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1 PERSPECTIVE

# 2 Local air pollution – a new factor for 3 climate change in West Africa?

4

5 *Peter Knippertz<sup>\*1</sup>, Mat J. Evans<sup>2</sup>, Paul R. Field<sup>3</sup>, Andreas H. Fink<sup>1</sup>, Catherine  
6 Liousse<sup>4</sup> and John H. Marsham<sup>5</sup>*

7

8 *<sup>1</sup>Institute for Meteorology and Climate Research, Karlsruhe Institute for  
9 Technology, 76128 Karlsruhe, Germany*

10 *<sup>2</sup>Wolfson Atmospheric Chemistry Laboratories / National Centre for Atmospheric  
11 Science, University of York, York YO10 5DD, UK*

12 *<sup>3</sup>Met Office, Exeter EX1 3PB / School of Earth & Environment, University of  
13 Leeds, Leeds LS2 9JT, UK*

14 *<sup>4</sup>Laboratoire d'Aérodologie, CNRS / Université de Toulouse, Observatoire Midi-  
15 Pyrénées, 31400 Toulouse, France*

16 *<sup>5</sup>National Centre for Atmospheric Science / [water@leeds](mailto:water@leeds), University of Leeds,  
17 Leeds LS2 9JT, UK*

18

19 \* e-mail: [peter.knippertz@kit.edu](mailto:peter.knippertz@kit.edu)

20 **The climate of West Africa is characterised by a sensitive monsoon system**  
21 **that is associated with marked natural precipitation variability. This region**  
22 **has been and is projected to be subject to substantial global and regional-**  
23 **scale changes including greenhouse-gas induced warming and sea-level**  
24 **rise, land-use and land-cover change and substantial biomass burning. We**  
25 **argue that more attention should be paid to the rapidly increasing air**  
26 **pollution over the explosively growing cities of West Africa, as experiences**  
27 **from other regions suggest that this development will change regional**  
28 **climate through effects of aerosols on clouds and radiation, and impact on**  
29 **human health and food security. We need better observations and models**  
30 **to quantify the magnitude and characteristics of these impacts.**

31

## 32 **Introduction**

33 The West African monsoon is one of the most important large-scale atmospheric  
34 circulation systems in the tropics. It controls winds, temperature, clouds and most  
35 importantly precipitation over a land area of about  $6 \times 10^6 \text{ km}^2$  ( $\sim 5\text{--}25^\circ\text{N}$ ,  $15^\circ\text{W--}15^\circ\text{E}$ )  
36 and has remote impacts, e.g. through hurricane genesis. Through water resources,  
37 agriculture and power generation the health and livelihoods of hundreds of millions of  
38 people depend on monsoonal rainfall.

39 The West African monsoon is a sensitive system that can be perturbed through  
40 different factors across a wide range of scales. A prominent example is the devastating  
41 drought in the 1970s and 1980s<sup>1</sup> that most severely affected the Sahel, one of the regions  
42 with the largest precipitation variability worldwide. A large fraction of decadal-scale

43 rainfall variability in the West African monsoon area is explained by variations in  
44 Atlantic sea-surface temperatures, which have been linked to natural oscillations but also  
45 to changes in manmade aerosol emissions during the 20<sup>th</sup> century, predominantly from  
46 industrialised areas in the midlatitudes<sup>2,3</sup>. It is anticipated that the West Africa regional  
47 climate will change due to effects of global-scale warming, implying an increased  
48 likelihood of unprecedented heat waves and a threat to low-lying, densely populated  
49 coastal areas from sea-level rise<sup>4</sup>, and due to land-use and land-cover change, as the  
50 increasing transformation of rain and savannah forests into agricultural land creates  
51 considerable changes in the surface energy and water balance through effects on albedo,  
52 evapotranspiration, water transport and storage as well as surface roughness<sup>5,6</sup>.

