DACCIWA

PROJECT FINAL REPORT

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Name, title and organisation of the scientific representative of the project's coordinator	Prof. Dr. Peter Knippertz Karlsruher Institut für Technologie (KIT)
Tel:	+49 721 608 43565
Fax:	+49 721 608 46102
E-mail:	peter.knippertz@kit.edu
Project website address	www.dacciwa.eu

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1.1 Final publishable summary report

1.1.1 Executive Summary

The densely populated southern parts of West Africa are currently experiencing unprecedented population and economic growth that has created a marked and accelerating increase of anthropogenic emissions from domestic, agricultural, waste and forest burning, as well as from traffic and oil exploitation. The emitted particles and gases – together with natural emissions from deserts, oceans, soils and the biosphere – can adversely affect the health of humans, plants and animals. At the same time aerosol particles can affect weather and climate through their role as cloud condensation nuclei and ice nucleating particles as well as through scattering and absorbing radiation. These two aspects were explored in great detail in the DACCIWA project for the first time.

Due to the lack of adequate observational data, a component of utmost importance for DACCIWA was the organisation of a major international field campaign in June-July 2016 involving three ground-based supersites in Kumasi (Ghana), Savè (Benin) and Ile-Ife (Nigeria), extensive aircraft measurements from three research aircraft operated from Lomé (Togo), and 772 weather balloon launches from seven locations. Moreover, a network of rain gauges was installed around Kumasi as well as instruments to measure air pollution in Abidjan and Cotonou and ample health data were collected. The observational base was further enhanced through the digitisation of station data and through satellite-based products. The scientific analysis was also complemented by a wide range of own and external modelling experiments and operational products that were evaluated with the unique observational database that DACCIWA has created.

DACCIWA quantified for the first time the level, sources and impact of air pollution in southern West Africa on a city and regional scale. Particle pollution is the major problem with particularly high concentrations being related to domestic fires, while gaseous pollutants (including ozone) are usually below international standards. During the dry season, particle levels are highest with contributions from city pollution, local biomass burning and mineral dust from the north, while during the wet season, a significant fraction of the (overall lower) particle concentrations are related to the extensive forest burning in remote Central Africa. The widespread high aerosol concentrations provide an abundance of cloud condensation nuclei, leading to a low susceptibility of clouds to aerosol changes. However, radiative effects of aerosol particles modify local meteorology by reducing surface solar radiation, which delays the diurnal cycle of the boundary layer and thus rainfall evolution. Water uptake of aerosol particles enhance this effect. DACCIWA research also has contributed to a significant advance of the understanding of meteorology in southern West Africa. In particular, a new conceptual model of the diurnal cycle of the boundary layer and low clouds was developed, specifying for the first time the relative roles of cold-air advection, radiation and turbulence as well as the maritime inflow from the Gulf of Guinea. Furthermore, the importance of the radiative effect of these low clouds for rainfall generation was demonstrated, and rainfall systems and their typical environmental conditions were classified for the first time. Future changes of rainfall and aerosol over the region remain highly uncertain due to the many model deficits and high sensitivities identified by DACCIWA but some skill was found on the regional scale for weather and seasonal prediction.

DACCIWA published dedicated summary documents for policymakers and stakeholders in operational services to foster the impact of the scientific results on society and improvements of atmospheric monitoring and prediction.

1.1.2 A summary description of project context and objectives

Southern West Africa (southern West Africa) is currently experiencing unprecedented population and economic growth with concomitant impacts on land-use change and anthropogenic emissions. West Africa will continue to be in its demographic transition stage throughout the next decades. The current population of around 345 million is predicted to reach about 800 million by 2050 and be mostly urbanised. There will be increased industrialisation and demands for energy (biofuel, oil), leading to increases in atmospheric emissions. Already anthropogenic pollutants are thought to have tripled in southern West Africa between 1950 and 2000 with similar increases expected by 2030. These dramatic changes have been hypothesised to affect three areas of large socio-economic importance in a vulnerable region with complex human-ecosystem-climate impacts and feedbacks:

1) Human health: High concentrations of pollutants, particularly fine particles, in existing and evolving cities along the Guinea Coast including the mega-city of Lagos cause respiratory diseases with potentially large impacts on health costs and the capacity of the local work force. Environmental changes including atmospheric pollution have already significantly increased the cancer burden in Africa in recent years.

2) Regional ecosystem health, biodiversity and agricultural productivity: Anthropogenic emissions may lead to enhanced ozone production outside of urban conglomerations with detrimental effects on humans, animals, natural plants and crops. In southern West Africa small-scale farming immediately downstream of big cities is important for food production and would be seriously affected by high ozone concentrations. On a regional scale air quality is also affected by biomass burning and natural dust aerosol.

3) Regional weather and climate: Aerosol particles produced from biogenic and human emissions can change the climate and weather locally through their effects on radiation and clouds, which can modify the regional response to global climate change. Associated effects on temperature, rainfall and cloudiness can feedback on the land surface, ecosystems and crops and affect many other important socio-economic factors such as water availability, production systems, physical infrastructure and energy production, which relies on hydropower in many countries across southern West Africa. Our physical understanding of the West African monsoon is limited and model predictions across a range of scales are uncertainty. This is partly due to the lack of sufficient long- and short-term observational data across the region.

The main objectives of DACCIWA were:

O1 Quantify the impact of multiple sources of anthropogenic and natural emissions, and transport and mixing processes on the atmospheric composition over southern West Africa during boreal summer.

O2 Assess the impact of surface/lower-tropospheric atmospheric composition, in particular that of pollutants such as small particles and ozone, on human and ecosystem health and agricultural productivity, including possible feedbacks on emissions and surface fluxes.

O3 Quantify the two-way coupling between aerosols and cloud and raindrops, focusing on the distribution and characteristics of cloud condensation nuclei, their impact on cloud characteristics and the removal of aerosol by precipitation.

O4 Identify controls on the formation, persistence and dissolution of low-level stratiform clouds, including processes such as advection, radiation, turbulence, latent-heat release, and how these influence aerosol impacts.

O5 Identify meteorological controls on precipitation, focusing on planetary boundary layer development, the transition from stratus to convective clouds, entrainment and forcing from synoptic-scale weather systems.

O6 Quantify the impacts of low- and mid-level clouds (layered and deeper congestus) and aerosols on the radiation and energy budgets with a focus on effects of aerosols on cloud properties.

O7 Evaluate and improve state-of-the-art meteorological, chemistry and air-quality models as well as satellite retrievals of clouds, precipitation, aerosols and radiation in close collaboration with operational centres.

O8 Analyse the effect of cloud radiative forcing and precipitation on the West African monsoon circulation and water budget including possible feedbacks.

O9 Assess socio-economic implications of future changes in regional anthropogenic emissions, land use and climate for human and ecosystem health, agricultural productivity and water.

O10 Effectively disseminate research findings and data to policy-makers, scientists, operational centres, students, and the general public using a graded communication strategy.

