Africa.

Improve observational basis

- Sustain and expand networks of meteorological surface and upper-air stations in West Africa.
- Surface observations should ideally be hourly to sample the large diurnal cycle and at least some measurements of global solar radiation would be useful.
- Make sure that – where possible – observations adhere to international standards (specifically those of the World Meteorological Organisation) and label information that does not.
- Adopt open-data policies for all available meteorological observations (current and past).
- Use available ground truth to evaluate and develop satellite products of clouds, aerosol, radiation and precipitation, taking into account the specific meteorology of the region.
- Measure sector-specific emission factors in West Africa and release relevant socio-economic data to produce and update emission inventories.

Improve numerical models

- Run weather-forecast models in convection-permitting resolution over a West African subdomain and globally in the longer run.
- Analyse cost-benefit of including interactive aerosol and impacts on radiation across all prediction timescales.
- Analyse cost-benefit of sophisticated cloud microphysics to realistically represent sedimentation processes in drizzling stratiform and convective warm rain clouds.
- Evaluate the coupled diurnal evolution of the boundary layer and low clouds using the comprehensive DACCIWA ground observations and the new conceptual model.

Introduction

Funded by €8.75M from the European Commission's Framework 7 programme, the Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa (DACCIWA) project investigated the processes controlling air pollution, atmospheric composition, weather and climate over southern West Africa and their influence on health [*Knippertz et al., 2015*].

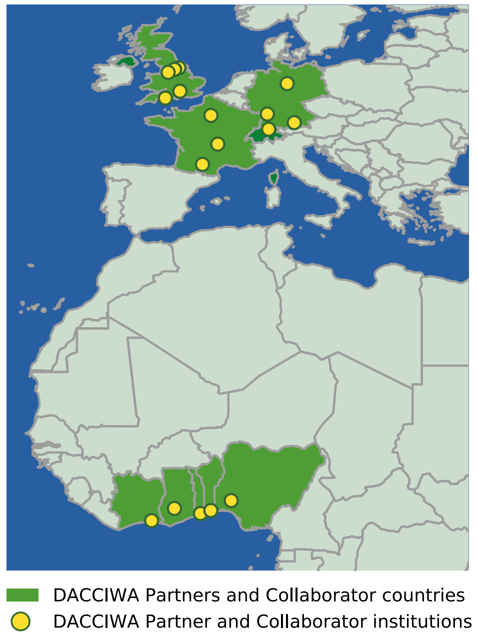


Figure 1. Yellow dots indicate location of the DACCIWA partners and collaborators. Shading shows countries involved in the project. Evans et al. [2018]

The project website http://www.dacciwa.eu hosts information about the project. The observational dataset is available from http://baobab.sedoo.fr/DACCIWA

From 2014–2018 DACCIWA scientists analysed data over West Africa from field programmes, satellites and computer models. This document outlines their conclusions relevant for operational meteorological services.

The field campaigns

A major component of the project was the collection of new measurements of the atmosphere over this observation-sparse region.

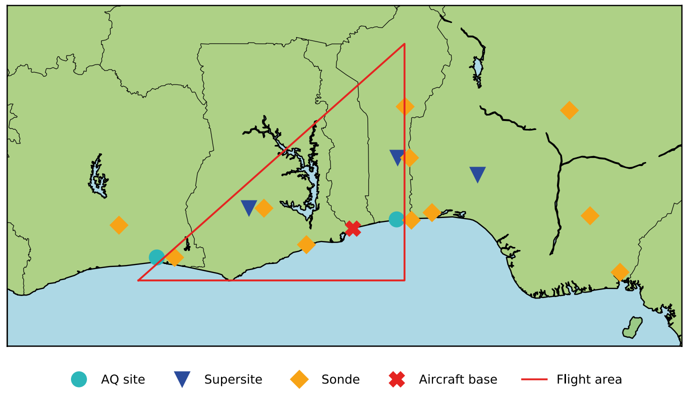


Figure 2. Location of measurement sites during the DACCIWA campaigns in 2016. Air Quality (AQ) sites measured the concentration of air pollutants. Supersites measured a range of meteorological and chemical parameters. Meteorological balloon sondes were released from eleven sites, partly in collaboration with West African weather services. Three research aircraft were based in Lomé (Togo) and sampled inside the red triangle. Evans et al. [2018]

The measurements acquired at the three supersites in Kumasi (Ghana), Savè (Benin) and Ile-Ife (Nigeria) are gathered under six DOIs [*Brooks et al., 2016; Derrien et al., 2016; Handwerker et al., 2016; Jegede et al., 2016; Kohler et al., 2016; Wieser et al., 2016*].

During June-July 2016 extensive measurements were made from three surface meteorological supersites, eleven meteorological balloon launch sites and three research aircraft (Figure 2) [*Flamant et al., 2018*]. In addition, measurements of urban pollution were made from four air quality sites between 2015 and 2017.

The project had partner and collaborator institutions from Benin, Côte d'Ivoire, France, Germany, Ghana, Nigeria, Switzerland, Togo and the United Kingdom.

Meteorological observations for southern West Africa

Long-term, homogeneous and reliable observations are needed for climate monitoring, to evaluate forecast models, for data assimilation and reanalyses, and to understand processes. Satellite observations provide an ever increasing wealth of information but ground truth is needed to evaluate the quality of products. For weather forecasting and early warning, real-time availability is necessary. The operational network in Africa is the sparsest land network worldwide. This section briefly describes the most important DACCIWA findings regarding the observational network and shortcomings in satellite products in southern West Africa.

The meteorological station network in West Africa is sparse and existing data are not always available for research and operations, limiting evaluation of model and satellite products.

In West Africa, surface and upper-air observations according to World Meteorological Organisation (WMO) standards are carried out by national weather services in collaboration with ASECNA, a pan-African organisation responsible for aerial safety. The network of surface stations provides a reasonable coverage of the region, but problems with the availability of 3-hourly observations in the Global Telecommunication System (GTS) persist. Private organisations such as KUKUA (https://www.f6s.com/kukuaweatherservices) and TAHMO (https://tahmo.org) are establishing networks of Automated Weather Stations (AWSs) in various countries, but these data usually do not comply with WMO standards and are not generally freely available for operational and research purposes. The upper-air network remains very sparse (Figure 3) and data from some stations, e.g. five alone in Nigeria, are hardly ever distributed to other weather services [e.g. *Flamant et al., 2018*]. Operational centres should feed messages into the GTS by Email (as successfully done during the 2016 DACCIWA campaign) and seek ways to use the new AWS networks.

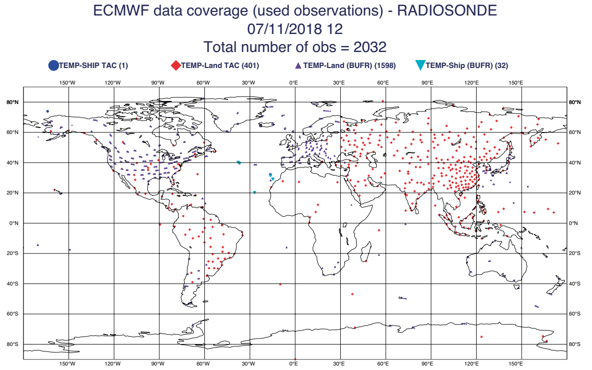


Figure 3. Meteorological sondes available to international meteorological services for inclusion into weather forecasts on 07 November 2018 at 12 UTC. Africa stands out as a continent with poor data coverage. Figure provided by European Centre for Medium-Range Weather Forecasts (ECMWF).