53 Studies on the Indian and East Asian monsoons suggest that anthropogenic  
54 emissions of aerosols and aerosol precursor gases from these densely populated and  
55 increasingly industrialised areas can affect the amount and seasonality of rainfall. Earlier  
56 studies concentrated on scattering aerosol such as sulphates, which reduce monsoonal  
57 circulation and precipitation through a reduction of short-wave radiation reaching the  
58 surface, sometimes termed “solar diming”<sup>7</sup>. The inclusion of absorbing aerosol such as  
59 black carbon creates a more complicated response in models that amongst other things  
60 depend on whether a coupling to the ocean is taken into account<sup>8</sup>. According to the  
61 “elevated heat pump” concept, aerosol heating over the Tibetan Plateau causes large-  
62 scale circulation changes over South and East Asia<sup>9</sup>, but this idea is difficult to prove  
63 from observations<sup>10</sup>. Recent studies are increasingly including effects of aerosols on  
64 clouds and typically find a reduction of monsoon-season precipitation through combined  
65 effects of clouds and radiation changes<sup>11,12</sup>.

66 In West Africa anthropogenic emissions of aerosols and aerosol precursor gases  
67 have increased rapidly in recent years and are projected to keep increasing<sup>13,14</sup>. This is  
68 particularly the case for the explosively growing cities along the Guinea Coast, as  
69 illustrated by high aerosol optical thickness along the coastal strip in the satellite image  
70 shown in Fig. 1, particularly in the area of Lagos. In this Perspective we will discuss the  
71 question whether this increasing pollution can be expected to perturb the sensitive West  
72 African monsoon system and thereby contribute to regional climate change in addition to  
73 the more established long-term factors global warming and regional land-use and land-  
74 cover change. In contrast to the Indian and East Asian monsoon, this emerging research  
75 topic has not received much attention yet and therefore the relative magnitude of this  
76 problem and possible interactions of different factors are unclear. Undoubtedly urban air  
77 pollution has already become a significant threat for human and ecosystem health across  
78 West African cities such that any regulatory actions could have multiple benefits. We will  
79 begin this paper with a short overview of the meteorological conditions over West Africa  
80 followed by a discussion of anthropogenic aerosols and aerosol-climate interactions.  
81 Concrete steps needed to improve our understanding of the role of air pollution for the  
82 West African climate are given in the concluding section.

83

#### 84 **The meteorology of West Africa**

85 The West African monsoon is associated with a marked seasonal cycle. From November  
86 to February most of the region is dominated by dry northeasterly winds from the Sahara.  
87 Clouds and precipitation are confined to the coastal strip, where the sea-breeze circulation  
88 brings in moister air and creates near-surface convergence. Large amounts of mineral

89 dust aerosol from the Sahel and Sahara are transported across the region, which in  
90 combination with human-induced biomass burning lead to persistent haze due to the lack  
91 of wet removal. From March onwards the southwesterly monsoon winds begin to  
92 penetrate deeper into the continent, bringing with them moister air, more clouds and  
93 precipitation<sup>15</sup>. The monsoon retreats back to the southern parts of West Africa in  
94 September and October. At the peak of the wet season in July and August, the large  
95 meridional low-level pressure gradient between the cold sea-surface temperatures in the  
96 eastern equatorial Atlantic Ocean and the Saharan heat low drive a strong monsoon flow  
97 with southwesterlies reaching about 20°N (Fig. 2a). The reduction in turbulence and  
98 therefore depth of the frictional layer from day to night leads to the formation of strong  
99 nocturnal low-level jets<sup>16-18</sup> (Fig. 2b) that transport moist air far into the continent.

100 A complex meridional pattern of different types of clouds, usually with a marked  
101 diurnal cycle, is observed across West Africa during the wet season<sup>19,20</sup>. Around 15°N  
102 long-lasting, organised convective systems favoured by the shear provided by the African  
103 Easterly Jet generate the bulk of annual precipitation<sup>21,22</sup>. Maximum rainfall and the  
104 deepest ascent is usually found around 11°N (Fig. 2a). The Guinea coastal zone is  
105 characterised by locally-initiated, less organised and often long-lasting convection during  
106 the afternoon and evening, for example associated with the land-sea breeze circulation<sup>22-24</sup>  
107 (evident from the cloud-free coastal strip in Fig. 1), and shallow warm-rain showers  
108 forming in the deep monsoonal layer (red shading in Fig. 2a). One striking feature in this  
109 region is the extensive coverage of mostly non-precipitating low stratus clouds related to  
110 the nocturnal low-level jet<sup>25-27</sup>. Dynamical controls on these clouds are subtle, with  
111 competing effects from temperature and moisture advection, radiative cooling,

