DACCIWA

Dynamics-aerosol-chemistry-cloud interactions in West Africa

Policy-relevant findings of the **DACCIWA project**

funded by the
European Commission

Acknowledgements

The research leading to these results has received funding from the European Union 7th Framework Programme (FP7/2007-2013) under Grant Agreement no. 603502 (EU project DACCIWA: Dynamics-aerosol-chemistry-cloud interactions in West Africa).

Cite as

Evans, M. J., et al., 2018: Policy-relevant findings of the DACCIWA project. doi:10.5281/zenodo.1476843

Contact

For more details about the project please contact:

Peter Knippertz
Karlsruhe Institute of Technology
Institute of Meteorology and Climate Research
Karlsruhe Institute of Technology
76131 Karlsruhe, Germany

peter.knippertz@kit.edu

funded by the European Union.

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

Authors

Mat J. Evans (University of York, York, UK)

Peter Knippertz (Karlsruhe Institute of Technology, Karlsruhe, Germany)

Aristide Akpo (University of Abomey-Calavi, Cotonou, Benin)

Richard P. Allan (University of Reading, Reading, UK)

Leonard Amekudzi (Kwame Nkrumah University of Science and Technology, Kumasi, Ghana)

Barbara Brooks (University of Leeds / National Centre for Atmospheric Science, Leeds, UK)

J. Christine Chiu (University of Reading, Reading, UK / Colorado State University, Fort Collins, USA)

Hugh Coe (University of Manchester, Manchester, UK)

Andreas H. Fink (Karlsruhe Institute of Technology, Karlsruhe, Germany)

Cyrille Flamant (Sorbonne University / CNRS, Paris, France)

Oluwagbemiga O. Jegede (Obafemi Awolowo University, Ile-Ife, Nigeria)

Catherine Leal-Liousse (Laboratoire d'Aérologie, University of Toulouse / CNRS, Toulouse, France)

Fabienne Lohou (Laboratoire d'Aerologie, University of Toulouse / CNRS, Toulouse, France)

Norbert Kalthoff (Karlsruhe Institute of Technology, Karlsruhe, Germany)

Celine Mari (Laboratoire d'Aerologie, University of Toulouse / CNRS, Toulouse, France)

John H. Marsham (University of Leeds, Leeds, UK)

Véronique Yoboué (University Félix Houphouët-Boigny, Abidjan, Ivory Coast)

Cornelia Reimann Zumsprekel (Karlsruhe Institute of Technology, Karlsruhe, Germany)

Contributors

Adler B., Annesi-Maesano I., Baeza A., Bahino J., Benedetti A., Brito, J., Deetz K., Deroubaix A., Dione C., Djossou J., Galy-Lacaux C., Haslett S., Hill P., Keita S., Kniffka A., Kouadio K., Léon J.-F., Maesano C., Maranan M., Menut L., Morris E., Reinares Martínez I., Stanelle T., Taylor J., Touré E., Vogel B.

Consortium Members

Project Coordinator

Karlsuhe Institut für Technolgie

Partners

France

Centre national de la recherche scientifique

Meteo France

Université Pierre Marie Curie, Sorbonne Universités

Université Clermont Auvergne

Université Paris Diderot

Université Toulouse III, Paul Sabatier

Germany

Deutsches Zentrum für Luft-und Raumfahrt

Ghana

Kwame Nkrumah University of Science and Technology

International

European Centre for Medium Range Weather Forecasting

Nigeria

Obafemi Awolowo University

Switzerland

Eidgenössische Technische Hochschule Zürich

United Kingdom

MetOffice

University of Leeds

University of Manchester

University of Reading

University of York

Collaborators

Benin

Direction Nationale de la Meteorologie

Institut National des Recherches Agricoles du Benin

Université d'Abomey-Calavi

Côte d'Ivoire

Institut Pasteur de Côte d'Ivoire

Société d'Exploitation et de Developpement Aéroportuaire, Aéronautique et Météorologique

Université Félix Houphouët-Boigny

France

SAFIRE

Germany

Technische Universität Braunschweig

Ghana

Ghana Meteorological Agency

Togo

Université of Lomé

United Kingdom

British Antarctic Survey

Key Findings

The EU funded project Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa (DACCIWA) produced the most comprehensive observational dataset of the atmosphere over southern West Africa to date. Analysing this dataset in combination with results of numerical modelling has led to the following conclusions:

Air pollution concentrations and sources

- Concentrations of small particles frequently exceed World Health Organization limits in southern West African cities.
- Annual concentration of gaseous pollutants do not currently exceed air quality guidelines but short term peaks may.
- Concentrations of small particles are highest in the dry season.
- During the rainy (summer) season, smoke from fires in Central Africa make a substantial contribution to air pollution in southern West Africa.

Health impacts

- The high particle concentrations in southern West African cities present substantial risks to public health and intensify common medical problems.
- The pollution impact is strongest in the rainy season and depends on pollution source.
- Domestic fires appear to be the most significant health risk due to extreme concentration levels.
- More aerosol observations, increased access to health statistics and associated socioeconomic data are needed.

Emissions

- Standard global estimates of human emissions are significantly underestimated for southern West Africa.
- 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.
- The underestimate in southern West African emissions likely leads to an underappreciation of the impacts of air pollution.

Pollution impacts on weather and climate

- A further increase in manmade pollution in southern West Africa will have a small effect on cloud properties due to the already high aerosol burden.
- An increased aerosol amount and/or shift to more water-loving particles will reduce the amount of sunlight reaching the Earth's surface, impacting on the circulation, clouds and possibly rainfall.
- More research is needed to better quantify the impacts of anthropogenic particles in southern West Africa.

Long-term outlook

- Temperatures over West Africa are projected to rise by 1 to over 3°C by 2050 depending on geographical location, emission scenario and model used.
- Even the sign of future changes in rainfall remains highly uncertain.
- Pollution exposure in the future will be influenced by local and remote anthropogenic emissions and altered patterns of transport and dust emissions.

Observations and models

- An adequate air quality monitoring system is absent in southern West Africa.
- The meteorological station network is sparse and existing data are not always available for research.
- Satellite observations provide a wealth of information but need more validating.
- Computer models still struggle to realistically represent the complex atmospheric dynamics and chemistry in West Africa.

Implications for policy

Improve air quality

- Reduce emissions associated with domestic burning. Alternative fuels and stoves using gas or electricity would help to achieve this (http://cleancookstoves.org).
- Reduce biomass burning locally in West Africa and work with Central African countries to reduce their enormous fire emissions.
- Establish regulations to reduce the sulfur content of fuels and to modernize the fleet of two wheel, four wheel and heavy goods vehicles.
- Work with Sahelian countries to reduce land degradation and thus dust emission.

Improve emission inventories

- Improve access to reliable socio-economic data for countries, regions and cities.
- Encourage studies on regionally specific emissions factors for activities such as waste burning, transport and domestic combustion.

Improve observations

- Install networks for long-term measurements of air pollutants focusing on cities and suburban areas.
- Sustain and expand networks for observations of meteorological data (e.g. surface stations and weather balloons), including an adequate sampling of the daily cycle.
- Make all these observations accessible to the international research, weather forecasting and climate community.

Support research and capacity building

- Fund and support follow-up research activities in Africa and Europe to work on the many open questions left at the end of DACCIWA.
- Support building capacity in weather, climate and air pollution science in Africa.
- Support improvements of computer models and satellite datasets for West Africa.

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.