The project was organised in seven scientific workpackages (WPs):

WP1: Boundary Layer Dynamics (lead: Norbert Kalthoff, KIT)

WP1 concentrated on achieving Objective O4 and contributed to Objectives O5 and O6. Specifically, WP1 was responsible for the preparation and installation of the surface-based instrumentation at the supersites in Kumasi (Ghana), Savè (Benin) and Ile-Ife (Nigeria) as well as to run the instrumentation for seven weeks during the campaign in June-July 2016. After the campaign a quality-controlled observational dataset was generated and uploaded to the DACCIWA database. The observational data were then analysed with respect to the diurnal evolution of the radiation and energy balance of the Earth's surface, the growth and conditions of the nocturnal and daytime planetary boundary layer, the formation and breakdown of nocturnal low-level jets, the formation, characteristics and dissolution of low stratus clouds, radiation and entrainment at cloud top and coupling to the land surface via soil moisture and vegetation. In addition, large-eddy simulations were used to investigate planetary boundary layer processes as well as low cloud formation and dissolution. Based on both observational and modelling results a conceptual model of planetary boundary layer evolution and low-cloud formation was developed and serves as a benchmark to evaluate coarser-resolution models used in other WPs.

WP2: Air pollution and Health (lead: Cathy Liousse, UPS)

WP2 concentrated on achieving Objective O2 and contributed to Objectives O1 and O9. WP2 linked emission sources, air pollution and health impacts in terms of lung inflammation and related diseases over representative differentiated urban sources in southern West Africa: traffic, domestic fires and waste burning in Abidjan (Ivory Coast) and traffic in Cotonou (Benin), for which active measurements were conducted and health data were collected. WP2 quantified the chemical speciation of aerosols by size classes for organic and inorganic species for the main combustion sources prevailing and investigated the toxicity of combustion aerosols in southern West Africa. Moreover, the impacts on sub-population groups living close to each predominant combustion source were investigated as well as the relationship between aerosol size differentiated composition and inflammation markers and between emissions and exposure to inflammation risks separated by type of emission source. In addition, the link between aerosol exposure and aerosol dose within the respiratory tract was investigated. Finally, aerosols emissions were estimated for 2030 and 2050 and ways to mitigate the emissions to reduce health impacts were proposed.

WP3: Atmospheric Chemistry (lead: Celine Mari, UPS)

WP3 concentrated on achieving Objective O1 and contributed to Objectives O2 and O9. WP3 advanced the scientific understanding of atmospheric chemistry in the context of a rapid economic and population growth in the southern West Africa region. More specifically, WP3 planned, organised and conducted observations of the gas and aerosol phase composition of the atmosphere in southern West Africa from the ground and aircraft, and delivered a high-quality dataset of this composition to the DACCIWA database. The performance of a wide range of models in simulating the composition of the atmosphere over southern West Africa was assessed with a focus on ozone and aerosol using the field and other observations. The impact of atmospheric composition on non-urban air-quality, human and ecosystem health, radiative forcing and climate in particular that of pollutants such as ozone and aerosols was quantified. Finally, implications of future (2030,2050) changes in regional anthropogenic emissions on human and ecosystem health and on climate relevant species were estimated.

WP4: Cloud-Aerosol Interactions (lead: Hugh Coe, UNIVMAN)

WP4 concentrated on achieving Objective O3 and contributed to Objectives O4–7. WP4 quantified cloud microphysical and dynamical behaviour across southern West Africa, with particular emphasis on the influence the variety of aerosol sources across the region have on stratus, cumulus and congestus clouds and their transition. More specifically, WP4 planned, organised and conducted observations of cloud and aerosol properties in southern West Africa from the aircraft and delivered a high-quality dataset to the DACCIWA database. WP4 quantified the two-way coupling between aerosols and cloud and raindrops, focusing on the distribution and characteristics of cloud condensation nuclei, their impact on cloud characteristics and the removal of aerosol by precipitation. Moreover, stratus and cumulus cloud micro- and macro-physical properties were determined across southern West Africa. Finally, the skill of regional models in predicting regional cloud behaviour was assessed to improve the predictive capability for cloud-aerosol interactions across the region.

WP5: Radiative Processes (lead: Christine Chiu, UREAD)

WP5 concentrated on achieving Objective O6 and contributed to Objectives O7 and O8. Specifically, WP5 contributed the satellite-based component of the DACCIWA climatological dataset and provided a comprehensive product of aerosol and cloud properties that is important for understanding radiative processes. WP5 performed broadband and spectral radiation closure at the surface, the aircraft altitudes and at the top of the atmosphere for all-sky situations and derived recommendations for potential improvement in satellite-based retrievals for aerosol, cloud and precipitation, based on DACCIWA observations. Finally, aerosol and cloud radiative effects on the West African monsoon circulation including possible feedbacks were assessed in close collaboration with WP7.

WP6: Precipitation Processes (lead: Andreas H. Fink, KIT)

WP6 concentrated on achieving Objective O5 and contributed to Objectives O3 and O6–8. Specifically, WP6 planned, organised and coordinated the DACCIWA radiosonde campaign in June-July 2016 and created a quality-controlled dataset for the DACCIWA data base. Different rainfall types, their seasonal and diurnal cycles, and the synoptic-dynamic environment in which they develop were identified for southern West Africa. Meso- and micro-scale dynamical controls on precipitation related to planetary boundary layer development and transition from stratus to convective clouds were analysed. In addition, a network of 17 rain gauges was set up around Kumasi (Ghana) and output was used to evaluate satellite rainfall products and for dynamical studies. Finally, the relationships between aerosols, cloud dynamics, entrainment and detrainment, and the development of rain in warm (ice-free) layered and deeper congestus clouds were determined and their representation in models evaluated.

WP7: Monsoon Processes (lead: Peter Knippertz, KIT)

WP7 concentrated on achieving Objective O8 and contributed to Objectives O7 and O9. More specifically, WP7 contributed the surface-based component of the DACCIWA climatological dataset including a coordination of the digitisation of station data. WP7 coordinated forecasting activities for the field campaign in June-July 2016 and evaluated the representation of the West African monsoon circulation in state-of-the-art meteorological models and operational products. Sensitivities to the representation of planetary boundary layer processes, low-level clouds, precipitation and radiation over the DACCIWA study area were assessed and recommendations for potential model improvement from these analyses were derived. Finally, potential changes to the West African monsoon due to future changes in regional anthropogenic emissions and climate as well as socio-economic implications were assessed.

Three further WPs addressed the ample dissemination activities of the project (WP8, lead: Mat Evans, UoY) as well as scientific and general management (WPs 9 and 10). WP8 was designed to achieve O10, i.e. to effectively disseminate specific research findings and data to scientists and operational services (modelling and satellite) and to inform policymakers, the media and the general public of the general results and policy implications of the project. A special dissemination team was elected from the senior scientists involved in the project. WP8 activities included amongst other things the development of an external website, a bi-annual newsletter, press releases and social media communication (particularly around the time of the main field campaign), the production of overview articles, the organisation of a special sessions at the annual meeting of the European Geosciences Union (EGU), the implementation of a special issue in Atmospheric Chemistry and Physics/Atmospheric Measurement Techniques, as well as the writing and publication of summary documents for policymakers and operational stakeholders including workshops to present these.

Finally, WPs 9 and 10 served to effectively manage and coordinate the project activities. This included the compilation of periodic reports, good communication within the project (internal SharePoint, project book) and with partners, the organisation of project and other meetings, the handling of all financial, administrative and legal matters of the consortium as well as gender issues.

1.1.3 A description of the main S&T results/foregrounds

S&T results/fore grounds

The DACCIWA project has significantly advanced our understanding of the climate system over southern West Africa and its interactions with humans in many ways, integrating scientific results across a range of disciplines and research tools. Both observational and model data in DACCIWA were processed in a standardised, consistent and documented way with common formats and joint data distribution facilities. This greatly facilitates the use of data by external partners and researchers.