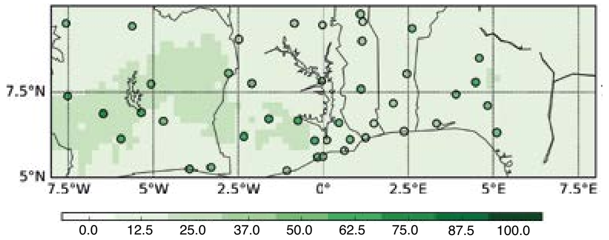
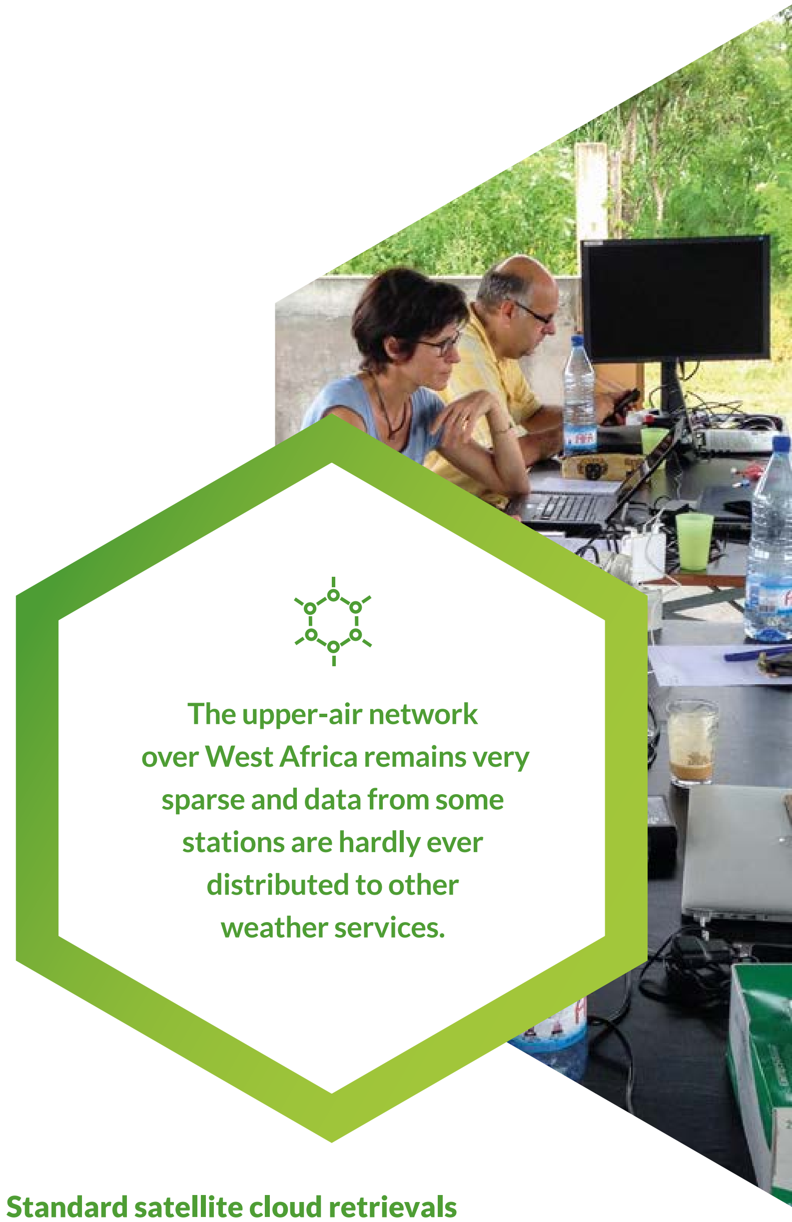


Figure 4. Daily mean cover of low clouds as estimated in the Optimal Cloud Analysis (OCA) satellite product (shading) and from surface observations for the period 01 June – 31 July 2016. Figure from Kniffka et al. [2020].



The upper-air network over West Africa remains very sparse and data from some stations are hardly ever distributed to other weather services.

Standard satellite cloud retrievals underestimate the frequency of low clouds during boreal summer by 30%, leading to errors in surface shortwave radiation.

Adequate temporal sampling of clouds and radiative properties of the atmosphere can only be achieved by geostationary satellites. The Meteosat Second Generation (MSG) Optimal Cloud Analysis (OCA) product is unique for passive retrieval methods from geostationary satellites in that it includes two cloud layers. However, DACCIWA research [*Kniffka et al., 2020*] has shown that OCA misses about 30% of aircraft and ground observations of low cloud cover (Figure 4). This discrepancy is at least partly caused by obscuring higher clouds. Currently, global radiation data are available from less than half a dozen surface stations in southern West Africa, rendering satellite estimates even more important. However, errors in cloud retrievals or potentially erroneous self-calibration due to the frequent presence of low clouds in the widely used Surface Solar Radiation Dataset–Heliosat (SARAH) product, produced by the Satellite Application Facility on Climate Monitoring (CM-SAF), lead to errors in surface shortwave radiation of 20 W m^{-2} and more [*Hannak et al., 2017; Kniffka et al., 2019*].

Meteorological observations for southern West Africa

Inconsistent retrievals of shortwave absorption lead to uncertainty in estimating the total aerosol radiative effect.

Satellite aerosol products from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Multi-angle Imaging SpectroRadiometer (MISR) were compared with observations from the DACCIWA supersite at Savè and nearby Aerosol Robotic Network (AERONET) sites [*Mollard et al., 2020*]. The aerosol optical depth (AOD) of the products is within 12% of observations, with MODIS slightly overestimating and MISR slightly underestimating (Table 1). This difference has little impact on the uncertainty of the radiative effect of aerosols in the region. However, retrievals of the single-scattering albedo (SSA) are significantly lower (i.e. less absorbing) and less variable in the satellite products than from ground-based observations. This produces differences in the top of atmosphere (TOA) outgoing shortwave radiation of 85% of the total direct aerosol effect and of 35% in shortwave radiation reaching the surface. Determining why such differences in aerosol absorption exist should be seen as a priority for future research.

	AOD Differences -Related		SSA Differences -Related	
	SW in at Surface	*SW out at TOA*	*SW in at Surface*	*SW out at TOA*
MISR *AOD = -0.018* *SSA = +0.031*	**+1.94**	**-0.39**	**+7.98**	**+4.37**
MODIS Deep Blue *AOD = +0.021* *SSA = +0.038*	*-2.89*	*+0.59*	*+8.97*	*+4.92*
MODIS Dark Target *AOD = +0.027*	*-3.51*	*+0.71*	*N/A*	
Total Aerosol Effect SW incoming: 26.08 Wm^{-2} SW outgoing: 5.82 Wm^{-2}				

Table 1. Radiative impact of calculated differences in aerosol optical depth (AOD) and single scattering albedo (SSA) on upwelling shortwave (SW) flux at the top of the atmosphere (TOA) and downwelling shortwave flux at the surface when using satellite products compared to ground-site retrievals. All radiative flux differences are given in units of W m^{-2}. Values of AOD and SSA provided are differences of averages taken over June and July 2016, and with respect to combined AERONET and DACCIWA ground-site retrievals. Information is based on Mollard et al. [2020].

Satellite-based rainfall datasets tend to overestimate the number and length of weak rainfall events while underestimating the intensity of strong events.

Three-hourly TRMM (Tropical Rainfall Measuring Mission) 3B42 rainfall estimates and its successor product GPM IMERG (Global Precipitation Mission, Integrated Multi-satellite Retrievals for GPM) have been tested against observational data from networks of National Weather Services and of DACCIWA. Both products show low biases over monthly periods, since they are calibrated with gauge observations. During the DACCIWA field phase GPM IMERG underestimated rainfall over almost entire southern West Africa except for relatively dry central Ivory Coast [*Kniffka et al., 2020*]. Using rainfall with a 30-minute temporal resolution from 17 DACCIWA rain gauges around Kumasi (Ghana), it was found that the gauge calibration in GPM IMERG leads to an error compensation between different rainfall types [*Maranan et al., 2020*]. False alarms are very frequent (Figure 5), particularly in the dry season, account for over one fifth of total rainfall within GPM IMERG and contribute crucially to achieve a monthly amount comparable to rain gauges during the rainy season. About 40% of False alarms are related to an overestimation of the length of short (and often weak) rainfall events, while intense and/or long rainfall events are underestimated. Misses also occur frequently, particularly for short and weak rainfall events during the little dry season in June–August, often related to relatively warm clouds. These findings are relevant for forecast verification at daily and sub-daily time scales.

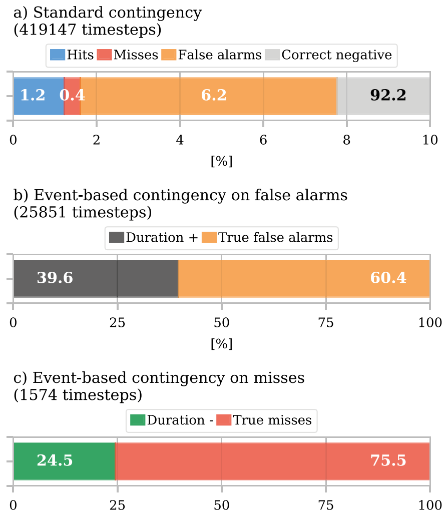


Figure 5. Comparison of 30 minute rainfall events (≥0.1mm) from satellite-based GPM IMERG and the DACCIWA 17-station raingauge network around Kumasi (Ghana) during 2016–2017. (a) Distribution of Hits (agreement on event), Misses (station detects event but GPM-IMERG does not), False alarms (GPM-IMERG detects event but station does not) and Correct negative (agreement on non-event). Note that the axis is truncated at 10% for clarity. Fraction of False alarms (b) and Misses (c) related to errors of mis-estimating event duration. Figure from Maranan et al. [2020].

Emission data for southern West Africa

To produce useful air pollution control strategies and forecasts, estimates of the magnitude of the different emission sources of aerosol and trace gases need to be made. DACCIWA calculated new emissions for Africa, evaluated them against standard international emissions and against local observations.