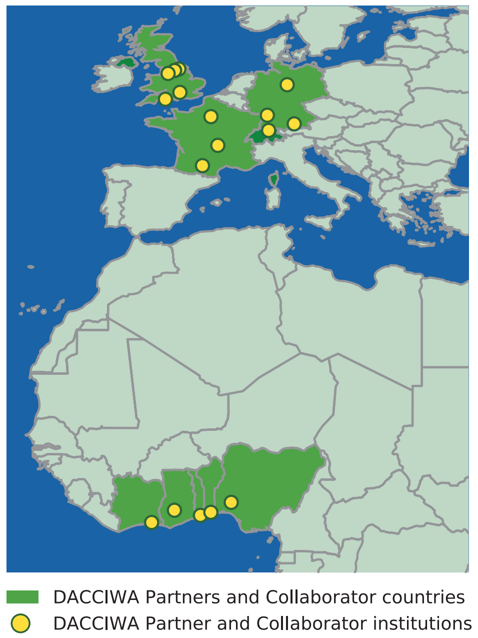


Figure 1. Yellow dots indicate location of the DACCIWA partners and collaborators. Shading shows countries involved in the project.

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

Over the last 2 years DACCIWA scientists have been analysing data collected over West Africa from field programmes and satellites. This document outlines their initial policy relevant conclusions.

The field campaigns

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

During June-July 2016 extensive measurements were made from three surface meteorological supersites, eleven meteorological balloon launch sites and three research aircraft (Figure 2). In addition, measurements of urban pollution were made from 4 air quality sites between 2015 and 2017.

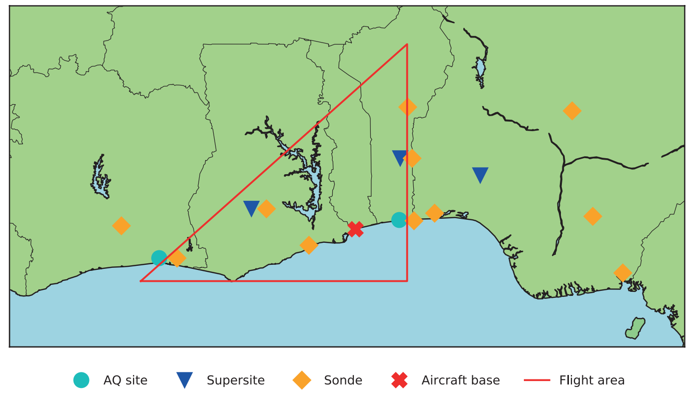
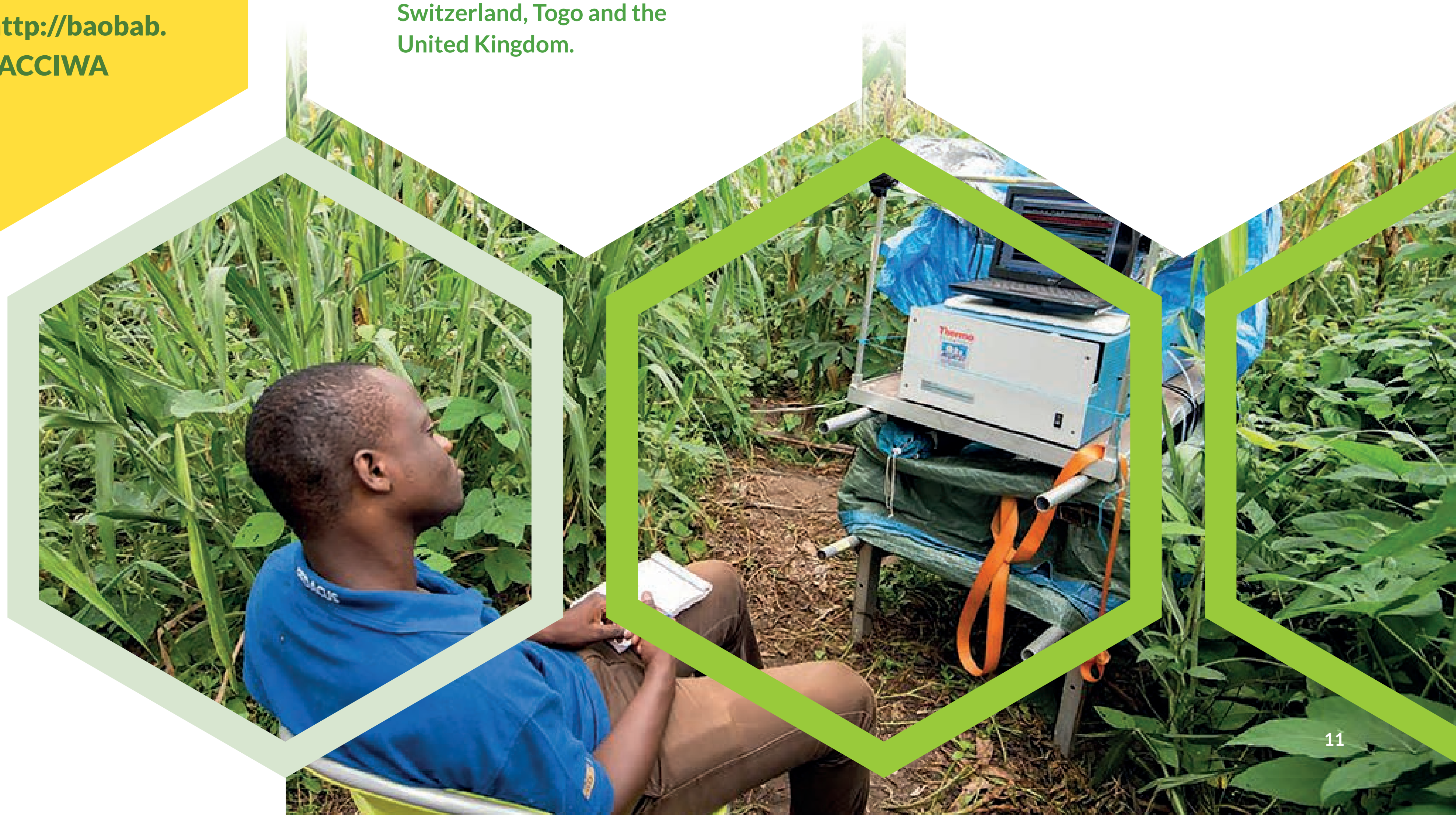


Figure 2. Location of measurement sites during the DACCIWA campaigns in 2016. Air Quality (AQ) sites measured the concentration of air pollutants. Supersites measured a range of meteorological and chemical parameters. Meteorological balloon sondes were released from 11 sites, partly in collaboration with West African weather services. Three research aircraft were based in Lomé (Togo) and sampled inside the red triangle.

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



Air pollution concentrations and sources

Air pollution is a key global risk with the World Health Organisation (WHO) estimating 8 million people a year dying prematurely from breathing polluted air. DACCIWA made observations from the ground and from the air, to measure the concentrations and sources of air pollutants.

Concentrations of small particles frequently exceed WHO limits in southern West African cities.

Measurements of small particles suspended in the air (known as PM2.5) were made in the cities of Abidjan and Cotonou [Djossou et al. 2018]. The sites were close to major sources of air pollution: waste burning at a local landfill site, motor vehicles and domestic fires for cooking. All sites show PM2.5 concentrations almost continuously above 10 µg m^{-3} (the WHO annual limit) and regularly above 25 µg m^{-3} (WHO 24 hour limit) (Figure 3). These concentrations are higher than those typical for European cities but are less than those in Asia.