112 condensational heating, subcloud evaporation, the sea-breeze circulation and the gentle  
113 upslope flow<sup>28</sup> (Fig. 2b). The stratus decks typically lift and break up in the course of the  
114 day to form more isolated cumulus<sup>20</sup>. Shallow midlevel layer clouds, sometimes caused  
115 by detrainment from convection, also frequently affect large parts of West Africa  
116 (Fig. 2a), but factors controlling their depth, extension and lifetime are not well  
117 understood. The combined radiative effect of these clouds has a strong impact on the  
118 surface energy balance<sup>29</sup> and thus on the diurnal cycle of the boundary layer and  
119 ultimately initiation of convection. During the wet season, natural aerosol contributions  
120 include dust from the Sahara, often found at midlevels associated with the northerly  
121 return flow (Fig. 2a), marine aerosol near the coast and biogenic aerosol further inland.  
122 The enhanced precipitation activity leads to a more effective wet removal of aerosol  
123 during this season.

124

### 125 **Anthropogenic aerosols**

126 Much of our current understanding of the regional atmospheric composition over  
127 West Africa stems from the African Monsoon Multidisciplinary Analysis (AMMA)<sup>30</sup>  
128 project<sup>31</sup> and other activities such as the DECAFE (Dynamique et Chimie Atmosphérique  
129 en Forêt Equatoriale) program, the IGAC (International Global Atmospheric Chemistry) /  
130 DEBITS (Deposition of Biogeochemically Important Trace Species) / AFRICA (IDAF)  
131 atmospheric chemistry and deposition monitoring network (<http://idaf.sedoo.fr>, in  
132 operation since 1995) and the AEROSOL ROBOTIC NETWORK (AERONET)<sup>32</sup>. The bulk of  
133 this work though focused on the substantial natural emissions from deserts, soils, forests

134 and oceans and thus on more remote parts of the region. This pertains to both  
135 observations and modelling.

136 In West Africa biomass burning is a large direct source of carbonaceous aerosol,  
137 which has a strong radiative effect, and also of volatile organic compounds, oxides of  
138 nitrogen, carbon monoxide etc., which can indirectly impact climate through perturbing  
139 ozone and methane concentrations and through creating secondary aerosol particles.  
140 Biomass burning occurs predominantly during the dry season. It is almost exclusively  
141 anthropogenic following century-old traditional practices<sup>31,33</sup>.

142 An additional factor that has surprisingly received relatively little attention thus far  
143 is anthropogenic emissions of domestic, traffic and industrial pollutants. While the  
144 increase of the global population is slowing down, the population of West Africa  
145 continues to increase by 2–3% per year (Fig. 3), with the current population of ca. 340  
146 million projected to reach more than 800 million by the middle of the century<sup>34</sup>. This  
147 increase is accompanied by strong economic growth of currently about 5% per year, as  
148 well as industrialization and rapid urbanization (Fig. 3). As a result, pollutants such as  
149 oxides of nitrogen and sulphur, hydrocarbons, carbon monoxide and carbonaceous  
150 aerosols have increased sharply over the last decades and, depending on compound and  
151 scenario, are projected to increase between 2 and 4-fold by 2030 (Fig. 4a). They would  
152 then contribute about 5 to 60% to global emissions, depending on compound and  
153 scenario<sup>13,14</sup>. A significant source of uncertainty in these predictions lies in the degree of  
154 regulatory constraint on emissions anticipated by the different West African countries  
155 over these decades.



156 A limited number of small-scale observational studies in West African cities, such  
157 as POLCA focusing on Dakar and Bamako, suggest that pollutants are already  
158 substantially above guidelines of the World Health Organization<sup>35-37</sup>. However, due to the  
159 lack of sufficient measurements, statistical information (e.g. on fuel consumption) and  
160 regulatory activities, there are no emission inventories for African cities with a high  
161 spatial resolution (e.g. currently 30 m for London). Given the short lifetime and thus  
162 spatial heterogeneity of many pollutants this makes estimating human exposure very  
163 challenging. It is notable from the limited studies that cities in West Africa suffer from a  
164 wide range of anthropogenic pollutants, some of which are also to be currently found in  
165 European cities (typically associated with high temperature combustion such as  
166 particulates, nitrogen dioxide NO<sub>2</sub> and ozone), but some that have not been a problem for  
167 many decades (associated with low temperature combustion, evaporative sources and  
168 others such as organic carbon particles, carbon monoxide, benzene, poly aromatic  
169 hydrocarbons and heavy metals).