DACCIWA compiled a new inventory of human emissions for Africa that compares better with observations than standard emissions datasets.

The EDGAR dataset [*Crippa et al., 2018*] is the global standard for air pollutant emissions. It can be inaccurate, especially in regions which have not been extensively studied. DACCIWA constructed new emissions [*Keita et al., 2018*] which used Africa-specific information. These are available from http://eccad.aeris-data.fr. Figure 6 shows a comparison between the mass of key air pollutants emitted over southern West Africa by the EDGAR and DACCIWA inventories, together with an enhanced DACCIWA emissions dataset that exploits the DACCIWA observations to optimize the emissions. For many species (notably organic carbon and black carbon) the EDGAR data underestimate emissions. PM2.5 in the lowest kilometre of the atmosphere as simulated by the air pollution model GEOS-Chem is about half when using EDGAR emissions as compared to those observed and found from using the DACCIWA specific emissions.

Emissions of particles and organic gases from vehicles in southern West African cities are higher than those in other locations.

DACCIWA made direct measurements of the particles and organic gases emissions from individual vehicles in Côte d'Ivoire [*Keita et al., 2018*]. They were much higher than had been assumed for the region (Figure 7) suggesting that the emission of organic compounds had been significantly underestimated over southern West Africa. Old gasoline vehicles are more polluting (factor of a thousand) than new vehicles. Older diesel vehicles were only a factor of five worse. New four-stroke engines have significantly lower emissions than new two-stroke engines.

Burning seemingly similar materials may lead to very different emissions.

Keita et al. [2018] found that the emissions of particles from domestic fires depend strongly on the type of wood burnt. Hevea wood was found to be the largest emitter. Thus when considering emissions from wood burning, notably for cooking, the type of wood as well as the volume needs to be considered.

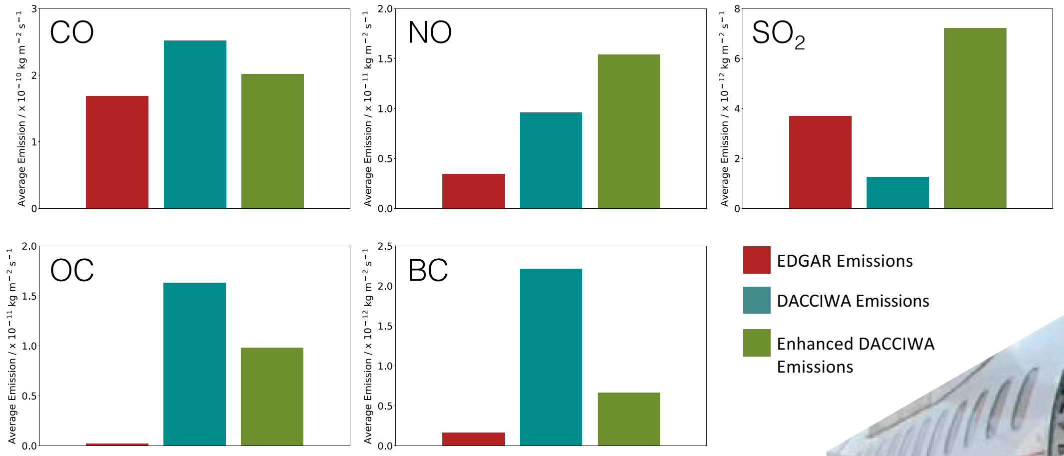


Figure 6. Comparison of average annual emission of CO, NO, SO_2, Organic Carbon (OC) and Black Carbon (BC) from southern West Africa as calculated by the EDGAR and DACCIWA emissions inventories together with an enhanced DACCIWA emissions dataset which exploits the DACCIWA observations to optimize the emissions inventory. Figure from Evans et al. [2018].

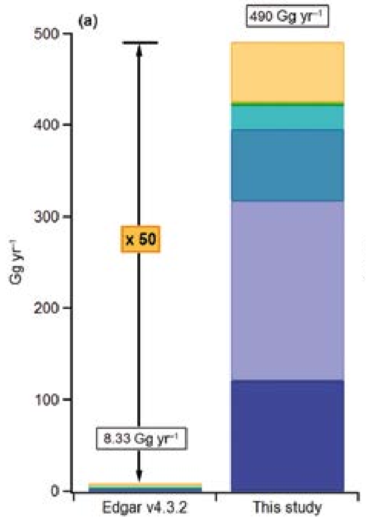
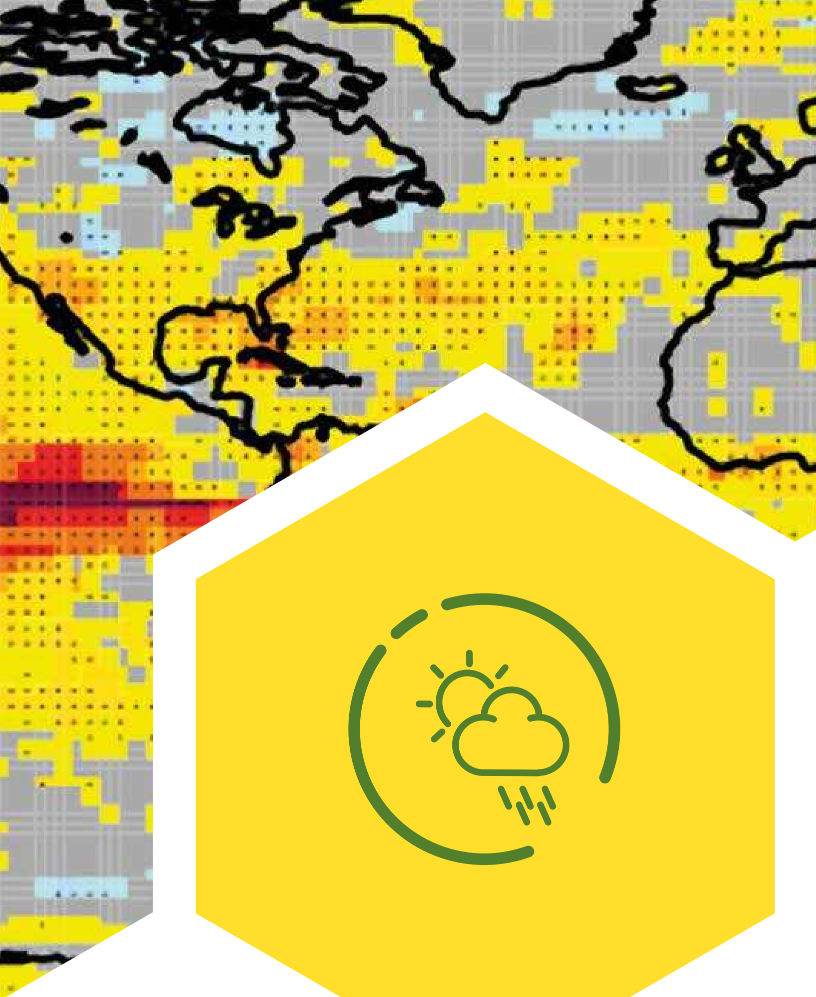


Figure 7. Mass of organic compound emitted by the transport sector from Côte d'Ivoire estimated by the EDGAR emissions (left) and by the DACCIWA project (right). There is a 50-fold underestimate in the emissions inventory for these compounds. Figure taken from Keita et al. [2018].

Standard global estimates of human emissions are significantly underestimated for southern West Africa.



Quality of operational forecasts

Reliably forecasting the weather and providing climate projections with sufficient confidence is of enormous socio-economic importance, particularly for an area dominated by rain-fed agriculture such as West Africa. In DACCIWA and related projects, the ability of models to represent the local and regional weather and climate was assessed in several ways. Evaluations included local-and regional-scale, day-to-day forecasts of numerical weather prediction (NWP) models, post-processed outputs of global ensemble prediction systems, a multi-model climate evaluation analysis and model sensitivity experiments.

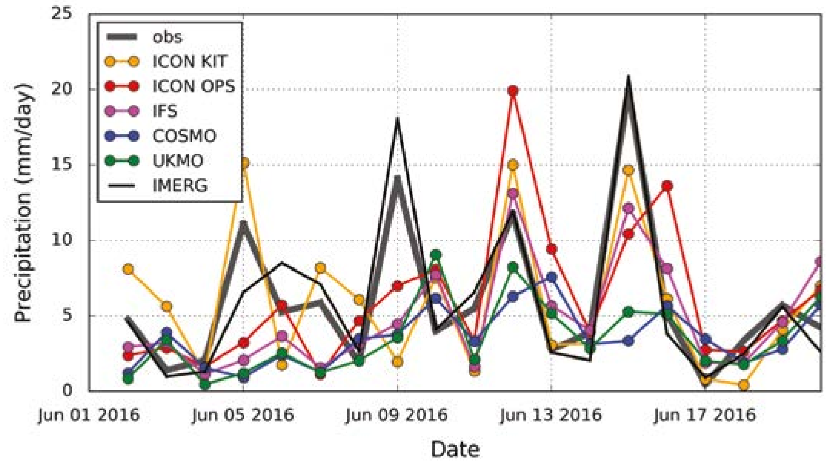


Figure 8. Time-series of one-day precipitation forecasts as predicted with five different NWP models (ICON is run in two different configurations) for 01–20 June 2016 as compared to all available station observations and GPM-IMERG satellite estimates over southern West Africa (5–10°N, 8°W–8°E). Only valid data pairs per location and time are included. Figure from Kniffka et al. [2020].