Annual concentration of gaseous pollutants do currently not exceed air quality guidelines but short term peaks may.

Long-term observations do not exist for gaseous pollutants (ozone O_3, nitrogen dioxide NO_2, sulfur dioxide SO_2) in southern West African cities. For DACCIWA bi-monthly surface observations were made during 2015-2017 at the four air quality measurement sites as well as the airborne observations during the summer of 2016. These pollutants did not exceed WHO limits [Bahino et al. 2018]. However, it seems likely that NO_2 exceedance could occur on specific days.

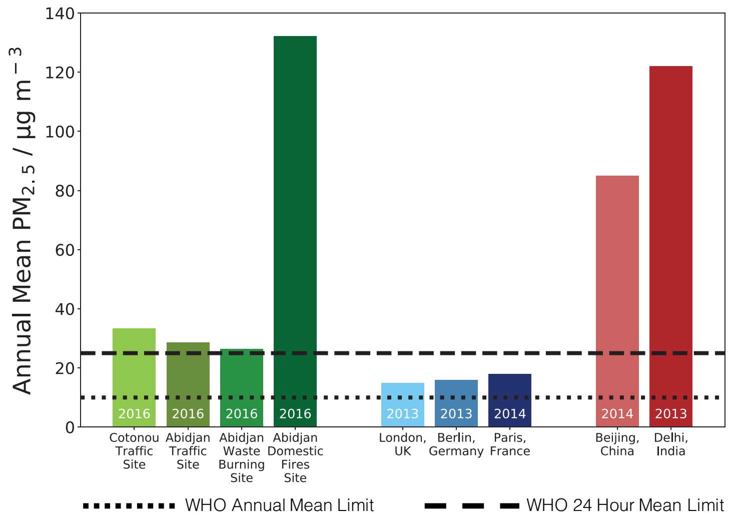


Figure 3. Observations of PM2.5 collected by the DACCIWA project from four sites in West Africa together with equivalent measurements made in Europe and Asia. Abidjan domestic burning site is indicative of an indoor site other sites represent the outdoor concentration. Dotted line indicates WHO annual standard, dashed line WHO 24 hour standard. Data from non-African cities comes from http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/.

Concentrations of small particles are highest in the dry season.

The highest monthly PM2.5 concentrations are seen in the dry (winter) season (Figure 4). This is due to a combination of enhanced desert dust from the Sahara and smoke from the burning of savannah / agricultural land within southern West Africa on top of the local human pollution. Local wood burning emissions maximize in the rainy (summer season) due to less efficient burning of wet wood. The same seasonality was seen for other pollutants such as NO_2.

During the rainy (summer) season, smoke from fires in Central Africa make a substantial contribution to air pollution in southern West Africa.

Changes in the circulation and rainfall in the wet (summer) season, reduce the impact of desert dust and local agricultural and savannah fires. However, smoke from savannah and agricultural burning in Central Africa can be blown thousands of kilometers to the coast of southern West Africa (Figure 5). Remarkably, in these months 20–40% of the particle mass is produced from these Central African fires and transported into the region.

Air pollution in southern West African cities has a complex mix of sources which changes over the year, but is often above WHO levels with implications for human health.

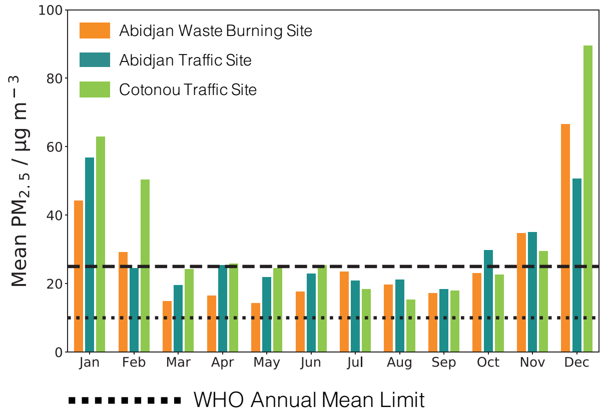


Figure 4. Monthly mean concentration of PM2.5 observed from Abidjan and Cotonou. Dotted line indicates WHO annual standard, dashed line WHO 24 hour standard.

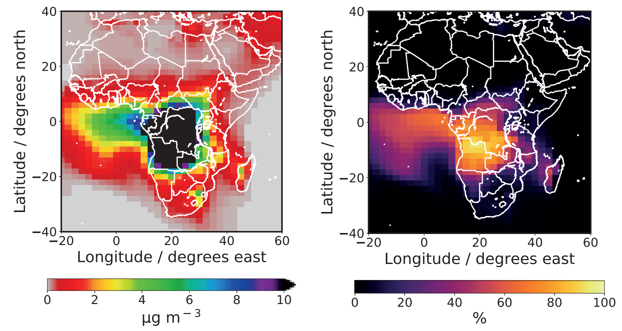


Figure 5. Absolute (left) and fractional (right) contribution of Central African agricultural and savannah burning, to June and July mean surface small particles concentrations, derived using the GEOS-Chem chemistry transport model. Over the coast of southern West Africa 25%-50% of the small particles come from fires in Central Africa.

Health Impacts

High concentrations of aerosols have an adverse impact on health through increased respiratory, cardiac and dermatological illness. A halving of air pollution emissions in Africa could reduce air quality deaths by a third [Liousse et al., 2014]. DACCIWA focused on the cities of Abidjan and Cotonou and for the first time investigated how the local population is impacted.

The high particle concentrations in southern West African cities present substantial risks to public health and intensify common medical problems.

Using the number of medical visits as a proxy for adverse health outcomes, long term relative risk values were calculated for each municipality in Abidjan. This describes the relationship between long-term exposure to PM2.5 and respiratory, cardiac and dermatologic health, as well as emergency room mortality. We estimate the number of visits to the emergency room could be reduced by 3–4% for respiratory or cardiac issues and that up to 4% of emergency room mortalities could be avoided with a reduction of PM2.5 concentrations to the WHO recommended limit of 10 µg m^{-3}.

The pollution impact is strongest in the rainy season and depends on pollution source.

Analyses for all three measuring sites in Abidjan show significant correlations between the number of hospital visits and PM2.5 concentrations, primarily during the rainy (summer) season. This suggests that humidity may play a significant role in the interaction between particulate matter and health, possibly through helping bring pollutants into the lungs. The associations we see between particulate matter and health outcomes differ for each metropolitan area, suggesting not only the concentration levels, but also the source of PM2.5 should be taken into consideration when addressing air quality impacts on health.

Due to the extreme concentration levels domestic fires are a huge health risk, while the risks from heavy traffic or waste burning were less extreme.

These are the first health research results for Abidjan showing the associations between PM2.5 and emergency room visits for respiratory and cardiac problems (~3% increase in risk), as well as emergency room mortality (~4% increase in risk) and respiratory visits to outpatient health centres.

Domestic fires appear to be the most significant health risk due to extreme concentration levels.

Due to the extreme concentration levels (see previous section) domestic fires are a huge health risk, while the risks from heavy traffic or waste burning were less extreme. As this study focused more generally on the inhabitants of the neighbourhoods around the DACCIWA measuring sites, rather than specifically on bus drivers, people working in food preparation or at the landfill site, our results may be obscuring the serious risk associated with long periods of time near a significant emission source.