At the heart of the project was a major international field campaign in June-July 2016 in West Africa including ground-based supersites, extensive aircraft measurements, additional radiosondes and urban measurements. The field data analysis was complemented by the analysis and evaluation of satellite data and a wide range of modelling and sensitivity experiments stretching from large-eddy to climate simulations. For example, aircraft and ground-observations were used in a synergistic way to derive cloud properties and radiative impacts, and to evaluate satellite products. Field and satellite observations were used to evaluate weather forecast models for the campaign period and beyond.

Different emission datasets were used to drive atmospheric chemistry models the output of which was then compared to aircraft measurements. Imposed changes to aerosol and cloud fields in models were used to test sensitivities of the dynamical response of the atmosphere, in particularly with respect to the monsoon circulation and rainfall systems. On the following pages the most important scientific results and outputs from the project will be described.

1) A benchmark observational dataset

The lack of data in southern West Africa has impeded an advance of our scientific understanding and a rigorous evaluation of models and satellite retrievals for a long time. To alleviate the situation, DACCIWA organised a major international field campaign with four main elements (see Flamant et al. 2018 for details):

(A) GROUND-BASED CAMPAIGN: Supersites in Kumasi (Ghana), Savé (Benin) and Ile-Ife (Nigeria) were designed to advance our understanding of boundary-layer processes such as formation and breakdown of low-level jets and cloud decks, the surface energy balance and precipitation processes. Low-level clouds are of primary importance for the regional weather, climate, and air quality owing to radiative effects, impacts on the convective boundary layer development, and interactions with pollutants. The ground-based campaign was conducted in areas strongly affected by low clouds. Measurements were designed to identify the controlling processes and factors for low-level cloud formation and to investigate cloud effects on planetary boundary layer conditions. Intensive measurements were performed from 14 June to 30 July 2016.

A comprehensive set of instruments was deployed at the three sites. Surface stations measuring the mean meteorological parameters, surface radiation and energy balance components, and soil temperature and humidity provided the lower boundary conditions and, at the same time, the low clouds' impact on the radiation balance at the surface. Thermodynamics and dynamics in the lower atmosphere were monitored continuously by active (wind profilers, Doppler lidars, sodars) and passive (microwave radiometers) remote sensing systems. In addition to radiosondes launched at synoptic times, tethered radiosondes in Ile-Ife and frequent radiosondes in Kumasi and Savè were launched in regular intervals during intensive operation periods. These measurements focus on the detection of the nocturnal low-level jet, monsoon and harmattan flows, the African easterly jet and the tropospheric stratification. Cloud characteristics, such as cloud base, top, and cover, as well as the spatial and temporal evolution of precipitation and cloud drop size distribution, were monitored by a set of in situ and remote sensing devices (distrometers, rain gauges, cloud radar, rain radar, infrared radiometer, cloud camera). Chemistry and aerosol measurements complete this dataset. Finally, two remotely piloted aircraft systems, Aladina and Ovli, were operated in Savè by Innovationsgesellschaft Technische Universität Braunschweig. The applied measurement strategy (e.g., scan patterns and radiosounding frequency) was optimized to capture processes expected from high-resolution simulations performed in preparation of the campaign, including horizontal advection from the Guinea coast and triggering of new clouds upstream of existing clouds due to an upward shift of the low-level jet in cloudy areas.

(B) RADIOSONDE CAMPAIGN: Operational upper-air stations are very sparsely distributed over West Africa. During DACCIWA the upper-air network was successfully augmented during June and July 2016 to an unprecedented spatial density with a network designed to characterise the vertical structure of the atmosphere at the regional level. Additional radiosondes were launched from the supersites, sites of West African weather services (Abidjan, Cotonou, Parakou) and additional sites operated by KIT together with African organisations (Accra, Lamto). Altogether, some 772 radiosondes were launched. In addition, standard radiosonde data and, if possible, high-resolution 1200 UTC data for June–July 2016 were acquired for Nigerian operational stations.

(C) AIRCRAFT CAMPAIGN: Extensive aircraft measurements of cloud properties, trace gases, aerosols and meteorological parameters from the German Deutsches Zentrum für Luft- und Raumfahrt (DLR) Falcon, the French Service des Avions Français Instrumentés pour la Recherche en Environnement (SAFIRE) ATR42 and the British Antarctic Survey (BAS) Twin Otter operated from the airport of Lomé (Togo) between 29 June and 15 July 2016. The trace gas instrumentation of the three aircrafts included ozone, key ozone precursor species (NOx, VOC, CO, HCHO), aerosol precursor species (SO_2 , secondary VOC), and long-lived greenhouse gases (CO_2, CH_4). The main objective for the aircraft detachment was to build robust statistics of cloud properties in southern West Africa in different chemical landscapes: from the background state over the Gulf of Guinea to ship/flaring emissions to the coastal strip of polluted multimillion-inhabitant cities to the agricultural areas and forest areas farther north, and eventually dust from the Sahel and/or Sahara. An ancillary objective of the detachment was to contribute to the reduction of uncertainties on emissions from big cities, ships, and oil rigs, as well as biogenic emissions from vegetation.

(D) URBAN CAMPAIGN: The urban campaign was conducted on four sites representative of the main combustion sources specific to southern West Africa (traffic, domestic fire, and waste burning), three of which are located in Abidjan (Ivory Coast) and one in Cotonou (Benin). The urban campaign took place on 4–10 July (Abidjan) and 10–13 July 2016 (Cotonou). The instrumented four sites were (1) Yopougon (Abidjan) within a courtyard surrounded by houses using fires for cooking and fish smoking, (2) Adjamé (Abidjan) on the roof of a pharmacy, above a large street with frequent traffic jams and close to a large crossroad, (3) Akouedo (Abidjan) on the roof of a building built on the biggest waste burning hill of the country, and (4) Dantokpa (Cotonou) in front of the biggest market of Benin, on the balcony of a building near a crossing with a high traffic density of both four- and two-wheel vehicles using gasoline fuel.

In addition, a network of 17 raingauges with a 1-minute temporal resolution has been operated around Kumasi jointly by KNUST and KIT since 2015. In close collaboration with the national weather services in West Africa, additional station data was obtained and measurements only available on paper were digitized. Raw and quality-checked rainfall datasets at resolutions of one day and one minute have been uploaded to the DACCIWA data base for 2016 and 2017, thus being made available to DACCIWA researches and the scientific community. The quality check was carried out manually using 24-h rainfall accumulations from Ghana Meteorological Agency (GMET) analogue gauges, collocated with DACCIWA gauges at ten locations, and using GPM IMERG satellite rainfall estimates for all sites. The raingauge network has been operated until the end of DACCIWA and will be maintained further, with raw and quality-controlled data for 2018 to be added to the DACCIWA data base. Being the first of its kind in coastal southern West Africa, it will allow validation of satellite rainfall at the sub-daily time scale and in relation to the rainfall types.

The data generated during DACCIWA (both field campaign and longer-term observations) are now freely available from http://baobab.sedoo.fr/DACCIWA/ for a wide community of researchers. Currently final summary files of the aircraft observations are being compiled that will be easier to use for modellers. We are confident that this comprehensive and unprecedented dataset will continue to be a widely used benchmark for southern West Africa that helps to further advance our understanding and to improve models and satellite products.

2) **Improved emission estimates**

Atmospheric chemistry and air pollution models require estimates of emissions of aerosols and trace gases to simulate the composition of the atmosphere, its evolution and potentially harmful impacts on humans and ecosystems. These emissions typically come from natural (e.g. desert dust, sea salt) and from anthropogenic sources (e.g. transportation, domestic and agricultural burning, industry).