NWP skill in rainfall and cloud prediction is overall low with some skill evident on the regional level when synoptic-scale vortices are present.

A comprehensive evaluation of global ensemble prediction systems with station and satellite data showed that raw and even post-processed precipitation forecasts cannot outperform statistical predictions based on climatological records [*Vogel et al., 2018*]. This statement holds for different West African sub-regions and for spatial scales up to several hundred kilometres and temporal accumulations of up to five days. Rainfall forecasts over tropical Africa are worse than in any other part of the tropics [*Vogel et al., 2020*]. Specifically for southern West Africa and the data-rich DACCIWA campaign period (1 June to 31 July 2016) a detailed evaluation of five operational NWP models was conducted [*Kniffka et al., 2020*]. While local daily variations in cloud and rainfall are almost uncorrelated with model predictions, measurable skill was detected for regional variations connected to synoptic-scale, slowly propagating vortex-like structures (Figure 8) [*Knippertz et al., 2017; Kniffka et al., 2020*].

Forecasts tend to be too cold and dry at the immediate Guinea Coast during the summer monsoon, possibly due to problems with the Maritime Inflow phenomenon.

Evaluating temperatures in the NWP models showed that after the summer monsoon onset towards the end of June most models are too cold and dry near the surface in coastal areas (Figure 9). This result was also seen at lower tropospheric levels when comparing models with near-coastal radiosondes and in a detailed comparison of the operational ECMWF analysis with aircraft measurements, which showed a mean dry bias of 1 g kg^{-1} [*Maier and Voigt, 2018, German Aerospace Center; pers. comm.*]. A closer inspection of other fields showed that models are too cloudy at the immediate coast, likely leading to suppressed daytime heating and vertical mixing [*Kniffka et al., 2020*]. This suggests that the Gulf of Guinea Maritime Inflow described in *Deetz et al. [2018a]*, *Adler et al. [2019]* and *Lohou et al. [2020]* is not reproduced realistically in these models.

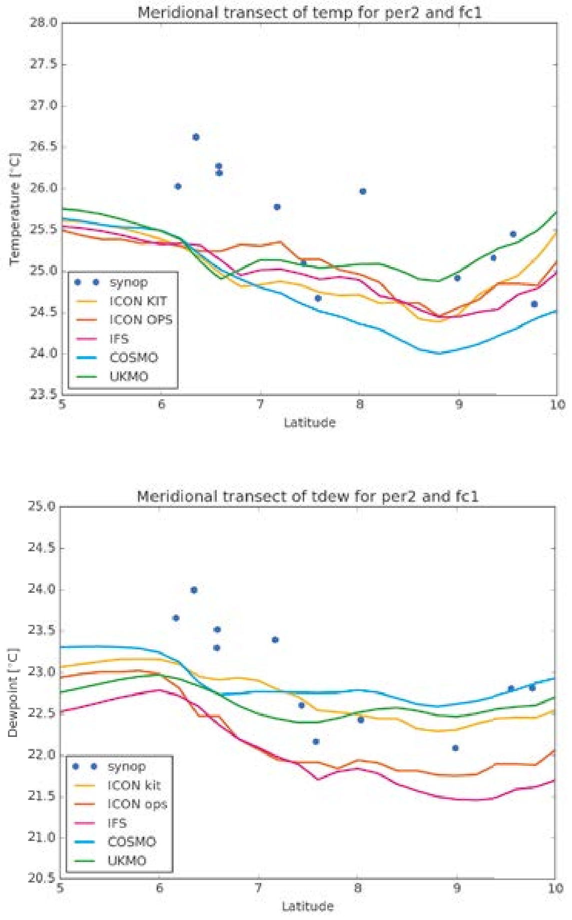


Figure 9. 2m-temperature (top) and dew point (bottom) along a meridional transect covering Benin, Togo and easternmost Ghana during 22 June – 31 July 2016. Dots are all available SYNOP stations, lines are zonal averages from five NWP models (ICON is run in two different configurations). Figure from Kniffka et al. [2020].

Quality of operational forecasts

Low clouds tend to be underestimated in many weather and climate models, leading to too much incoming solar radiation at the surface.

Low clouds are a ubiquitous feature of the atmosphere in summertime southern West Africa. They typically form in the course of the night and dissolve in the course of the day. Many atmospheric models tend to underestimate their cover and/or duration. This is seen for climate models (including a tendency for too high cloud elevation and too weak diurnal cycle) [*Hannak et al., 2017*] and NWP models [*Kniffka et al., 2019; 2020*]. The underestimation of cloud cover results in too much solar radiation reaching the Earth's surface, which increases vertical mixing and changes the daily evolution of the boundary layer. Specifically for the DACCIWA campaign period, the time-mean, model-averaged underestimation of fractional low-level cloud cover is 11% (Figure 10, top). The resulting bias in solar surface irradiance for the five models is 43 W m^{-2} (Figure 10, bottom).

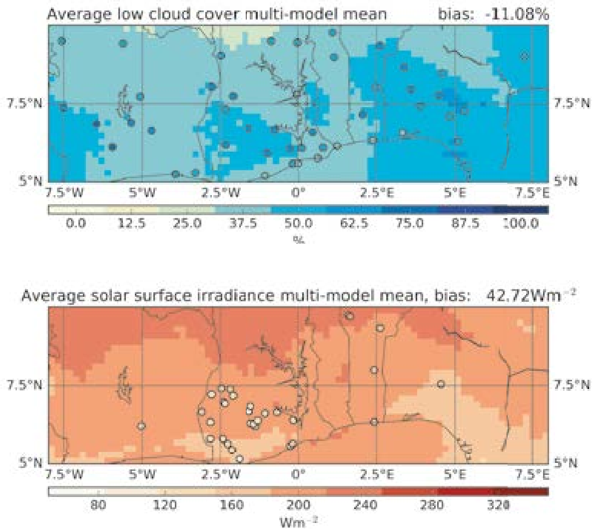


Figure 10. Average cloud cover (top) and surface solar irradiance (bottom) for the five NWP models (see Figure 9) used during the DACCIWA field campaign period from 01 June to 31 July 2016. The coloured circles indicate corresponding station observations. Figure from Kniffka et al. [2020].

A more realistic representation of convection in West Africa can improve medium-range forecasts in the extratropics including Europe.

Mesoscale convective systems are a dominant weather phenomenon over the summertime West African Sahel. These systems are not adequately represented in global weather and climate models, due to convective parameterisations. This leads to a misrepresentation of the entire West African monsoon circulation [*Marsham et al., 2013*] and also affects model results over the neighbouring North Atlantic/European sector [*Pante and Knippertz, 2019*]. Figure 11 exemplarily shows the widespread positive effect on the root mean squared error of geopotential at 500 hPa resulting from increased horizontal resolution and explicit convection over West Africa, particularly over the tropical belt, off the South African coast and over northern Europe. The fact that a substantial reduction of systematic errors occurs over West Africa after only a few days and then stays on a constant level suggests potential positive impacts on sub-seasonal to climate timescales.

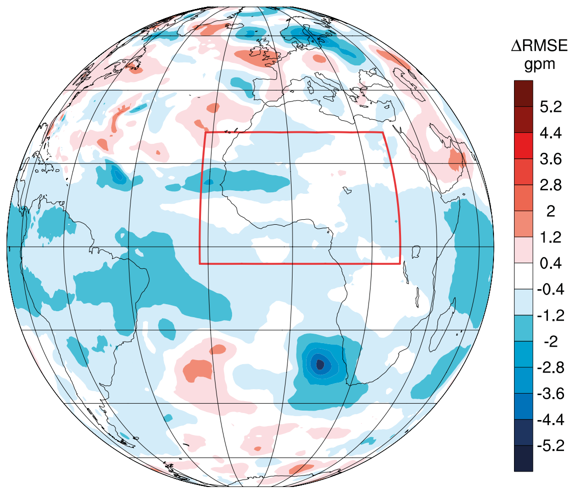


Figure 11. The impact of convection over West Africa on the forecast skill is illustrated by the difference of simulations with globally parameterised convection minus forecasts explicitly resolving convection in the red bordered region for July and August 2016 and 2017. Blueish colours show the average reduction of the root mean squared error of geopotential at 500 hPa for forecast days 5 to 8 due to explicit convection. Adapted from Pante and Knippertz [2019].