In-vitro experiments with aerosols taken from the four air quality sites show that primary organic matter particles cause the most inflammation. Thus the highest inflammatory impact on people occurs in the wet season at the domestic burning site.

Personal exposure measurements on different groups of the people around these sites showed that the health risk was highest for children in waste burning sites due to heavy metals, whereas for women the risk was highest in the domestic burning site in summer due to organic matter.

Sociological studies have shown significant differences between the occupational status of individuals and their vulnerability to air pollution in the four air quality sites.

More aerosol observations, increased access to health statistics and associated socioeconomic data are needed.

This study presents the first results of an epidemiological study on cardiorespiratory impacts of air pollution in the Guinea Coastal region using local measurements. We suspect that a larger, more significant effect would be observed with more detailed data. Both detailed health statistics and continuous, repeated pollutant measurements are necessary to improve epidemiological results and provide a deeper understanding of health impacts on urban, tropical metropolitan areas. Including socioeconomic information may also provide a lever to further understand the data, as not all inhabitants are equally likely to visit a doctor.

Figure 6. Food preparation produces large quantities of smoke and particulate matter. These fires in Yopougon, Abidjan, Côte d'Ivoire are responsible for the highest pollutant concentrations measured, yet primarily affect women and children.

Figure 7. A women brings her infant into see the doctor at the Soeur Catherine Medical Center in Yopougon, Abidjan, Côte d'Ivoire.

Emissions

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

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

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. Figure 8 shows a comparison between the mass of key air pollutants emitted over southern West Africa by the EDGAR and DACCIWA inventories, together with an emissions dataset that exploits the DACCIWA observations to optimize the emissions. For many species the EDGAR data underestimate the emissions in the region.

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 significantly higher than had been assumed for the region (Figure 9). 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.

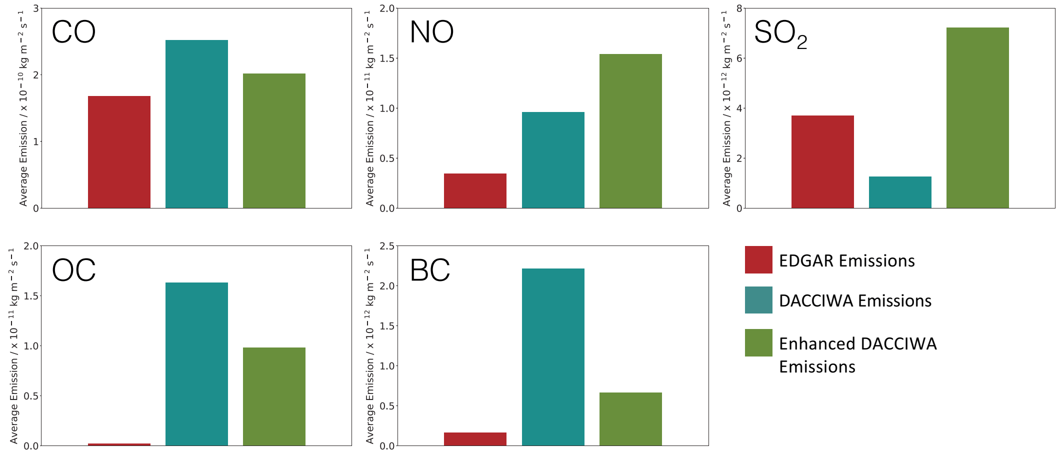


Figure 8. Comparison of average annual emission of CO, NO, SO_2, Organic Carbon and Black Carbon from southern West Africa as calculated by the EDGAR and DACCIWA emissions inventories together with an enhanced DACCIWA emissions datasets which exploits the DACCIWA observations to optimize the DACCIWA emissions inventory.

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. The manufacture of charcoal is a big source of particles, and emissions from waste burning are high and offer a risk to health.

The underestimate in southern West African emissions likely leads to an under appreciation of the impacts of air pollution.

As global estimates of the human health impact of pollutants often use the EDGAR emissions, these estimates will likely underestimate the impact of PM2.5 on human health in southern West Africa. This may influence global health choices.

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

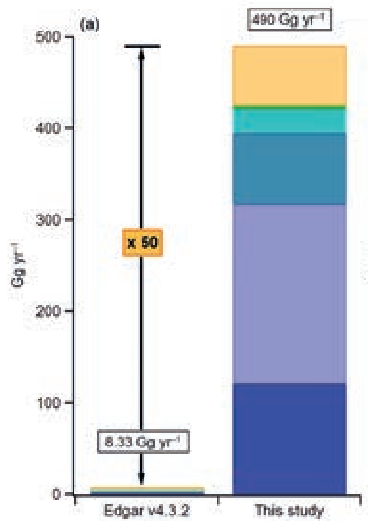


Figure 9. Mass of organic compound emitted by the transport sector from Côte d'Ivoire estimated by the EDGAR emissions (left) and by the DACCIWA project (right). There is a 50 fold underestimate in the emissions inventory for these compounds. Figure taken from [Keita et al., 2018].

Pollution impacts on weather and climate

A key uncertainty in our assessment of future climate change is how aerosol – tiny particles in the air – interact with the atmosphere, specifically by scattering or absorbing sunlight either themselves or through their influence on cloud properties. DACCIWA has specifically investigated this issue for southern West Africa for the first time.

A further increase in manmade pollution in southern West Africa will have a small effect on cloud properties due to the already high aerosol burden.

Clouds form through condensation of water vapour on particles. Changes in their number and characteristics can thus affect cloud properties and also precipitation.

Over southern West Africa, however, the concentration of particles from local emissions and smoke imported from Central Africa (Page 13) is already so high that there are always enough particles and further increases merely change cloud properties. A deterioration in particle pollution will, therefore, have a small effect on rainfall through changes in cloud properties (Figure 10).

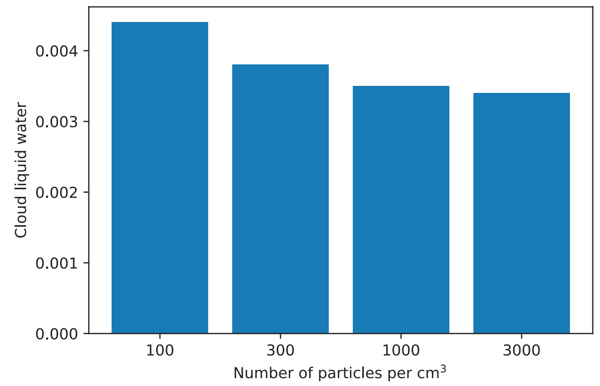


Figure 10. Total column liquid water across West Africa from the Met Office Unified Model for the 4th June 2016 using four different aerosol concentrations. Only the 100 cm^{-3} simulation representing very clean conditions shows appreciable differences in atmospheric liquid water content compared to the others. Typical concentrations of aerosol over West Africa are 500–1000 cm^{-3}.

An increased aerosol amount and/or shift to more water-loving particles will reduce the amount of sunlight reaching the Earth's surface, impacting on the circulation, clouds and possibly rainfall.

Aerosols also reduce the amount of sunlight reaching the Earth's surface. In a humid environment such as southern West Africa during the summer monsoon, aerosol particles can take up water, increasing their dimming effect by 5 to 7 times [Haslett et al., 2018]. Reductions in surface heating of 20 Wm^{-2} are seen [Deetz et al., 2018b]. 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 11, left) and the daytime development from low layer-clouds to deeper, more patchy clouds by 1–2 hours (Figure 11, right). There are first indications that the dimming leads to a reduction in rainfall, with possible impacts on food production, water availability and hydropower. The reduction of direct sunlight also affects plants and photovoltaic electricity generation. Increasing aerosol emissions and/or a shift to particles that more easily take up water such as sulfates or nitrates will exacerbate these impacts.