The EDGAR dataset 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, which use Africa specific information from 1990 to 2016 at 10km by 10km spatial resolution. A comparison between the mass of key air pollutants emitted over southern West Africa by the EDGAR and DACCIWA inventories, and an emissions dataset that exploits the DACCIWA observations to optimize the emissions on the basis of a atmospheric chemistry model shows that EDGAR data underestimate the emissions in the region for many species. DACCIWA made direct measurements of the particles and organic gases emissions from individual vehicles, domestic fires, charcoal making and waste burning in Côte d'Ivoire and Benin. They were significantly higher than had been assumed for the region. 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. DACCIWA 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. 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. Based on this, DACCIWA has generated future projections for emission scenarios from southern West Africa for international databases. These have potential to significantly advance our understanding of the causes of the air pollution problem and to develop sustainable mitigation strategies.

3) **Evaluation of satellite products**

Satellite observations help supplement the lack of surface observations in southern West Africa. However, the fidelity of satellite retrievals should be carefully examined against aircraft- or ground-based observations. Using the rich new observational database DACCIWA provided, the project has unveiled previously undocumented deficiencies in widely used satellite products. Examples include:

(A) Geostationary satellites provide adequate temporal sampling of clouds for us to evaluate their radiative properties against in-situ data collected from the DACCIWA campaign. The Meteosat Second Generation (MSG) Optimal Cloud Analysis (OCA) product is unique for passive retrieval methods from geostationary satellites, because it provides retrievals for two cloud layers in multi-layer cloud situations. While OCA generally provides good cloud optical properties for calculating radiative fluxes at the top of the atmosphere, DACCIWA research has shown that OCA misses at least 20% of aircraft and ground observations of low cloud occurrence. This discrepancy is at least partly caused by obscuring higher cloud.

(B) 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 surface albedo estimates due to the frequent presence of low clouds in the widely used Surface Solar Radiation Dataset–Heliosat (SARAH) product generated by the Satellite Application Facility on Climate Monitoring (CM-SAF) lead to errors in surface short wave radiation of 20 W m^{-2} and more.

(C) 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. The aerosol optical depths of the products agree within 12% with ground-based observations, with MODIS slightly overestimating and MISR slightly underestimating. This difference has little impact on the uncertainty of the radiative effect of aerosols in the region. However, retrievals of the single-scattering albedo are significantly higher (i.e. less absorbing) and less variable in the satellite products than from ground-based observations. This disagreement can lead to differences in the total direct aerosol effects by up to 85% for shortwave outgoing radiation at the top of atmosphere, and by about 35% for shortwave downward radiation at the surface. Determining why such differences in aerosol absorption exist should be seen as a priority for future research.

(D) 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. Not surprisingly, both products show low biases over monthly or longer periods, since they are calibrated with gauge observations. However, near the moist coastal zone of Ghana, the TRMM Product generally underestimates rainfall despite gauge corrections. This is potentially related to a larger importance of rainfall from warmer clouds. Using rainfall with a high temporal resolution from 17 DACCIWA rain gauges around Kumasi (Ghana), it was found that IMERG tends to overestimate the rainfall amount of weak and short rainfall events, but underestimates intense and/or long rainfall events, leading to error compensation between different rainfall types. IMERG has high false alarm rates, particularly in the dry season. False alarms account for over one fifth of total rainfall within IMERG and contributes crucially to achieve a monthly amount comparable to rain gauges during the rainy season. During the little dry season in June and August, IMERG tends to miss short and weak rainfall events, often from less cold clouds. There appears to be a too strong link between precipitation intensity and cloud optical thickness. These findings are relevant for forecast verification at daily and sub-daily time scales.

4) **Evaluation of weather and climate predictions**

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 of the region was assessed in several ways. Evaluations included local and regional scale day-to-day forecasts of five numerical weather prediction models, post-processed outputs of global ensemble prediction systems, a multi-model climate evaluation analysis and model sensitivity experiments.

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. 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. Specifically for southern West Africa and the DACCIWA campaign period (1 June to 31 July 2016), a detailed evaluation of five operational numerical weather prediction models with the much better observations available was conducted. While local daily variations in cloud and rainfall are almost uncorrelated with the model predictions, measurable skill was detected for regional variations connected to synoptic-scale, slowly propagating vortex-like structures. Evaluating temperatures in the numerical weather prediction models showed that after the wet monsoon onset towards the end of June most models are too cold and dry in coastal areas. This result was also seen in the lower layers when comparing models with near-coast 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}. A closer inspection of other fields shows that models are too cloudy at the immediate coast, likely leading to suppressed daytime heating and vertical mixing. This suggests that the Maritime (or Atlantic) Inflow of the Gulf of Guinea is not reproduced realistically in these models.

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) and numerical weather prediction models. The underestimation of cloud cover results in too much solar radiation reaching the Earth's surface, which increases vertical mixing and causes a qualitative change in 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 0.11. The resulting bias in solar surface irradiance for the five models is 43 W m^{-2}. 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 and also affects model results over the neighbouring North Atlantic/European sector. 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. However, 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.

Data denial experiments have proven useful in assessing the benefit of assimilating a certain type of observations into an atmospheric model, as for example done with respect to the influence of radiosonde measurements from the African Monsoon Multidisciplinary Analysis (AMMA) in August 2006 (mostly in the Sahel) on the European Centre for Medium-Range Weather Forecasts (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. For specific humidity near 925 hPa, the “noDACCIWA” analysis is much drier, mostly over Benin and parts of Ghana in qualitative agreement with a comparison between aircraft measurements during the DACCIWA campaign and the ECMWF operational analysis. In addition, 925-hPa temperatures in the morning are too cold by up to -0.4 K in large parts of southern West Africa, particularly downstream (i.e. north) of the radiosonde stations in Ivory Coast and Ghana. The 850-hPa southwesterly winds at 00 UTC in the “noDACCIWA” analysis are too strong over southern Ivory Coast and parts of Ghana, suggesting too strong nighttime cold air advection from the Gulf of Guinea. Forecasts started from the improved “DACCIWA” analyses do perform better, but only up to 12h lead times and mostly for temperature. This points to model errors being a substantial obstacle to better forecasts, rather than the availability of initialization data alone. This was already concluded for the AMMA radiosondes, indicating unsatisfactory progress in model development.

The identified issues demonstrate that the quality of daily weather forecasts in southern West Africa is generally low and the credibility of future changes in rainfall is limited, calling for much stronger efforts to improve models over this crucial region.

5) **Air pollution concentrations and sources**

DACCIWA has for the first time quantified the concentrations of air pollution in southern West Africa on a city and regional scale, including those most important sources and health aspects. It was shown that particle pollution is the major problem with particularly high concentrations being related to domestic fires, while gaseous pollutants (including ozone) are usually below international standards. Measurements of particulate matters with a diameter less than 2.5 µm (PM2.5) in the cities of Abidjan and Cotonou show PM2.5 concentrations almost continuously above 10 µg m^{-3} (the World Health Organisation (WHO) annual limit) and regularly above 25 µg m^{-3} (the WHO 24 hour limit). These concentrations are higher than those typical for European cities but are less than those in highly polluted cities in Asia (Beijing, New Delhi etc). Long-term observations do not exist for gaseous pollutants (ozone O_3, nitrogen dioxide NO_2, sulfur dioxide SO_2) in southern West Africa cities. For DACCIWA bi-monthly surface observations were made during 2015–2017 at the four air quality measurement sites in Ivory Coast and Benin, as well as the airborne observations during the summer of 2016. These pollutants did not exceed WHO limits. However, it seems likely that NO_2 exceedance could occur on specific days in some locations.