Impact of additional radiosonde observations on analyses and forecasts

Data denial experiments have proven useful in assessing the benefit of assimilating observations into an atmospheric model. A prime example is *Agustí-Panareda et al. [2010]*, who quantified the influence of radiosonde measurements from the African Monsoon Multidisciplinary Analysis (AMMA) in August 2006 (mostly in the Sahel) on the ECMWF analysis and forecasts. In DACCIWA we repeated this exercise with the most recent ECMWF model cycle for the eleven radiosonde stations active during the field campaign from 15 June until 31 July 2016 *[van der Linden et al., 2020]*. In the following, the experiments with and without assimilation of DACCIWA radiosonde data will be referred to as “DACCIWA” and “noDACCIWA”, respectively.

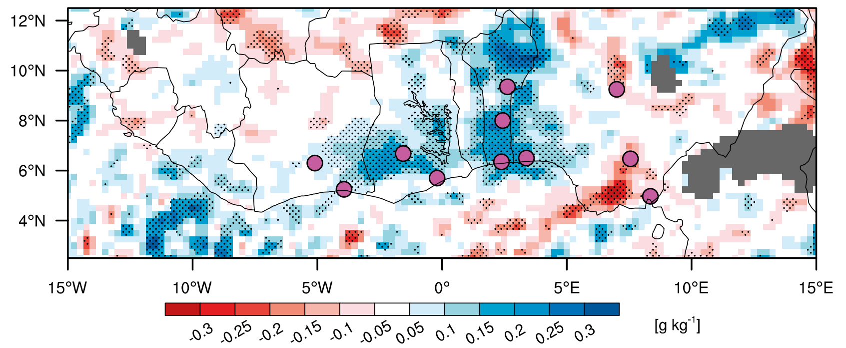


Figure 12. Early morning (06 UTC) bias of specific humidity on ECMWF model level 120 (near 925 hPa) calculated as the mean differences between the “DACCIWA” and “noDACCIWA” analyses at 0600 UTC during 15 June to 31 July 2016. Stippling highlights regions with statistically significant differences. Regions where the 925 hPa pressure level lies below orography are masked in grey. The filled circles indicate the locations of the radiosonde stations. Figure after van der Linden et al. [2020].

The assimilation of an unprecedented radiosonde dataset into the ECMWF model shows a lower-tropospheric dry bias in parts of southern West Africa during the wet summer monsoon.

For low-level specific humidity the “DACCIWA” analysis is much moister than “noDACCIWA”, mostly over Benin and parts of Ghana (Figure 12). This dry bias in the model is in qualitative agreement with a comparison between aircraft measurements during the DACCIWA campaign and the ECMWF operational analysis *[Maier and Voigt, 2018, German Aerospace Center; pers. comm.]*.

The same ECMWF model also shows a general cold bias, possibly due to too strong cold advection from the Gulf of Guinea during the night.

The assimilation of DACCIWA data makes 925 hPa temperatures in the ECMWF analysis at 06 UTC warmer by up to 0.4 K in considerable parts of southern West Africa, particularly downstream (i.e. north) of the radiosonde stations in Ivory Coast and Ghana (Figure 13, top). The wind differences at 00 UTC at the same level indicate a slow-down of the monsoon wind over southern Ivory Coast and parts of Ghana in response to the extra observations (Figure 13, bottom), suggesting too strong nighttime cold air advection from the Gulf of Guinea in the model.

Forecast improvements due to better observations are moderate at best, pointing to model and data assimilation deficits being a substantial obstacle to better forecasts.

An evaluation of forecasts started from “DACCIWA” and “noDACCIWA” analyses was done with respect to the supposedly improved “DACCIWA” analysis. As expected, the former does in fact perform better, but only up to 12h lead times and mostly for temperature. The overall rather small observation impact suggests that model and data assimilation deficits are the main limiting factors for better forecasts in West Africa. A similar conclusion was drawn by *Agustí-Panareda et al. [2010]* for the AMMA radiosondes, indicating unsatisfactory progress in model development.

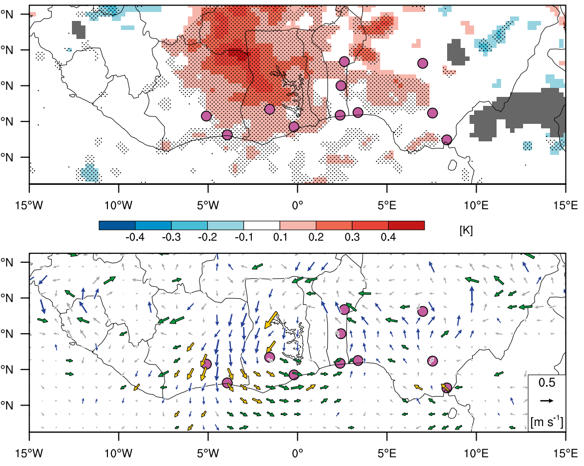


Figure 13. Early morning (06 UTC) 925-hPa temperature bias (top) and night-time (00 UTC) 925-hPa vector wind bias (bottom) calculated as the mean differences between the “DACCIWA” and “noDACCIWA” analyses during 15 June to 31 July 2016. Stippling highlights regions with statistically significant differences. Only every third vector is shown. Colours of vectors indicate statistical significance of vector differences: blue vectors where only meridional component is significant, green vectors where only zonal component is significant, yellow vectors where both components are significant and grey vectors where no component is significant. Regions where the 925 hPa pressure level lies below orography are not plotted. The filled circles indicate the locations of the radiosonde stations. Figure after van der Linden et al. [2020].

Importance of aerosol

Aerosols are important players in the Earth's radiation balance, directly or through their influence on clouds, particularly on climate time-scales. Prognostic aerosols are now increasingly being used in NWP models, but only rarely so far on sub-seasonal to seasonal time scales. *Benedetti et al. [2018]* provide a detailed review of the status and future of aerosol predictions within NWP worldwide, with a focus on the data required. DACCIWA used a range of modelling experiments to demonstrate the effect of aerosol on the atmosphere over West Africa and investigated the added value of including it in forecasts.

Aerosol influences the atmosphere mostly through radiative and less through cloud microphysical effects with an important role for water uptake by aerosol particles.

Modelling studies suggest that the overall aerosol concentrations in southern West Africa are so high that cloud condensation nuclei are abundant and that sensitivities with respect to cloud-aerosol interactions are low (indirect aerosol effect). This is due to a combination of local emissions with import of biomass burning aerosol from Central Africa [*Haslett et al., 2019a*]. In contrast, aerosols do affect meteorology by reducing the amount of sunlight reaching the Earth's surface. Remarkably, the humid environment during the wet summer monsoon allows a substantial uptake of water, particularly in the morning hours [*Haslett et al., 2019b*]. Extinction can increase by about a factor of 6, leading to an overall doubling of the aerosol optical depth (AOD; Figure 14). Reductions in surface heating of 20 Wm^{-2} through this process are seen [*Deetz et al., 2018b*].