More research is needed to better quantify the impacts of anthropogenic particles in southern West Africa.

DACCIWA has demonstrated that interactions between aerosol particles, clouds, precipitation and sunlight over southern West Africa are complex. Several new processes have been discovered such as the coastal front and the relevance of water uptake. Yet, many details are unclear, for example how larger drops falling through the cloud from its top redistribute cloud water and thus change cloud lifetime [Dearden et al., 2018]. High sensitivities and compensating effects, together with variations with distance from the coast and time of day, make a quantitative analysis very challenging. Substantial uncertainties remain due to both limited observational data – even after the DACCIWA field campaigns – and large differences between computer models of different resolution and complexity.

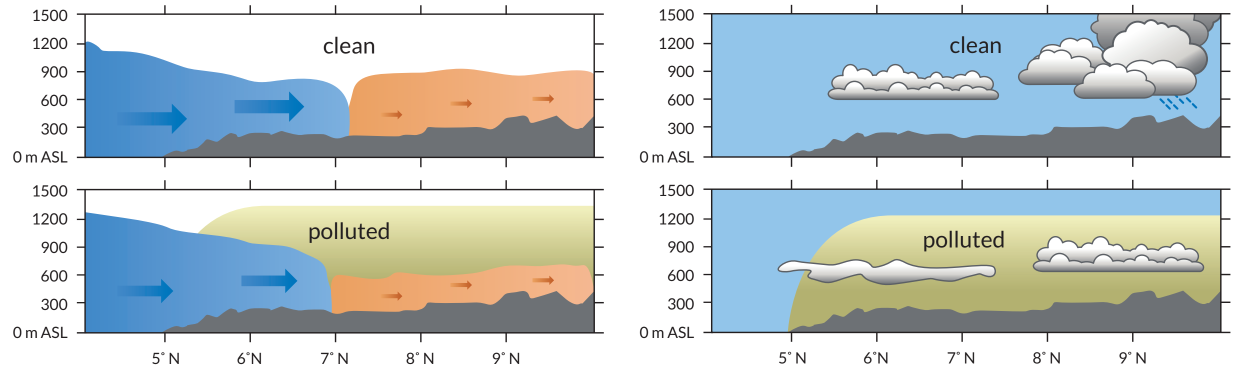


Figure 11. South–north vertical transects through southern West Africa illustrating impacts of pollution on clouds and precipitation (right) and the coastal front, a daily feature that moves inland during the evening and night (left). In the polluted case (bottom) the front is delayed relative to the 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.

Long-term outlook

The future state of the atmosphere over southern West Africa is critically important for human health, food production and the economy. Local changes need to be considered within the context of a globally changing climate. DACCIWA has used computer models to investigate which factors are relevant for future developments.

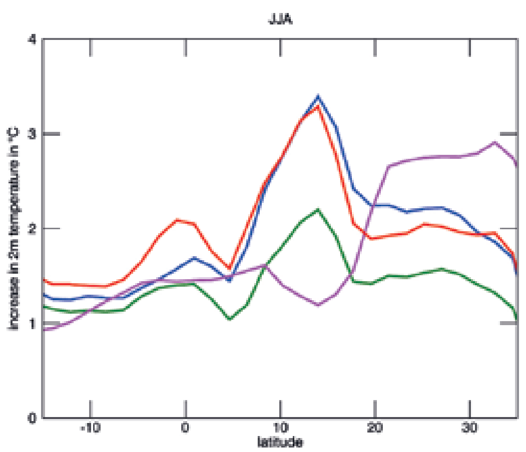


Figure 12. Increase in summer (June to August) near surface temperature between the present day and 2050 from a climate model under different assumptions. Blue, red, and magenta lines indicate simulations assuming a scenario with high emissions of climate gases; the green line is a low emission scenario. The blue, red and magenta lines indicate different assumptions about sea-surface temperatures, cloud-aerosol interactions and vegetation

Temperatures over West Africa are projected to rise by 1 to over 3°C by 2050 depending on geographical location, emission scenario and model used.

In line with projections for global warming, temperatures in southern West Africa will likely increase considerably from now until the middle of the 21st century. However, the exact size of this increase remains uncertain. DACCIWA has investigated several factors that determine the size of the increase in the summer June–August (Figure 12):

1) **Proximity to the ocean:** The temperature rise along the Guinea Coast will tend to be smaller than farther inland.
2) **Emission of climate gases:** For a low emission scenario (green line in Figure 15), temperature increases are mostly below 2°C across entire northern Africa but could exceed 3°C for high emissions (red, blue and magenta lines in Figure 12).
3) **Ocean:** Different assumptions about sea-surface temperature evolution have a small impact on the magnitude of the warming inland (compare blue and red lines in Figure 12).
4) **Aerosol, vegetation and other factors:** Warming is very sensitive to how vegetation and interactions between aerosol and clouds are represented in a climate model (compare blue and magenta lines in Figure 12).

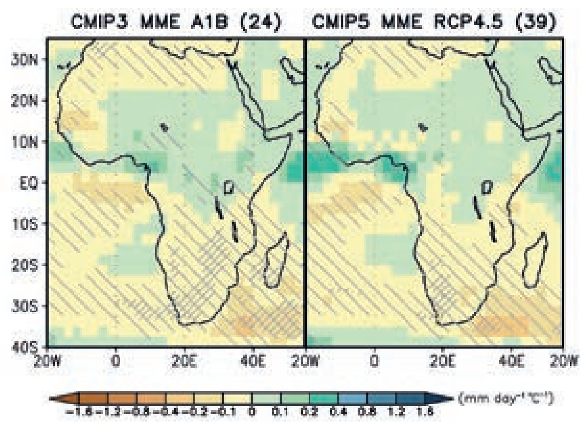


Figure 13. Change in June to September average rainfall for Africa in 2080–2099 with respect to 1986–2005. Left: SRES A1B scenario (CMIP3, 24 models); right: RCP4.5 scenario (CMIP5, 39 models). Precipitation changes are normalized by the global annual mean surface air temperature changes in each scenario. Light/dense hatching denotes where more than 66%/90% of models (or members) have the same sign with the ensemble mean changes. Taken from IPCC Fifth Assessment Report (IPCC 2013, Figure 14.23).

Even the sign of future changes in rainfall remains highly uncertain.

Computer models still struggle to realistically represent the West African monsoon [e.g. Hannak et al. 2017]. The last two IPCC multi-model assessments (CMIP3 and CMIP5) both show a rainfall increase along the Guinea Coast until the end of the 21st century but with a very low agreement between different models, even about the sign of the change (Figure 13). This impedes an assessment of the frequency of future droughts and floods. DACCIWA model experiments further confirm large sensitivities, showing that our understanding of future precipitation in the region remains to be poor.

Pollution exposure in the future will be influenced by local and remote anthropogenic emissions and altered patterns of transport and dust emissions.

Increased population and economic development over the next decades will likely lead to increased emissions of man-made aerosol and gaseous pollutants. At the same time, a changing climate will influence how much desert dust and biomass burning smoke is produced and transported into the region, while changes in rainfall will change the lifetime of these particles. Thus predicting the overall human exposure to pollutants is challenging. DACCIWA modelling results indicate that a potential increase in anthropogenic aerosol concentrations may be partly compensated by a decrease in dust concentrations during winter, while summer changes are more locally controlled (Figure 14). Evaluations of multiple modelling systems with different local emission scenarios will be needed to enhance confidence in future air pollution projections over the region.