The highest monthly PM2.5 concentrations are seen in the dry (winter) season. This is due to a combination of desert dust transported southward from the Sahara and smoke from the burning of savannah / agricultural land within southern West Africa, occurring 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. 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 kilometres to the coast of southern West Africa. Remarkably, in these months 20–40% of the particle mass is produced from these Central African fires and transported into the region.

Historically, the long-term, publicly 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 also be monitored to assess their impact which is currently unknown.

6) **Health impacts**

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.

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. 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.

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, black carbon and water-soluble organic carbon particles, cause the most inflammation. Thus the highest inflammatory impact on people occurs in the dry 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. Modelled regional distribution of mortalities due to PM2.5 emitted by all the anthropogenic sources show high premature deaths for adults older than 30 years in Ivory Coast and Benin with, respectively, 18223 and 8479 premature deaths of all causes. 6% and 8% of these deaths are attributed to respiratory diseases, 42% and 56% to cardiovascular diseases. In Ivory Coast, the highest values are for the biggest cities such as Abidjan, Bouaké and Khorogo. For example, the relative contribution of Abidjan district is about 40% of national premature deaths. Sociological studies have shown significant differences between the occupational status of individuals and their vulnerability to air pollution in the four air quality sites.

DACCIWA has conducted the first 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 socio-economic information may also provide a lever to further understand the data, as not all inhabitants are equally likely to visit a doctor.

7) Improved understanding of meteorology of southern West Africa

DACCIWA has created significant advances in our understanding of a range of meteorological processes in southern West Africa. The most significant are:

It is well established that low, warm clouds frequently occur over southern West Africa. Based on the 7-weeks campaign with extensive field observations at Savè (Benin), Kumasi (Ghana) and Ile-Ife (Nigeria), detailed data analyses, as well as modelling experiments, DACCIWA improved the understanding of the conditions and processes that cause or suppress low-level cloud formation. Based on these studies, a new and comprehensive conceptual model for the diurnal cycle of the boundary layer and nights with low clouds was developed. This model is divided into five physically separable phases and should be used as a benchmark for model evaluation and development in the future. 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. Sensible heat flux and radiation are the main contributors to the formation of the stable surface inversion. The advective phase starts with the arrival of the Maritime Inflow from the Gulf of Guinea, a frontal feature that is quasi-stationary during the day and moves inland during the night, and involves the onset of the nocturnal low-level jet. Additionally, the Maritime Inflow is characterised by cold air advection causing the relative humidity to increase considerably. In the third and fourth phases, low-level clouds form and thicken, mostly as a consequence of continuous cold-air advection and to a lesser extent of radiation and sensible flux divergence. In some cases, a stratus fractus deck (stratus fractus phase) forms before the appearance of a more homogeneous deck (stratus phase). Shear-driven turbulence associated with the low-level jet creates mixing during this phase. The strength of the shear-driven turbulence also determines the base of the low-level clouds. The start of the vertical development of the convective boundary layer after sunrise marks the last phase finally leading to cloud breakup. The low-level clouds have a strong impact on the surface energy balance, reducing the buoyancy flux during daytime in case of late breakup. In that case, the convection is reduced and the boundary-layer depth shallower. The impact of the boundary-layer clouds on radiation and turbulent surface fluxes was quantified for the first time. Comparison of cloud-free and cloudy nights reveal that the main differences are due to large-scale pressure patterns, indicating a stronger Saharan heat low for stratus nights, which are also on average colder and moister than the stratus-free nights. The interplay between the magnitude of cooling related to the horizontal cold-air advection from the Gulf of Guinea and the background level of moisture were found to be crucial factors for low-level cloud formation.

There are also significant new insights into microphysical aspects of these low clouds. Despite the shallow nature of warm clouds over southern West Africa an appropriate parameterization of the effects of sedimentation is required to represent them in models, even when they are not precipitating. 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 significantly (up to a factor of 2) reduces liquid water path variability until the morning and also elevates the mean cloud-base height by an additional 200 m.

Model sensitivity experiments demonstrated that modifications of the low clouds have a large impact on the diurnal evolution of the boundary layer and finally rainfall generation. It was shown for the first time that rainfall over the DACCIWA region depends logarithmically on the optical thickness of low clouds, as these control the diurnal evolution of the planetary boundary layer, vertical stability and finally convection. In our experiments, the increased precipitation over southern West Africa had small direct effects on the downstream Sahel, as higher temperatures due to increased surface radiation are accompanied by decreases in low-level moisture due to changes in advection, leading to almost unchanged equivalent-potential temperatures in the Sahel. The results are sensitive to the use of a convective parameterisation. The results demonstrate that relatively minor errors, variations or trends in low-level cloudiness over the DACCIWA region can have substantial impacts on precipitation. Similarly, they suggest that the dimming likely associated with an increase in anthropogenic emissions in the future would lead to a decrease of summer rainfall in the densely populated Guinea Coastal area.

In addition, the dynamical understanding and climatology of Guinea Coastal rainfall systems was significantly enhanced, including a characterisation of environmental factors leading to different rainfall types as well as geographical, seasonal and diurnal variations. Highly organized Mesoscale Convective System (MCS) events are the dominating rain-bearing systems in southern West Africa (SWA). They tend to occur in highly sheared environments as a result of mid-level northeasterlies ahead of a cyclonic vortex. Their contribution to annual rainfall decreases from 71% in the Soudanian to 56% in the coastal zone. This is far less than in the Sahel. MCSs in SWA also propagate slower than their Sahelian counterparts and occur predominantly at the start of the first coastal rainy season. However, in terms of numbers, about 90% of rainfall systems are weakly organized and smaller in size. These systems occur during and after the passage of a cyclonic vortex within a regime of deep westerly anomalies, low wind shear and low to moderate CAPE (convective available potential energy), bearing some resemblance to what has been termed “monsoon” or “vortex rainfall”. This novel approach stresses the relevance of mid-level (wave) disturbances on the type and lifetime of convective systems and thereby their regionally, seasonally, and diurnally varying contribution to rainfall amount. The DACCIWA findings suggest further investigations into the character of the disturbances as well as possible implications for operational forecasting and the understanding of rainfall variability in SWA.

A first-ever quantification of rainfall from purely liquid clouds was achieved. 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 reveals frequent warm rain over ocean and coastal regions, but infrequent warm rain inland. This is consistent with radar observations from the DACCIWA supersite in Savè (Benin). A 12-year satellite climatology derived from SEVIRI retrievals shows that warm rain prevails over orographic regions in the morning and coastal regions after midday, enhanced by orographic lifting and land-sea breeze effects.

DACCIWA research confirmed that organized mesoscale convective systems are key to precipitation generation in West Africa, with a decreasing importance from the Sahel towards the Guinea Coast. Convection-permitting simulations capture this much better than parameterized convection with positive impacts on the diurnal cycle. Capturing convection explicitly has a large effect on the distribution of rainfall in the West African monsoon region but this does not automatically lead to improved rainfall fields. A closer analysis suggests that differences in vertical mixing and non-precipitating clouds that in turn affect radiation play an important role.