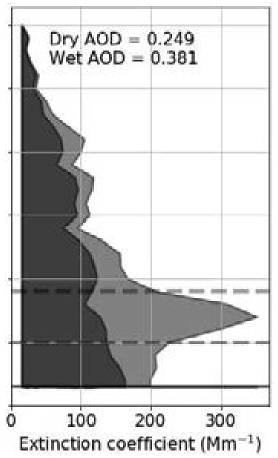
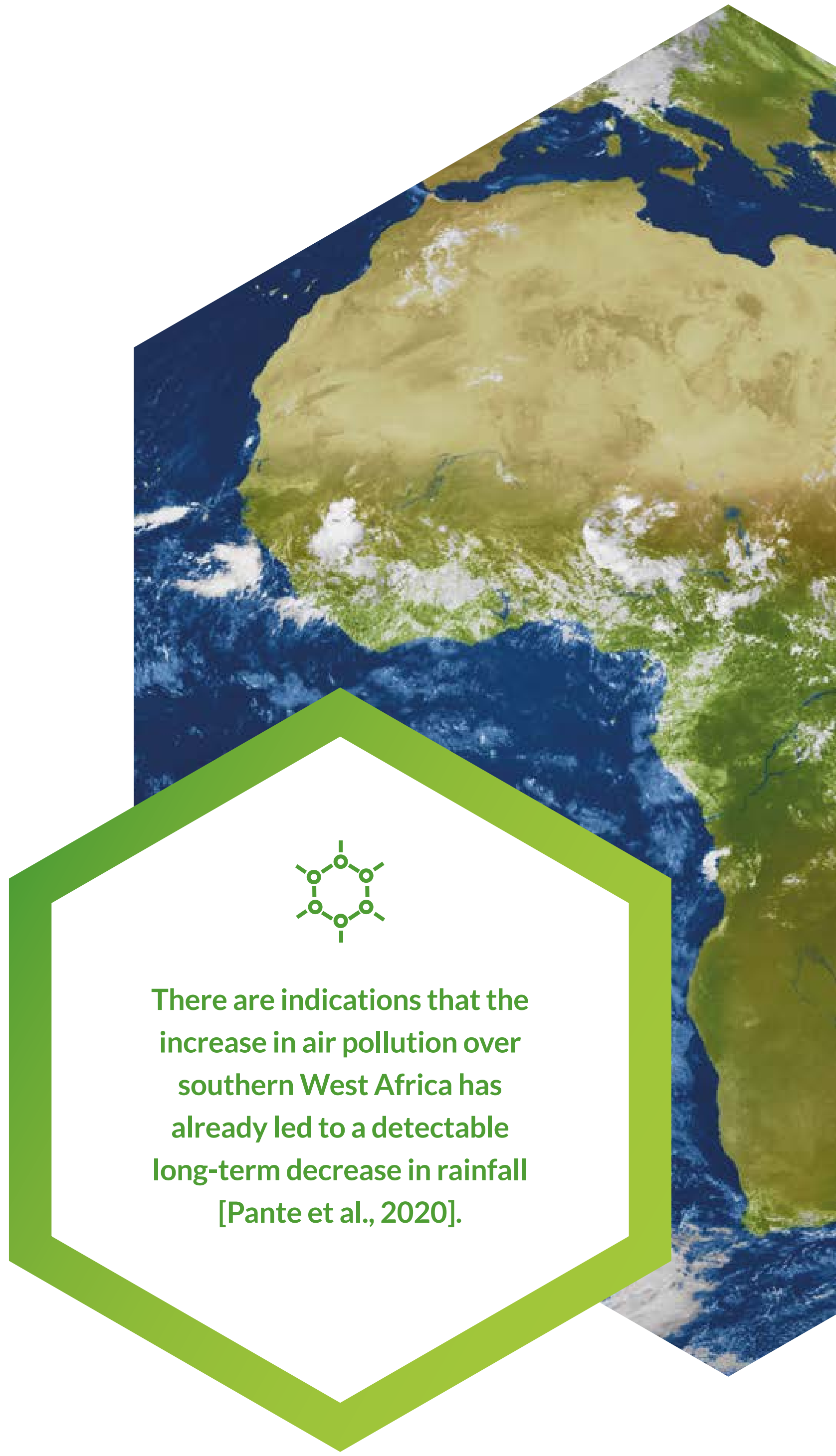


Figure 14. Exemplary calculation of a vertical profile of the extinction coefficient based on relative humidity from a radiosonde ascent at Savè (Benin) at 11 UTC on 08 July 2016 and a representative aerosol concentration. AOD stands for aerosol optical depth. The dashed grey lines outline the layer with relative humidity greater than 95%. Figure from Haslett et al. [2019b].

The radiative effect of aerosol likely delays the daytime stratus-to-cumulus transition, the advancement of the coastal front and convective triggering, leading to more intense storms but less rainfall overall.

The radiative effects of aerosol slow down the daytime surface heating and build-up of the planetary boundary layer. This decreases the temperature contrast between land and sea and so delays the inland progression of the coastal front during the late afternoon and evening by up to 30 km (Figure 15, left) and the daytime development from low layer-clouds to deeper, more patchy clouds by 1–2 hours (Figure 15, right) [*Deetz et al. 2018a*]. Model studies varying the optical depth of the low clouds show similar effects on surface solar radiation and demonstrate that dimming leads to a reduction in rainfall [*Kniffka et al., 2019*]. Equally, an increase in dust aerosol leads to less but more intense organised convective systems but less total rainfall [*Reinares Martínez et al., 2018a*]. There are indications that the increase in air pollution over southern West Africa has already led to a detectable long-term decrease in rainfall *[Pante et al., 2020]*.



There are indications that the increase in air pollution over southern West Africa has already led to a detectable long-term decrease in rainfall [Pante et al., 2020].

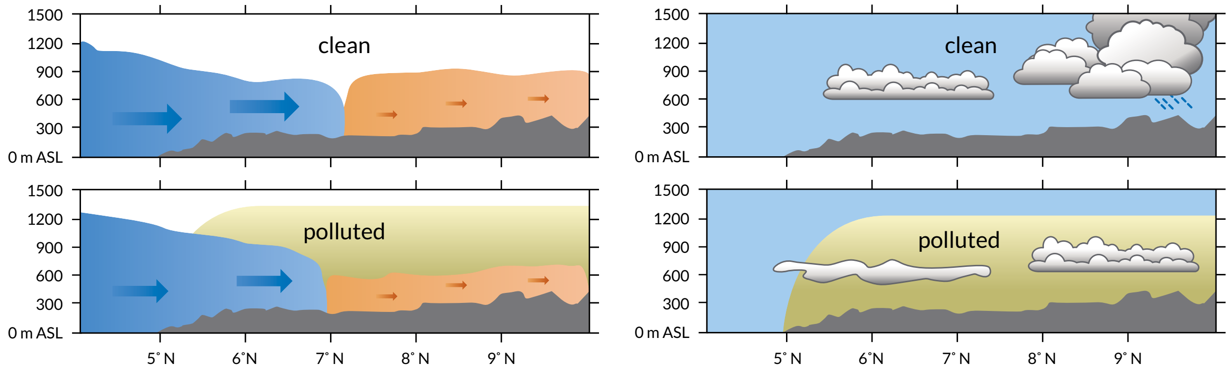


Figure 15. South–north vertical transects through southern West Africa illustrating impacts of pollution on clouds and precipitation (right) and the coastal front, a daily feature that moves inland during the evening and night (left). In the polluted case (bottom) the front is delayed relative to the clean case (top), which is related to reduced surface heating leading to a shallower and less warm layer over land and weaker inflow of cool maritime air. With respect to clouds reduced heating during the day leads to a delayed transition from shallow layer-clouds to deeper (potentially raining) clouds. Figure from Evans et al. [2018].

An interactive representation of dust and biomass burning aerosol from central Africa can improve subseasonal predictions.

Aerosol biases that produce small effects on timescales of days might accumulate over weeks to months. Comparing direct aerosol effects on monthly predictions using ECMWF's Ensemble Prediction System with climatological and interactive aerosol indeed show an improvement for dust, the emission of which depends strongly on meteorological variables [*Benedetti and Vitart, 2018*]. Furthermore, interactive aerosols improve monthly predictions for the spring/summer season in the northern hemisphere (Figure 16, middle). It is suggested that this is related to a modulation of dust by the Madden-Julian Oscillation, which in turn creates an aerosol radiative forcing. For the entire tropics, however, changes in subseasonal prediction quality between interactive and climatological aerosol are small (Figure 16, right), while those for West Africa (Figure 16, left) are larger but show both positive and negative effects depending on the meteorological parameter. Removing all biomass burning emissions, seriously degrades the forecasts of several meteorological variables over West Africa with respect to a forecast including all aerosol species [A. Benedetti, manuscript in prep.].