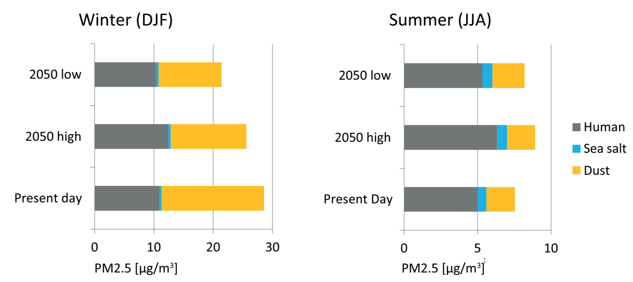


Figure 14. Multi-seasonal mean surface PM2.5 concentrations averaged over southern West Africa for December–February (left) and June–August (right). "low" and "high" refers to different scenarios of local emissions of air pollutants which remain highly uncertain.

Observations and models

High quality and accessible meteorological and air quality data are largely missing in Africa. This slows advances in weather forecasting, impedes solution to air pollution and leads to uncertainty in climate change prediction. DACCIWA has collected a plethora of data, made it freely available, and pinpointed deficiencies in how computer models represent the West Africa monsoon.

An adequate air quality monitoring system is absent in southern West Africa.

Historically, the long-term, publically accessible, monitoring of air pollutants has been the basis of assessing air quality and producing efficient solutions. The lack of this of data means that our understanding air quality in southern West Africa remains poor. Local, daily measurements of primary pollutants such as NO_x, SO_2, O_3 and particles are needed. Potentially other chemicals such as poly-aromatic hydrocarbons and heavy metals may play a disproportionately important role in West Africa (as they did historically in Europe). They should be monitored to assess their impact which is currently unknown.

The meteorological station network is sparse and existing data are not always available for research.

Meteorological observations have economic benefits that far exceed the expenses of their collection (http://www.wmo.int/pages/prog/amp/ pwsp/documents/wmo_1153_en.pdf). They are critical for producing accurate weather forecasts, to establish efficient early warning systems and to monitor climate change. Africa is notorious for its poor coverage of available data (Figure 15). DACCIWA established short term, state-of-the art meteorological networks and made the data freely available for research. It has also demonstrated how better data can advance our

A lack of observations of meteorology and air pollution in Africa holds back understanding.

understanding of the West African monsoon system which will ultimately lead to improved weather forecasts.

Making the case of an improved, open-access meteorological observing system in Africa to policymakers and wider society should be seen as a priority. Clearly, African National Weather Services need support to monitor weather and climate, and also to establish data centres that could also provide access to the currently unavailable historical data.

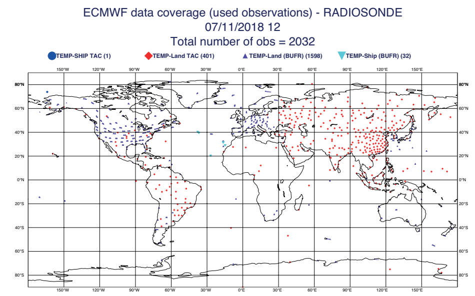


Figure 15. Meteorological sondes available to international meteorological services for inclusion into weather forecasts on 7th November 2018 at 12 UTC. Africa stands out as a continent with poor data coverage. Figure provided by European Centre for Medium-Range Weather Forecasts (ECMWF).

Satellite observations provide a wealth of information but need more validating.

Satellite observations can help supplement this lack of surface observations but there are limitations on their use. Real-time monitoring of rainfall is one of the grand challenges due to the immense socio-economic value of precipitation. Data from a dense rain gauge network around Kumasi set up by DACCIWA, show that satellite-based rainfall estimation have large errors and poorly sample extreme rainfall events (Figure 16). Although satellite observations of air pollutant concentration are available at increasing resolutions, they are still unable to capture spatial or temporal variations suitable for health. They can, however, provide useful regional climatologies for assessing model performance.

To capitalize on satellite-sensed parameters, ground truth for calibration is essential. The lack of observations in the region makes this difficult.

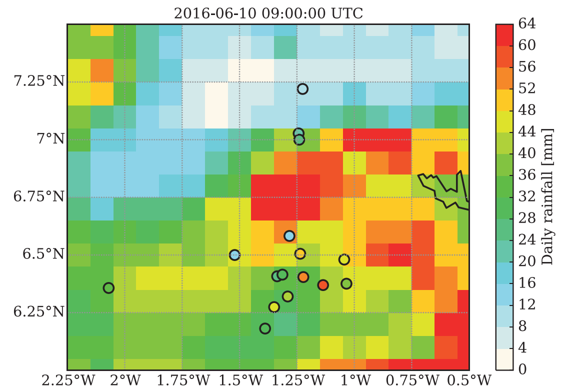


Figure 16. Daily rainfall measured on 10 June 2016, 0900 UTC by the Kumasi rain gauge network (coloured dots) and estimated by the satellite product "Integrated Multisatellite Retrievals for GPM" (IMERG, Version 5). The rain gauge network has been fully operational since December 2015 and is maintained by the Kwame Nkrumah University of Science and Technology (KNUST).

Computer models still struggle to realistically represent the complex atmospheric dynamics and chemistry in West Africa.

Computer models still struggle to realistically simulate the weather, climate and air pollution of West Africa. Even high-resolution, state-of-the-art weather forecasting models cannot reproduce the observed south–north distribution of rainfall and sensitivities to model resolution are immense (Figure 17). Generally, the quality of daily weather forecasts in southern West Africa is low [Vogel et al. 2018] and the credibility of future changes in rainfall is limited (see Figure 13).

DACCIWA has shown that one issue is the poor representation of the extensive and persistent low-level clouds. These clouds are important in regulating the amount of solar radiation reaching the surface and the rainfall [Kniffka et al. 2018]. In addition, DACCIWA research has shown that including aerosols improves seasonal forecasts for Africa [Benedetti and Vitard, 2018].

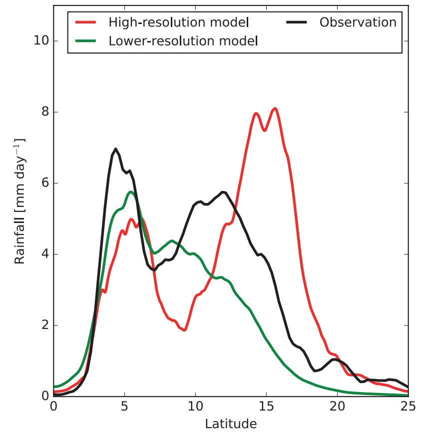


Figure17. North–south distribution of rainfall averaged from 8°W to 8°E in July 2006. Shown are satellite-based observations (black) and simulations with the ICON model currently operational at the German Weather Service in high-resolution (red) and somewhat lower resolution (green). All curves are smoothed for better visibility. Figure adapted from Kniffka et al. [2018]).