8) Influence of aerosols

A key uncertainty in our assessment of future climate change is how aerosol particles 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 and has demonstrated that interactions between aerosol particles, clouds, precipitation and sunlight are highly complex. 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 is already so high that there are always a large number of particles and whilst further additions affect cloud properties such enhancements have little effect on precipitation. A further deterioration in particle pollution will, therefore, have a small effect on rainfall through changes in cloud properties.

Aerosols also reduce the amount of sunlight reaching the Earth’s surface. The humid environment during the wet summer monsoon allows a substantial uptake of water, particularly in the morning hours. The optical extinction can increase by about a factor of 6 during these periods, leading to an overall doubling of the aerosol optical depth. Reductions in surface heating of 20 Wm^{-2} through this process were seen. Model simulations show that 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 and the daytime development from low stratus clouds to deeper stratocumulus and then cumulus by 1–2 hours. 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, as is likely with increased industrialization, will exacerbate these impacts.

Weather forecast model results with and without interactive aerosols show that aerosol biases which produce small effects on time-scales 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 emissions of which depend strongly on meteorological variables. Furthermore, interactive aerosols improve monthly predictions for the spring/summer season in the northern hemisphere. 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, while those for West Africa 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.

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. 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. DACCIWA hopes to inspire new research in this area looking specifically into long-term trends and future evolution. Given the large overall sensitivity of the system, changes in aerosol amount and chemically composition may have substantial impacts but this needs further study.

9) Future evolution

Given the substantial deficits in our computer models, confidence in future projections for climate and air pollution for southern West Africa remain low. 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) as for example, the proximity to the ocean suggesting that the temperature rise along the Guinea Coast will tend to be smaller than farther inland. For a low emission scenario of the Intergovernmental Panel on Climate Change (IPCC), temperature increases are mostly below 2°C across entire northern Africa but could exceed 3°C for high emissions. Different assumptions about sea-surface temperature evolution have a small impact on the magnitude of the warming inland. However, the warming is very sensitive to how vegetation, and the interactions between aerosol and clouds, are represented in a climate model

Computer models still struggle to realistically represent the West African monsoon. 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. This impedes an assessment of the frequency of future droughts and floods, food security, energy generation etc. in this region. DACCIWA model experiments further confirm large sensitivities, showing that our understanding of future precipitation in the region remains to be poor.

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. Improved process (meteorological, land-surface etc.) level representation of this complex region coupled to the evaluation of multiple modelling systems with different local emission scenarios will be needed to enhance confidence in future air pollution projections over the region.

1.1.4 The potential impact and the main dissemination activities and exploitation of results

IMPACT

DACCIWA addressed three of the main topics of Seventh Framework Programme (FP7) Environmental Research: climate change, environment and health, and Earth observation. It had secondary objectives within natural resources management, and land and urban management. DACCIWA was designed to achieve impact in the areas of policy, climate science, education and society. For policy impact was achieved through the production of a policy brief document and associated policymaker workshops in Africa and Europe (see Dissemination section) as well as indirectly through our assessments of processes and models that we hope will find its way to the coming assessments of the Intergovernmental Panel on Climate Change (IPCC). Impacts on climate science are achieved through the benchmark observational dataset DACCIWA produced and based on this through the identification of deficiencies in computer models and satellite products that can guide future improvements. Finally, an impact on education was achieved through the training of European and African PhD students and through field teaching. The ample media activities of DACCIWA, particularly around the field campaign, has helped to make the general public in Africa and Europe more aware of the southern West Africa air pollution problem (see Dissemination section). As a large European-African project DACCIWA had critical mass to be sufficiently visible on the international stage and to attract interest from the media and general public. More details on individual aspects are presented in the following.

1. Impact on policy

Southern West Africa is a region of very rapid population and economic development on Europe's doorstep. It will face numerous problems balancing protecting human and ecosystem health against providing for its people. This task will be made more complex by a changing global climate. The forecast population and economic change will drive changes in the composition of the air over West Africa with likely detrimental impacts on public health within cities and on regional air quality and ecosystems and food productivity, e.g. through increased concentrations of ozone and aerosols. The impact of increased emissions on the regional climate were studied extensively in DACCIWA. With an ever-larger number of people chasing limited environmental resources in the region, the next 30 years will be challenging for the governments of the region. Europe bares a historic responsibility in southern West Africa, spending significant development resources in the region. Europe has a range of economic, political, cultural and humanitarian interests in southern West Africa. DACCIWA provided necessary scientific evidence to underpin sustainable development policies to better protect human and ecosystem health in southern West Africa.

DACCIWA produced improved scientific understanding in three key policy areas linked to anthropogenic emissions: impacts on public health on the city scale, regional-scale impacts on health, ecosystems and food security and regional-scale impacts on climate. DACCIWA increased our understanding of the role of aerosol types and loadings on public health, linking different sources to different aerosol types. This way DACCIWA has provided guidance on the likely evolution of this problem over the next 30 to 50 years in association with population growth, changes in emissions and climate change. This will allow the impact of future economic choices (industry, transport, energy) on human health to be evaluated. DACCIWA also increased our understanding of the concentrations of ozone and aerosols in the region and their link to human emissions. DACIWA estimated the impact this has on human health and on crop and ecosystems, this way giving guidance of how to minimise these impacts. In the next decades southern West Africa will be subject to changes in climate brought about by the increase in greenhouse gases and associated global warming. At the same time, changes in local anthropogenic emissions can change climate regionally by altering aerosol concentrations, which can lead to changes in cloud characteristics, radiation, precipitation and even the West African monsoon circulation. This will have a range of possible impacts on the region from changes in the occurrence of extreme weather through to a changing water cycle, and from changing cloud cover to changes in temperature and radiation. These factors impact on many socio-economic areas such as hydroelectric energy generation, transportation, food and crops. DACCIWA provided the basic science to assess the impacts of changes in anthropogenic emissions on the regional climate and developed recommendations to policymakers based on the findings.

In addition, DACCIWA hopes to create policy impact through current international efforts on climate change. Output from DACCIWA climate simulations and models will enter the IPCC process and are ready in time to affect the sixth Assessment Report (AR6; expected for 2021). IPCC model data are freely available to a large community of researchers, allowing much wider application and further research into the West African monsoon and aerosol-cloud interactions in other parts of the planet. The IPCC ARs are the most widely used basis for policymaking in the area of climate and environmental change and will create maximum impact for DACCIWA research. DACCIWA will also influence the IPCC process through scientific publications and reports documenting the improved process understanding and model sensitivities and uncertainties. DACCIWA has also built on other on-going activities of international agencies with a science-into-policy role. The International Global Biogeochemistry Program (IGBP) and the International Commission on Atmospheric Chemistry and Global Pollution (ICACGP) co-sponsor their International Global Atmospheric Chemistry (IGAC) activity. Several DACCIWA researchers have been involved in activities such as the Deposition of Biogeochemically Important Trace Species (DEBITS) and the Megacities projects. DACCIWA scientists have brought an African emphasis to other IGAC activities such as ‘air pollution and climate’ and ‘atmospheric chemistry and health’, e.g. by contributing to the African Group on Atmospheric Sciences (ANGA; http://www.igacproject.org/activities/african-group-atmospheric-sciences-anga).