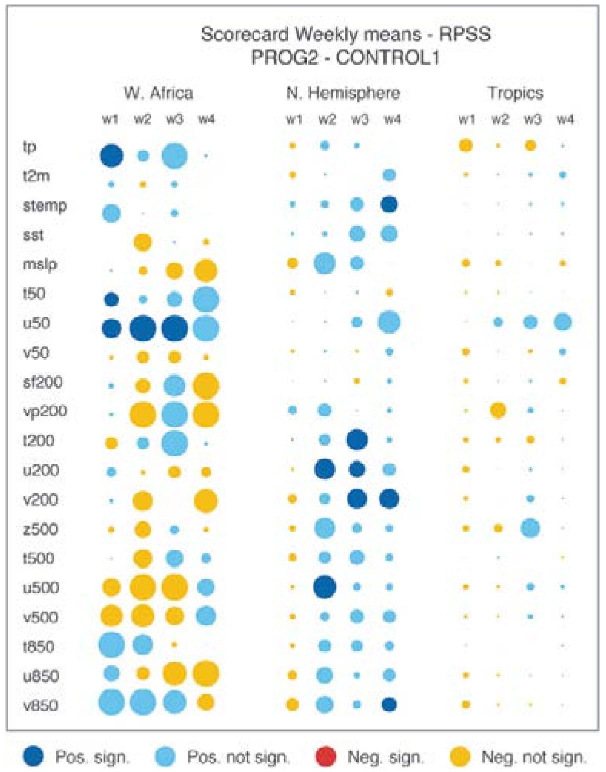
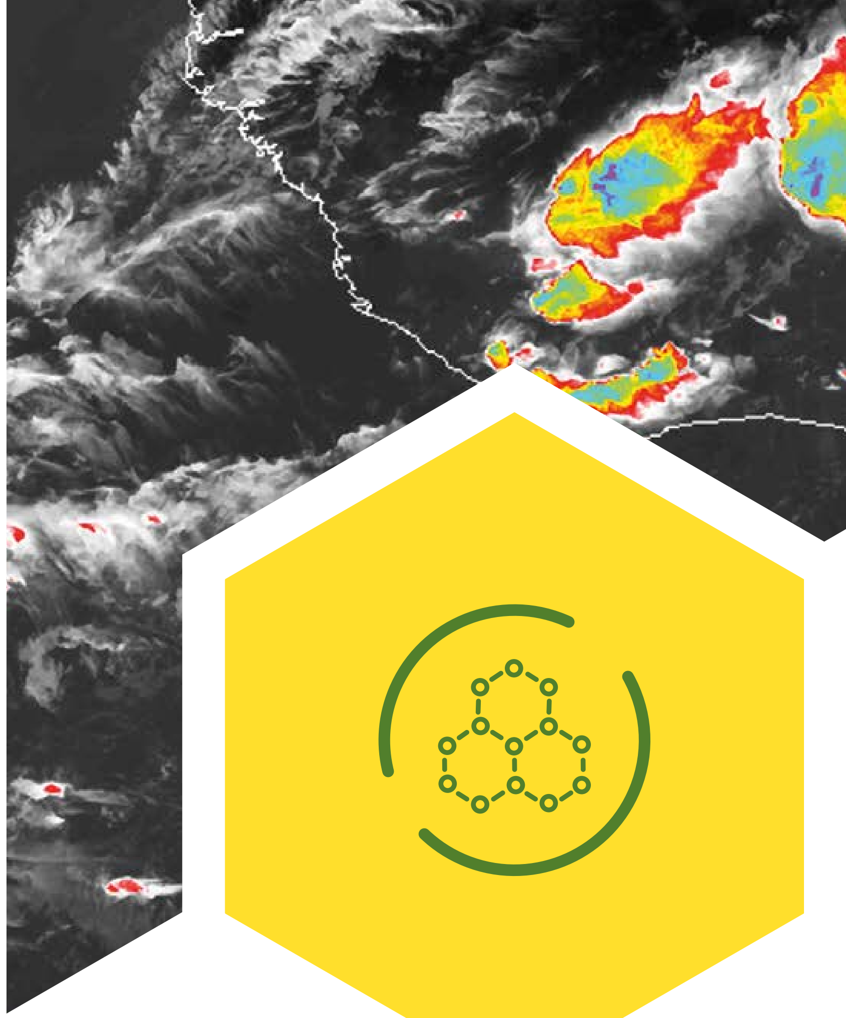


Figure16. Scorecard for an experiment with prognostic aerosols (PROG2) compared to one using an aerosol climatology (CONTROL1), both started on 01 May. w1 corresponds to forecast days 5–11, w2 to 12–18, w3 to 19–25 and w4 to 26–32. Verified variables are total precipitation (tp), 2m temperature (t2m), surface temperature (stemp), sea surface temperature (sst), mean sea level pressure (mslp), temperature (tX), zonal wind (uX), meridional wind (vX), streamfunction (sfX) and velocity potential (vpX), where X is the respective pressure level in hPa. Twelve years of re-forecasts with 50 ensemble members of the ECMWF system were analysed. Adapted from Benedetti and Vitard [2018].



Critical processes suspected to cause model error

DACCIWA research has unveiled a number of processes, the representation of which appear particularly critical in state-of-the-art models. These are low clouds and nocturnal low-level jets, warm rain and drizzle, convective organisation, and tropical wave phenomena. Modelling centres around the world should pay particular attention to these meteorological features and actively seek to improve their representation.

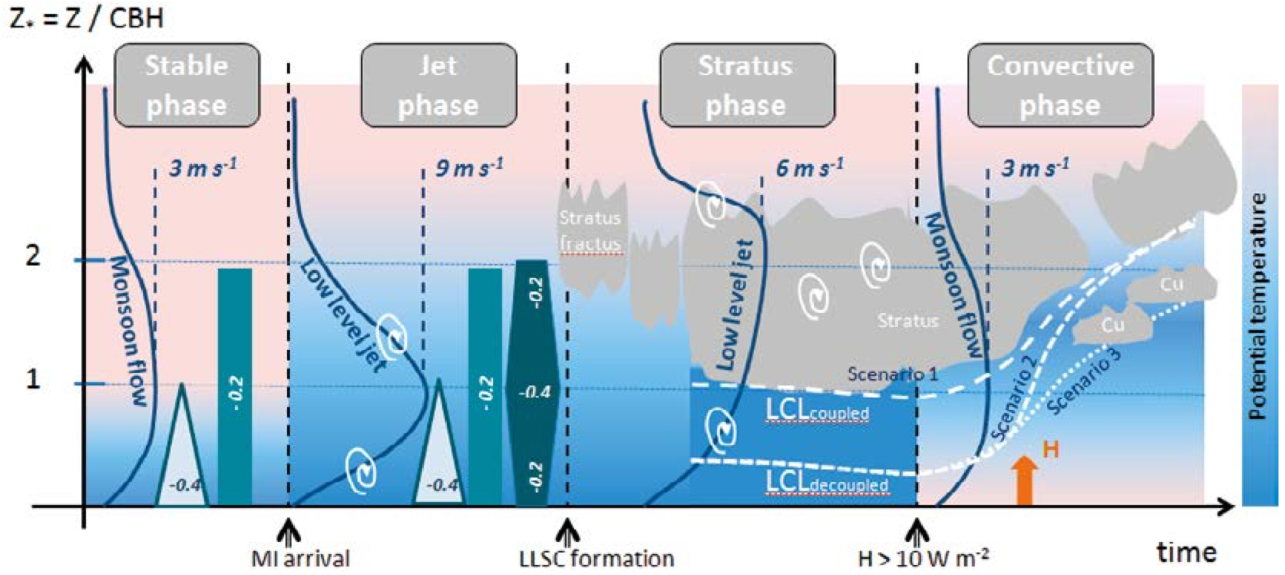


Figure 17. Conceptual model for the diurnal cycle of low-level stratiform clouds over southern West Africa. The height is normalized by the cloud base height when the stratus clouds form. The grey shades represent the stratus fractus or stratus or cumulus cloud (Cu). The three dashed white curves indicate the lifting condensation level (LCL). Each of them represents one scenario (of three) of convective boundary layer development found during the DACCIWA field campaign. The dark blue lines reproduce the vertical profiles of the wind with an indication of its maximum value for each phase. The various blue symbols at the bottom represent processes involved in temperature changes. H stands for the surface sensible heat flux and is symbolized by an orange arrow during the convective phase. The curled white arrows symbolize nocturnal dynamical turbulence either due to the radiative cooling at the cloud top or to the wind shear in the nocturnal low-level jet. Figure from Lohou et al. [2020].

DACCIWA's new observations-based conceptual model for the formation and dissolution of the extensive low cloud decks of southern West Africa can be used as a benchmark for models.

It is well established that low, warm clouds frequently occur over southern West Africa [e.g. *van der Linden et al., 2015; Hill et al., 2018; Kalthoff et al. 2018*]. Based on extensive field observations at Savè (Benin), Kumasi (Ghana) and Ile-Ife (Nigeria) [*Kalthoff et al., 2018; Adler et al., 2019; Babić et al., 2019a, b; Dione et al., 2019*], DACCIWA has developed a new conceptual model for such clouds divided in four phases (Figure 17), which can serve as a benchmark for model evaluation. The stable phase starting in the late afternoon is characterised by a weak monsoon flow, vanishing thermal convection and the formation of a stable layer close to surface. The jet phase starts with the arrival of the Gulf of Guinea Maritime Inflow [*Adler et al., 2017; Deetz et al., 2018a; Lohou et al., 2020*] and involves the onset of the nocturnal low-level jet. In the third phase low-level clouds form and thicken, mostly as a consequence of cold air advection and to a lesser extent of radiation and flux divergence. Shear-driven turbulence creates mixing during this phase. The start of the vertical development of the convective boundary layer marks the last phase, finally leading to cloud breakup, which can take place according to three scenarios [*Pedruzo-Bagazgoitia et al., 2020; Lohou et al, 2020*].