Journal publications produced by DACCIWA

Adler B, Babić K, Kalthoff N, Lohou F, Lothon M, Dione C, et al. **Nocturnal low-level clouds in the atmospheric boundary layer over southern West Africa: an observation-based analysis of conditions and processes.** Atmos Chem Phys Discuss. 2018;1–31. https://www.atmos-chem-phys-discuss.net/acp-2018-775/

Adler B, Kalthoff N, Gantner L. **Nocturnal low-level clouds over southern West Africa analysed using high-resolution simulations.** Atmos Chem Phys 2017;17(2):899–910. https://www.atmos-chem-phys.net/17/899/2017/

Amekudzi LK, Osei MA, Atiah WA, Aryee JNA, Ahiataku MA, Quansah E, et al. **Validation of TRMM and FEWS Satellite Rainfall Estimates with Rain Gauge Measurement over Ashanti Region, Ghana.** Atmos Clim Sci 2016;06(04):500–18. http://www.scirp.org/journal/doi.aspx?DOI=10.4236/acs.2016.64040

Amekudzi L, Yamba E, Preko K, Asare E, Aryee J, Baidu M, et al. **Variabilities in Rainfall Onset, Cessation and Length of Rainy Season for the Various Agro-Ecological Zones of Ghana.** Climate 2015;3(2):416–34. http://www.mdpi.com/2225-1154/3/2/416

Aryee JNA, Amekudzi LK, Atiah WA, Osei MA, Agyapong E. **Overview of surface to near-surface atmospheric profiles over selected domain during the QWeCI project.** Meteorol Atmos Phys 2018;1–15. **http://link.springer.com/10.1007/s00703-018-0618-1**

Babić K, Adler B, Kalthoff N, Andersen H, Dione C, Lohou F, et al. **The observed diurnal cycle of nocturnal low-level stratus clouds over southern West Africa: a case study.** Atmos Chem Phys Discuss 2018; 1–29. https://www.atmos-chem-phys-discuss.net/acp-2018-776/

Bahino J, Yoboué V, Galy-Lacaux C, Adon M, Akpo A, Keita S, et al. **A pilot study of gaseous pollutants' measurement (NO_2, SO_2, NH_3, HNO_3 and O_3).** Atmos Chem Phys 2018;18(7):5173–98. https://www.atmos-chem-phys.net/18/5173/2018/

Bärfuss K, Pätzold F, Altstädter B, Kathe E, Nowak S. **New Setup of the UAS ALADINA for Measuring Boundary Layer Properties, Atmospheric Particles and Solar Radiation.** Atmosphere 2018;9(1):28. http://www.mdpi.com/2073-4433/9/1/28

Benedetti A, Reid JS, Knippertz P, Marsham JH, Di Giuseppe F, Rémy S, et al. **Status and future of numerical atmospheric aerosol prediction with a focus on data requirements.** Atmos Chem Phys 2018;18(14):10615–43. https://www.atmos-chem-phys.net/18/10615/2018/

Benedetti A, Vitart F. Can the Direct Effect of Aerosols Improve **Subseasonal Predictability?** Mon Weather Rev 2018;146(10):3481–98. http://journals.ametsoc.org/doi/10.1175/MWR-D-17-0282.1

Bessardon GEQ, Fosu-Amankwah K, Petersson A, Brooks BJ. **Evaluation of Windsond S1H2 performance in Kumasi during the 2016 DACCIWA field campaign.** Atmos Meas Tech Discuss 2018; 1–31. https://www.atmos-meas-tech-discuss.net/amt-2018-179/

Brito J, Freney E, Dominutti P, Borbon A, Haslett SL, Batenburg AM, et al. **Assessing the role of anthropogenic and biogenic sources on PM1 over southern West Africa using aircraft measurements.** Atmos Chem Phys 2018;18(2):757–72. https://www.atmos-chem-phys.net/18/757/2018/

Brosse F, Leriche M, Mari C, Couvreux F. **LES study of the impact of moist thermals on the oxidative capacity of the atmosphere in southern West Africa.** Atmos Chem Phys 2018;18(9):6601–24. https://www.atmos-chem-phys.net/18/6601/2018/

Cabos W, Sein D V, Pinto JG, Fink AH, Koldunov N V, Alvarez F, et al. **The South Atlantic Anticyclone as a key player for the representation of the tropical Atlantic climate in coupled climate models.** Clim Dyn; 2017; ;48(11–12):4051–69. http://link.springer.com/10.1007/s00382-016-3319-9

Dearden C, Hill A, Coe H, Choularton T. **The role of droplet sedimentation in the evolution of low-level clouds over southern West Africa.** Atmos Chem Phys 2018;18(19):14253–69. https://www.atmos-chem-phys.net/18/14253/2018/

Deetz K, Vogel B. **Development of a new gas-flaring emission dataset for southern West Africa.** Geosci Model Dev 2017;10(4):1607–20. https://www.geosci-model-dev.net/10/1607/2017/

Deetz K, Vogel H, Haslett S, Knippertz P, Coe H, Vogel B. **Aerosol liquid water content in the moist southern West African monsoon layer and its radiative impact.** Atmos Chem Phys 2018;18(19):14271–95. https://www.atmos-chem-phys.net/18/14271/2018/

Deetz K, Vogel H, Knippertz P, Adler B, Taylor J, Coe H, et al. **Numerical simulations of aerosol radiative effects and their impact on clouds and atmospheric dynamics over southern West Africa.** Atmos Chem Phys 2018;18(13):9767–88. https://www.atmos-chem-phys.net/18/9767/2018/

Deroubaix A, Flamant C, Menut L, Siour G, Mailler S, Turquety S, et al. **Interactions of atmospheric gases and aerosols with the monsoon dynamics over the Sudano-Guinean region during AMMA.** Atmos Chem Phys 2018;18(1):445–65. https://www.atmos-chem-phys.net/18/445/2018/

Deroubaix A, Menut L, Flamant C, Brito J, Denjean C, Dreiling V, et al. **Diurnal cycle of coastal anthropogenic pollutant transport over southern West Africa during the DACCIWA campaign.** Atmos Chem Phys Discuss 2018;1–44. https://www.atmos-chem-phys-discuss.net/acp-2018-766/

Djossou J, Léon J, Akpo AB, Liousse C, Yoboué V, Bedou M, et al. **Mass concentration, optical depth and carbon composition of particulate matter in the major southern West African cities of Cotonou (Benin) and Abidjan (Côte d'Ivoire).** Atmos Chem Phys 2018;18(9):6275–91. https://www.atmos-chem-phys.net/18/6275/2018/

Dunning CM, Allan RP, Black E. **Identification of deficiencies in seasonal rainfall simulated by CMIP5 climate models.** Environ Res Lett 2017;12(11):114001. http://stacks.iop.org/1748-9326/12/i=11/

Dunning CM, Black ECL, Allan RP. **The onset and cessation of seasonal rainfall over Africa.** J Geophys Res Atmos 2016;121(19):11,405-11,424. http://doi.wiley.com/10.1002/2016JD025428

Flamant C, Knippertz P, Fink AH, Akpo A, Brooks B, Chiu CJ, et al. **The Dynamics–Aerosol–Chemistry–Cloud Interactions in West Africa Field Campaign: Overview and Research Highlights.** Bull Am Meteorol Soc 2018; 99(1):83–104. http://journals.ametsoc.org/doi/10.1175/BAMS-D-16-0256.1

Flamant C, Deroubaix A, Chazette P, Brito J, Gaetani M, Knippertz P, et al. **Aerosol distribution in the northern Gulf of Guinea: local anthropogenic sources, long-range transport, and the role of coastal shallow circulations.** Atmos Chem Phys 2018;18(16):12363–89. https://www.atmos-chem-phys.net/18/12363/2018/