DACCIWA contributed to the research needed to underpin policies of adaptation to and mitigation of adverse effects of climate change in tropical Africa, an important aspect in the *Africa-EU Strategic Partnership (https://www.africa-eu-partnership.org/en)*. The adaptation to climate change is an important issue in the EU's bilateral relations with other countries in the developed and developing worlds alike. The EU is the world's biggest provider of official development assistance (ODA) with more than half of global ODA. In April 2009 the EC presented a policy paper known as the White Paper, which sets the framework for adaptation measures and policies to reduce the EU's vulnerability to the impacts of climate change. DACCIWA contributed to several key areas of this framework: *(A) Building a stronger knowledge base since sound data is vital in the development of climate policy:* DACCIWA advanced our understanding of how human emissions impact on a sensitive tropical regional climate system with interactions between aerosol and clouds being particularly uncertainty. DACCIWA generated a dataset that will equip the European modelling and satellite community with the information needed to improve operational procedures used for climate monitoring and prediction. *(B) Taking climate change impacts into consideration in key EU policies:* DACCIWA informed the EU and other national and international policymakers about the potential risks of regional climate change in southern West Africa in connection with rapidly increasing local emissions superposed on effects of global warming. *(C) Supporting wider international efforts on adaptation by helping for example non-EU countries to improve their resilience and capacity to adapt to climate change:* DACCIWA created the scientific knowledge to assess the impact of certain development choices in industry, traffic and energy generation. The involvement of African researchers and weather services, the training of African PhD students and the dissemination to African policymakers created capacity to understand possible scenarios and to develop sustainable adaptation strategies.

2. Impact on climate science

DACCIWA has had a substantial impact on the climate community by fostering our understanding of the physical and chemical processes occurring in the atmosphere over southern West Africa. This will help reducing uncertainties of current state-of-the-art predictions across a range of spatial and temporal scales.

Geographically DACCIWA concentrated on scales from local (supersite or urban measurements) to regional (West African monsoon). DACCIWA improved our understanding of important and currently understudied components of the West African monsoon system, which has a strong impact on the livelihoods of hundreds of millions of people, some of which are amongst the poorest on the planet. The West African monsoon poses an important challenge to state-of-the-art climate models, which show significant rainfall biases and disagree even about the sign of projected changes in the course of the 21st century. The improvements of satellite retrievals for monitoring and computer models for predicting monsoon processes that DACCIWA science has supported will likely have a positive impact beyond southern West Africa, e.g. in monsoon regions in Asia.

Temporally, the research span from weather timescales (field measurements, diurnal cycle, cloud processes, atmospheric dynamics etc.) to climate timescales (ground-based and satellite climatologies, pollution and emission monitoring, longer-term simulations, climate projections). An increasing number of operational centres are now pursuing a “seamless” modelling strategy, where the model development activities for weather, seasonal, decadal and climate timescales are merged (including the DACCIWA partners ECMWF and MetOffice). Particularly seasonal predictions are a key requirement of effective planning for agriculture, water and energy resources with potentially large socio-economic benefits.

A key contribution of DACCIWA to climate science is the creation of a unique dataset for West Africa, mostly from the 2016 field campaign but also through extensions using data from existing projects, surface stations (including digitisation efforts) and satellites. This dataset serves as a benchmark for a rigorous analysis of dynamics-aerosol-chemistry-cloud interactions. The generation of the remote-sensing component of the DACCIWA benchmark dataset included a rigorous validation, which will hopefully inspire new retrieval developments by international satellite centres or ground-based remote-sensing networks (e.g. Satellite Application Facility on Climate Monitoring (CM-SAF), Baseline Surface Radiation Network (BSRN)). Although DACCIWA already included a substantial effort to exploit the dataset, further exploitation by other groups and for other purposes is expected and facilitated by an easy and free access to the data through http://baobab.sedoo.fr.

This new benchmark dataset and the improved process understanding was used to validate (and develop) operational models, in particular their aerosol-cloud and air quality components. Effective and fruitful interactions with the operational modelling community were fostered through different measures: Two leading European operational centres, the ECMWF and UK Met Office, were partners in DACCIWA and directly fed results into model development. This process was further facilitated through existing formal relationships between weather services and universities involved in DACCIWA such as the Partnership between the Met Office and UNIVLEEDS and UREAD, and the link between the German Weather Service and KIT. Interactions with these centres were fostered through the use of their models for research, model evaluation and flight planning (e.g. the German ICON model). Dr Leo Donner (Princeton University), lead scientist for the development of the Geophysical Fluid Dynamics Laboratory (GFDL) model, served on the DACCIWA Advisory Board and therefore helped communicating DACCIWA results to the North America modelling community. The operational modelling systems were used for simulations, sensitivity tests and scenario experiments on all scales from weather to climate within DACCIWA and follow-up simulations based on the results have been advertised. In addition, DACCIWA contributed to improved climate projections through an assessment of future anthropogenic emissions from southern West Africa sources that should be fed into international databases used to provide boundary data for climate simulations.

DACCIWA partners have been involved in a number of national and international research activities of direct relevance to DACCIWA and collaborated with programmes not directly involving DACCIWA scientists, adding considerable value to DACCIWA science, strengthening its international network and increasing the visibility of the project. For example, the African Monson Multidisciplinary Analysis (AMMA) project has currently entered a 2nd phase (until 2020) with greatly reduced funding and an emphasis on coordination that aims to integrate results from the 1st phase of AMMA into operational procedures in order to enhance the impact of AMMA research. DACCIWA contributed to all three main objectives of AMMA II (long-term environmental monitoring, process studies, integration of environmental and socio-economic observations). The international AMMA chair Serge Janicot was a member of DACCIWA's Advisory Board. Another example is the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL; www.wascal.org). WASCAL is building observational networks for meteorological, hydrological, land, biological and socio-economic data in several target countries including Benin, Togo, Ghana and Ivory Coast. DACCIWA has integrated several WASCAL funded PhD students into the project (see also section on impact on education below). In the UK, DACCIWA scientists have been involved strongly in the "Future Climate for Africa" programme (http://www.futureclimateafrica.org) and GCRF African Science for Weather Information and Forecasting Techniques (GCRF African-SWIFT) programme (https://africanswift.org).

3. Impact on education

The DACCIWA project engaged with a variety of training and educational activities. In total 13 European and 12 African PhD students were trained, research visits of more senior African scientists to European labs were organised and field training for African scientists and members of national weather services was organised during the main field campaign. In this way DACCIWA strongly supported the development of the next generation of climate scientists both in the EU and Africa.

The training of PhD students is of central importance to the development of a European knowledge based economy. DACCIWA produced PhD students skilled in a variety of disciplines (analysis of large datasets, modelling, observations, health impacts). Additional students funded from other sources were integrated into the wider DACCIWA programme. These students have the potential to become leaders not only in academia but also in the industrial, policy and governmental arenas. Providing these studentships within a EU project created a cohort of individuals used to working together within a European context, which has increased the mobility of researchers across the EU and helped create a single European 'science space'. Several PhD students (and also more senior scientists) spent a period of time working in the labs of other DACCIWA beneficiaries. For example, UPS had a close collaboration with the University Félix Houphouët-Boigny (Côte d'Ivoire) and Université Abomey-Calavi (Benin) and several researchers had longer research stays in Toulouse and some of them also at KIT. Furthermore, KIT invited a member of the Nigerian Meteorological Service for two 3-month research stays to Karlsruhe. This is a very substantial and effective means to build capacity in the African research community. DACCIWA members also offered co-supervision of PhD students funded through the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) graduate school (www.wascal.org). This German initiative is designed to help West African countries to tackle the challenge to develop effective adaptation and mitigation measures in response to climate change.