Critical processes suspected to cause model error

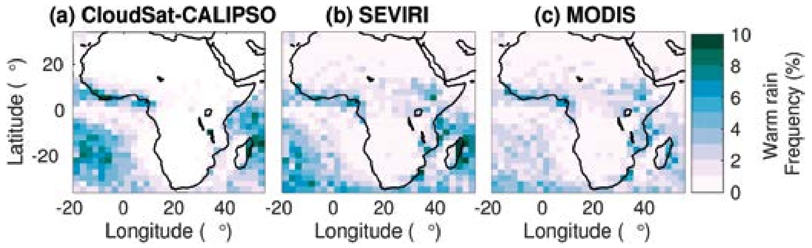


Figure 18. Geographic distributions of warm rain frequency (%) from (a) CloudSat-CALIPSO, (b) SEVIRI, and (c) MODIS during JJA, 2007–2010. All frequencies are computed with respect to the total number of collocated observations, at common grids of 2.5°×2.5°. Figure from Young et al. [2018].

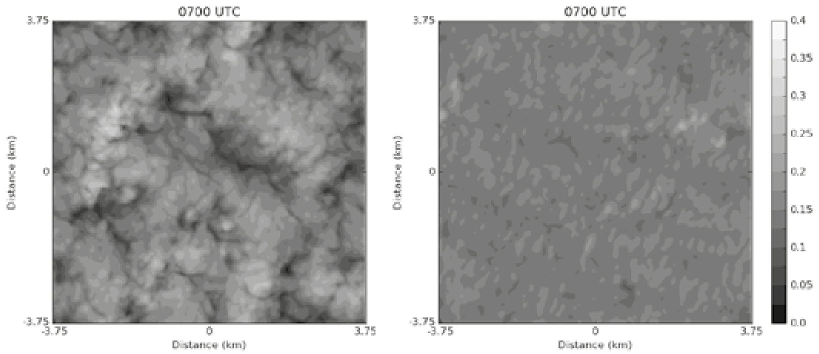


Figure 19. Spatial distribution of liquid water path (kg m^{-2}) at 07 UTC for a version of the MONC large eddy model with (left) and without (right) droplet sedimentation. The highly idealised model runs are designed to mimic low clouds over southern West Africa. Taken from Dearden et al. [2018].

Warm rain and drizzle frequently occur in southern West Africa during the summer monsoon season impacting on cloud lifetime and the vertical distribution of moisture.

Passive-satellite rainfall retrievals can miss warm rain from shallow liquid phase clouds, while active spaceborne radars such as CloudSat, detect warm rain but provide limited time-space coverage. A new warm rain detection method developed by DACCIWA based on geostationary satellite cloud retrievals from SEVIRI [*Young et al., 2018*] reveals frequent warm rain over ocean and coastal regions, but infrequent warm rain inland (Figure 18). This is consistent with radar observations from the DACCIWA supersite in Savè (Benin) [*Reinares Martínez et al., 2020*]. A 12-year satellite climatology derived from SEVIRI retrievals shows that warm rain prevails over orographic regions in the morning and coastal hinterlands after midday, enhanced by orographic lifting and land-sea breeze effects [*Young et al., 2018*]. Rain from relatively warm clouds is also suspected to create failed detection of rain events in the satellite product GPM IMERG [*Maranan et al., 2020*].

Despite the shallow nature of warm clouds over southern West Africa, an appropriate parameterisation of the effects of sedimentation is required to represent them in models, even when they are not precipitating [*Dearden et al., 2018*]. Sedimentation acts to remove liquid water from the entrainment zone near cloud top, reducing the magnitude of evaporative and longwave radiative cooling during entrainment mixing. This increases the rate of growth of liquid water path during the night-time and early morning period. Ignoring droplet sedimentation completely reduced liquid water path variability by around a factor of 2 at 07 UTC (Figure 19) and also elevated the mean cloud-base height by an additional 200 m by the end of the simulation period.

Convective organisation is a key element of the meteorology of southern West Africa, creating large sensitivities to model resolution.

It is well established that organized mesoscale convective systems are key to precipitation generation in West Africa, with a decreasing importance from the Sahel towards the Guinea Coast [*Maranan et al., 2018*]. Convection-permitting simulations capture this much better than parameterised convection with positive impacts on the diurnal cycle [*Reinares Martínez and Chaboureau, 2018b; Pante and Knippertz, 2019*]. Organised convection generates a large fraction of dust in West Africa (haboobs), but explicit convection does not always pull through to improved modelled dust fields [*Marsham et al., 2011; Chaboureau et al., 2016; Roberts et al., 2018*]. Capturing convection explicitly has a large effect on the distribution of rainfall in the West African monsoon region [*Marsham et al., 2013; Birch et al., 2014; Pante and Knippertz, 2019*] but this does not automatically lead to improved rainfall fields (Figure 20). Vertical mixing and non-precipitating clouds that affect radiation play an important role, too [*Kniffka et al., 2019*]. Finally, assessments of future climate change are sensitive to the explicit treatment of convection [*Jackson et al., 2020*].

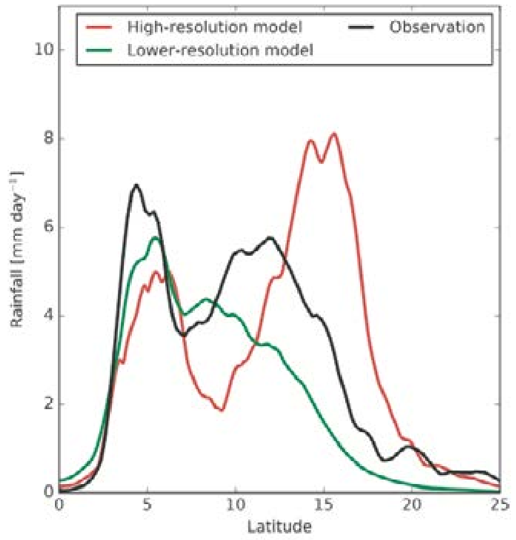


Figure 20. North–south distribution of rainfall averaged from 8°W to 8°E in July 2006. Shown are satellite-based observations from TRMM (black) and simulations with the ICON model currently operational at the German Weather Service in high-resolution (6.6 km, explicit convection, red) and somewhat lower resolution (13.2 km, parameterised convection, green). All curves are smoothed for better visibility. Figure adapted from Kniffka et al. [2019].

African easterly waves and Kelvin waves considerably modulate rainfall and need to be better represented in models

Different types of synoptic- to planetary-scale waves modulate rainfall over West Africa on timescales from several hours to several days by changing conditions for convective organisation such as moisture, instability and shear [*Schlueter et al. 2019a,b*]. The largest amplitudes are found for African easterly waves and Kelvin waves (Figure 21). Models tend to underestimate the modulation strengths of the waves, even when convection is explicitly represented [*Jackson et al., 2019*]. This calls for further sensitivity testing and model development into the mechanisms of convection-wave coupling [*Bengtsson et al., 2019*].

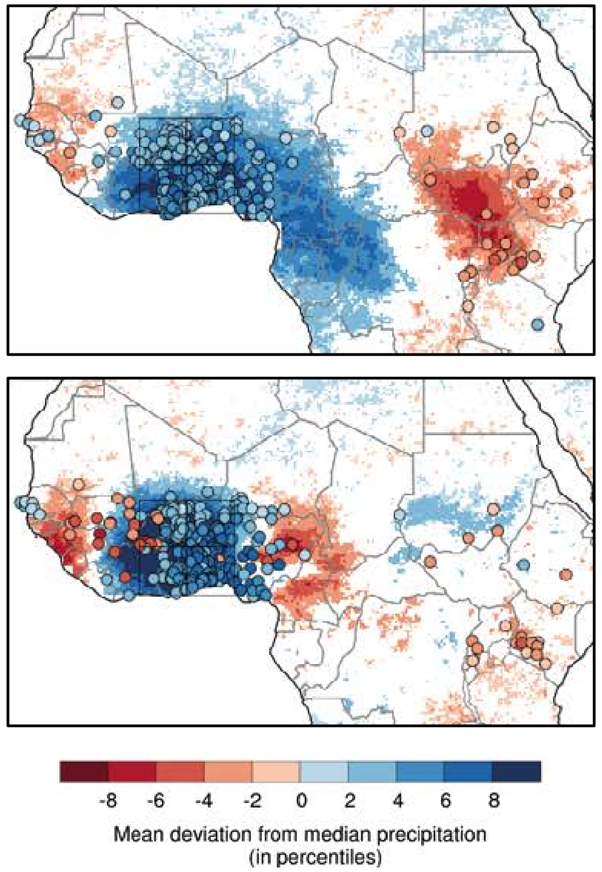


Figure 21. Rainfall composite based on CHIRPS (shading) and the station database KASS-D (circles) for days with significant Kelvin (top) and African easterly wave (bottom) signal over West Africa during April–October 1981–2013. Figure adapted from Schlueter et al. [2019a].

Publications used in this report

(*=DACCIWA funding)

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