Hannak L, Knippertz P, Fink AH, Kniffka A, Pante G. **Why Do Global Climate Models Struggle to Represent Low-Level Clouds in the West African Summer Monsoon?** J Clim 2017;201;30(5):1665–87. http://journals.ametsoc.org/doi/10.1175/JCLI-D-16-0451.1

Haslett SL, Taylor JW, Deetz K, Vogel B, Babić K, Kalthoff N, et al. **The radiative impact of out-of-cloud aerosol hygroscopic growth during the summer monsoon in southern West Africa.** Atmos Chem Phys Discuss 2018; 1–25. https://www.atmos-chem-phys-discuss.net/acp-2018-805/

Hill PG, Allan RP, Chiu JC, Bodas-Salcedo A, Knippertz P. **Quantifying the Contribution of Different Cloud Types to the Radiation Budget in Southern West Africa.** J Clim 2018;31(13):5273–91. http://journals.ametsoc.org/doi/10.1175/JCLI-D-17-0586.1

Hill PG, Allan RP, Chiu JC, Stein THM. A **multisatellite climatology of clouds, radiation, and precipitation in southern West Africa and comparison to climate models.** J Geophys Res Atmos 2016;121(18):10,857-10,879. http://doi.wiley.com/10.1002/2016JD025246

Kalthoff N, Lohou F, Brooks B, Jegede G, Adler B, Babić K, et al. **An overview of the diurnal cycle of the atmospheric boundary layer during the West African monsoon season: results from the 2016 observational campaign.** Atmos Chem Phys 2018;18(4):2913–28. https://www.atmos-chem-phys.net/18/2913/2018/

Keita S, Liousse C, Yoboué V, Dominutti P, Guinot B, Assamoi E, et al. **Particle and VOC emission factor measurements for anthropogenic sources in West Africa.** Atmos Chem Phys 2018;18(10):7691–708. https://www.atmos-chem-phys.net/18/7691/2018/

Kniffka A, Knippertz P, Fink AH. **The role of low-level clouds in the West African monsoon system.** Atmos Chem Phys Discuss 2018;(September):1–37. https://www.atmos-chem-phys-discuss.net/acp-2018-743/

Knippertz P, Coe H, Chiu JC, Evans MJ, Fink AH, Kalthoff N, et al. **The DACCIWA Project: Dynamics–Aerosol–Chemistry–Cloud Interactions in West Africa.** Bull Am Meteorol Soc 2015;96(9):1451–60. http://journals.ametsoc.org/doi/10.1175/BAMS-D-14-00108.1

Knippertz P, Evans MJ, Field PR, Fink AH, Liousse C, Marsham JH. **The possible role of local air pollution in climate change in West Africa.** Nat Clim Chang Nature Publishing Group; 2015;5(9):815–22. http://www.nature.com/doifinder/10.1038/nclimate2727

Knippertz, P.; Fink, A. H.; Deroubaix, A.; Morris, E.; Tocquer, F.; Evans, M.; Flamant, C.; Gaetani, M.; Lavaysse, C.; Mari, C.; Marsham, J. H.; Meynadier, R.; Affo-Dogo, A.; Bahaga, T.; Brosse, F.; Deetz, K.; Guebsi, R.; Latifou, I.; Maranan, M.; Rosenberg, P. D.; Schlueter, A., 2017: **A meteorological and chemical overview of the DACCIWA field campaign in West Africa in June–July.** Atmos. Chem. Phys. 2017; 17, 10893–10918. https://www.atmos-chem-phys.net/17/10893/2017/

Maranan M, Fink AH, Knippertz P. **Rainfall types over southern West Africa: Objective identification, climatology and synoptic environment.** Q J R Meteorol Soc 2018;144 (714):1628–48. http://doi.wiley.com/10.1002/qj.3345

McFarquhar GM, Baumgardner D, Bansemer A, Abel SJ, Crosier J, French J, et al. **Processing of Ice Cloud In Situ Data Collected by Bulk Water, Scattering, and Imaging Probes: Fundamentals, Uncertainties, and Efforts toward Consistency.** Meteorol Monogr 2017; 58:11.1-11.33. http://journals.ametsoc.org/doi/10.1175/AMSMONOGRAPHS-D-16-0007.1

Menut L, Flamant C, Turquety S, Deroubaix A, Chazette P, Meynadier R. **Impact of biomass burning on pollutant surface concentrations in megacities of the Gulf of Guinea.** Atmos Chem Phys 2018;18(4):2687–707. https://www.atmos-chem-phys.net/18/2687/2018/

Pacifico F, Delon C, Jambert C, Durand P, Morris E, Evans MJ, et al. **Measurements of nitric oxide and ammonia soil fluxes from a wet savanna ecosystem site in West Africa during the DACCIWA field campaign.** Atmos Chem Phys Discuss 2018; 1–37. https://www.atmos-chem-phys-discuss.net/acp-2017-1198/

Pfeifroth U, Trentmann J, Fink AH, Ahrens B. **Evaluating Satellite-Based Diurnal Cycles of Precipitation in the African Tropics.** J Appl Meteorol Climatol 2016;55(1):23–39. http://journals.ametsoc.org/doi/10.1175/JAMC-D-15-0065.1

Reinares Martínez I, Chaboureau J-P. **Precipitation and Mesoscale Convective Systems: Radiative Impact of Dust over Northern Africa.** Mon Weather Rev 2018;146(9):3011–29. http://journals.ametsoc.org/doi/10.1175/MWR-D-18-0103.1

Reinares Martínez I, Chaboureau J-P. **Precipitation and Mesoscale Convective Systems: Explicit versus Parameterized Convection over Northern Africa.** Mon Weather Rev 2018;146(3):797–812. http://journals.ametsoc.org/doi/10.1175/MWR-D-17-0202.1

van der Linden R, Fink AH, Redl R. **Satellite-based climatology of low-level continental clouds in southern West Africa during the summer monsoon season.** J Geophys Res Atmos 2015;120(3):1186–201. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2014JD022614

Young MP, Chiu JC, Williams CJR, Stein THM, Stengel M, Fielding MD, et al. **Spatio-temporal variability of warm rain events over southern West Africa from geostationary satellite observations for climate monitoring and model evaluation.** Q J R Meteorol Soc 2018; http://doi.wiley.com/10.1002/qj.3372

Other publications used in this report

Crippa, M.,Guizzardi, D.,Muntean, M., Schaaf, E.,Dentener, F., van Aardenne, J. A., Monni, S. , Doering, U., Olivier, J. G. J., Pagliari, V., Janssens-Maenhout, G., **Gridded Emissions of Air Pollutants for the period 1970--2012 within EDGAR v4.3.2**, Earth System Sci. Data Disc., 1-40, 2018, https://doi.org/10.5194/essd-2018-31

IPCC, 2013: **Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change** [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Liousse, C., Assamoi, E., Criqui, P., Granier, C., Rosset, R., **Explosive growth in African combustion emissions from 2005 to 2030**, Environmental Research Letters, 9 (3), 035003, 2014, https://doit.org/10.1088/1748-9326/9/3/035003

Vogel, P.; Knippertz, P.; Gneiting, T.; Fink, A. H.; Schlueter, A., 2018: **Skill of global raw and postprocessed ensemble predictions of rainfall over northern tropical Africa**. Wea. Forecasting, 33, 369–388, doi:10.1175/WAF-D-17-0127.1.

For more information on the
DACCIWA project visit:

www.dacciwa.eu

funded by the
European Commission

Printed on FSC recycled paper