In addition, many DACCIWA scientist are teaching undergraduate students on a regular basis. 'Research led teaching' is central to most university's teaching missions and efforts were made to integrate DACCIWA topics and results into teaching activities, e.g. in the form of final dissertation topics. DACCIWA scientist will make a significant teaching contribution to a planned summer school in Ghana in summer 2019 on the campus of the DACCIWA beneficiary KNUST building on past the positive experience of past summer schools in 2008 and 2010. This will be a great opportunity to include DACCIWA science results into the training of students in Africa.

During the field campaign, DACCIWA members organised field and classroom teaching to local students, academics and weather service personal (particularly at KNUST where a meteorology degree programme has recently been established). This included presentations with a general overview of the project objectives, scope and potential socio-economic implications and demonstrations of the instrumentation used. DACCIWA also provided funding for members of the involved national weather services to attend relevant training courses, for example offered by the World Meteorological Organisation (WMO).

4. Impact on society

Currently, the awareness of air pollution as a serious environmental problem, with significant impacts on people, agriculture and ecosystems, is rising. While air pollution problems in major Asian cities such as Beijing and New Delhi have been researched and covered in news around the world, air pollution is Africa has traditionally been regarded as secondary to issues with infectious diseases such as Malaria, Meningitis or HIV. DACCIWA has for the first time provided quantitative data on urban and regional air pollution levels, the most important sources and health implications. The results show that air pollution already contributes significantly to heart, respiratory and skin diseases in West African cities and that a quick deterioration of the situation is to be expected. The many dissemination activities targeting the general public and policymakers that DACCIWA has launched contributed to make people much more aware of the problem. In the long run, this awareness will hopefully foster behavioural change and motivate politicians in Africa and amongst European donors to put in place better regulations and to implement cleaner technologies.

Main dissemination activities

DACCIWA was very active in disseminating its scientific results and their implications to a wide group of interested parties inside and outside of academia. The main activities conducted were:

1) External websites: The main project website www.dacciwa.eu holds information on the project and its participants, the different WPs, publications, deliverables, links, events etc. In addition a joint website was set up with the two other projects active under the same EU call, Impact of Biogenic versus Anthropogenic emissions on Clouds and Climate: towards a Holistic UnderStanding (BACCHUS) and Stratospheric and upper tropospheric processes for better climate predictions (StratoClim): http://www.aerosols-climate.org. Quicklooks from the DACCIWA field campaign, model forecast, satellites images etc. are available from http://dacciwa.sedoo.fr. The DACCIWA database is accessible from http://baobab.sedoo.fr.

2) Bi-annual newsletter: The DACCIWA dissemination team published a bi-annual newsletter starting from spring 2015 (8 in total). These are available from the main webpage, where interested individuals can sign up to a mailing list (https://www.dacciwa.eu/stay-informed/newsletter), through which the newsletter is distributed. This mailing list was compiled through a careful compilation of a wide range of sources and with input from many DACCIWA members. The newsletters report about new scientific findings, publications, field activities, project meetings, individual early-career DACCIWA researchers, media coverage etc.

3) DACCIWA movie: In collaboration with the press office at KIT a short movie was produced that gives a quick and easy introduction to the project, its motivation and activities and the anticipated outcomes. The movie is available on youtube: https://www.youtube.com/watch?time_continue=3&v=zjDrEvTmZt8

4) Press releases: A number or press releases were published during the course of the project by individual consortium members and in coordinated ways in different countries. This activity culminated around the field campaign in June-July 2016. In response to this, a great number of articles and interviews for newspapers, websites, radio and television appeared. Additionally a final press release will be published in February 2019 referring to the results of DACCIWA.

5) Social media: DACCIWA has been running accounts on Twitter and Instagram, where news on the field campaign, conference contributions, papers and events were disseminated.

6) Overview articles: DACCIWA published several highly visible overview articles over the course of the project. In 2015, two papers appeared: The first by Knippertz et al. (2015a) in *Nature Climate Change* details the underlying scientific motivation for DACCIWA, while Knippertz et al (2015b) in the for *Bulleting of the American Meteorological Society* explains the aims, scope and structure of the project. These were followed by overview articles in 2017 and 2018 that addressed specific aspects of the field campaign. While Flamant et al. (2018) details the actual campaign, its objectives, instrumentation and conducted measurements, Knippertz et al. (2017) provides an overview over the meteorological and chemical evolution during June-July 2016. With a more specific focus, Kalthoff et al. (2018) give an overview of the boundary layer component of the field campaign.

7) Articles published: Until February 2019, 44 articles were published or accepted by relevant peer-reviewed journals. Seven articles were accepted as discussion papers and are still in the review process. Further 15 articles have passed the internal approval process and are in preparation to be submitted.

8) Special sessions: DACCIWA scientists organised a special session entitled "Atmospheric composition, weather and climate in Sub-Saharan Africa" at the General Assembly of the European Geosciences Union in 2017, 2018 and 2019, which was well attended by DACCIWA and other scientists interested in Africa. The programme can be found here:
https://meetingorganizer.copernicus.org/EGU2017/session/24727
https://meetingorganizer.copernicus.org/EGU2018/session/27477
https://meetingorganizer.copernicus.org/EGU2019/session/30256

9) Special issue: Special issue was set up jointly between the Copernicus journals *Atmospheric Chemistry and Physics* and *Atmospheric Measurement Techniques* (see https://www.atmos-chem-phys.net/special_issue914.html). Editors are M.J. Evans, D. Spracklen, S. Janicot, A. Mekonnen, and S. van den Heever. It currently (as of January 2019) holds 22 papers and will remain open until 2020. This special issue allows seeing the breadth of DACCIWA research and will contribute to the visibility of the science.

10) Policy briefs: In October 2018 a policy brief document summarising all policy-relevant findings of DACCIWA in a compact and easy-to-understand form was completed. It contains our main conclusions with respect to air pollution, health impacts, emissions, impacts of pollution on

weather and climate as well as a long-term outlook and an assessment of our observational and modelling capabilities. Concrete recommendations for policymakers are given. The document is freely available from https://zenodo.org/record/1476843#.XDm1Ai2bp24. High-quality hard copies have been produced and distributed to relevant stakeholders. A translation into French is currently under way. To advertise this policy brief and to enter a dialogue with stakeholders workshops were organised around the final project meeting in October: Accra on 12 October, Abidjan on 18 October and Lomé on 19 October 2018. These workshops were covered prominent in the African media, including national TV. A final workshop in Brussels that was organised jointly with BACCHUS took place on 15 November with several representatives of the European Commission present.

11) Summary for operational stakeholders: In November 2018 a second summary document was compiled targeting operational stakeholders (e.g. weather services, climate centres, satellite providers). It contains our main conclusions with respect to the currenty observational system, emission inventories, the quality of current forecasting systems, the impact of additional observations, the role of aerosols for predictions as well as an identification of the most critical atmospheric processes. Concrete recommendations for policymakers are given. The document will be published as Deliverable 8.6 on the DACCIWA website but also in a more professional lay-out on https://zenodo.org as already done for the DACCIWA Policy Brief (see Point 9 above).

Exploitation of results

A key result of DACCIWA is the comprehensive dataset from the main field campaign in June-July 2016, which is freely available for the scientific community to use under a CC-BY license. For details, see http://baobab.sedoo.fr/DACCIWA.

1.1.5 Project public website and relevant contact details

Figure 1: DACCIWA project logo

Project website: www.dacciwa.eu

DACCIWA data: http://baobab.sedoo.fr/DACCIWA.

Policy brief: https://zenodo.org/record/1476843

Coordinator: Prof. Peter Knippertz
peter.knippertz@kit.edu
+49 721 60843565

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