170 In terms of regional anthropogenic emissions, global inventories<sup>13</sup> provide some  
171 basis, but these suffer from coarse spatial resolution (typically 1°) and lack of West  
172 African specificities of both sector activity (cars and motorbikes, fire wood, charcoal  
173 production, animal waste usage, generator usage, population density etc.) and emission  
174 factors (compound specific emission per kg of fuel used by a car, a stove, in house  
175 burning etc.). Recently continental-scale emission inventories have been created at 25-km  
176 spatial resolution based on African specific fuels and activities<sup>14</sup> (Fig. 4a), for example  
177 two-wheeled taxis<sup>38</sup> (Fig. 4b). These show the importance of domestic fires for black  
178 carbon, organic carbon, carbon monoxide and volatile organic compounds, of cars for

179 nitrogen oxides and of industry for sulphur dioxide, but substantial uncertainties remain.  
180 The limited observationally based assessments of the emissions for a city such as Lagos  
181 have historically not compared well with the coarser-resolution emission estimates<sup>39</sup> but  
182 such comparisons are few and far between. In addition to urban emissions, the rapid  
183 development of the oil industry along the Guinea Coast and its associated emission and  
184 flaring is an increasing source of anthropogenic pollution<sup>40,41</sup>.

185       Once emitted, anthropogenic primary pollutants can build up regionally (10–  
186 1000 km) and interact with other man-made (biomass burning) or natural emissions  
187 (vegetation, wind blown dust, lightening, oceanic) (Fig. 5). Chemical processes typically  
188 driven by sunlight can transform this complex mix of pollutants to produce secondary  
189 compounds such as ozone, acids (H<sub>2</sub>SO<sub>4</sub>, HNO<sub>3</sub>) and low volatile organics, which are  
190 harmful to humans and plants with potential impacts on agricultural productivity, and  
191 notably produce aerosol particles, which impact both health and climate as discussed in  
192 the next section.

193       Interactions between the increasing anthropogenic emissions and the large natural  
194 emissions still pose unresolved questions. The role of the naturally emitted isoprene and  
195 mono-terpenes on regional ozone is well documented for regions such as the southern  
196 USA<sup>42</sup> and our scientific understanding of this chemistry is evolving rapidly<sup>43–45</sup>, but  
197 studies assessing the situation for West Africa are few<sup>46,47</sup>. The impact on aerosol is even  
198 less clear. Secondary organic aerosol is formed from predominantly naturally emitted  
199 carbon compounds from trees but there appears to be a significant yield enhancement  
200 from anthropogenic emissions. This may be through the anthropogenics enhancing the  
201 oxidant concentrations or by them changing the volatility of the oxidation products, but

202 this is still subject to significant research<sup>48</sup>. Observations from AMMA during the wet  
203 season show low organic mass concentration in West Africa despite significant biogenic  
204 emission<sup>49</sup>.

205 Oxides of nitrogen (NO<sub>x</sub>) have both natural and anthropogenic sources and play a  
206 central role in the chemistry of the atmosphere. Globally their emissions are dominated  
207 by human activities. However for West Africa, the anthropogenic source (traffic,  
208 domestic fires, industries and power plants) is relatively small compared to the natural  
209 source, mostly from soils and lightning. The magnitude of the latter, however, is highly  
210 uncertain and variable on daily, seasonal and interannual timescales<sup>50</sup>. The impact of the  
211 rapidly increasing anthropogenic NO<sub>x</sub> emissions (Fig. 4a) on top of the large but highly  
212 variable and uncertain natural NO<sub>x</sub> emissions is not clear<sup>14</sup>. Other interactions such as  
213 those between anthropogenically emitted compounds and mineral dust<sup>51</sup> and ocean-  
214 sourced halogens<sup>52,53</sup> are also highly uncertain and speculative.

215 Our understanding of the interactions between the natural and anthropogenic  
216 systems is made more complex given the anticipated impacts on the region's ecosystems  
217 from an increasing population, from land-use and land-cover changes and from a  
218 changing climate. As with other regions there is also an impact of long-range transport of  
219 pollutants into the area, for example from biomass burning plumes from southern  
220 Africa<sup>31,33,54</sup>.

221

## 222 **Aerosol-climate interactions**

223 Generally, aerosols affect climate through impacts on radiation and clouds. The physical  
224 understanding of direct radiative effects is comparably good, but uncertainties are

225 introduced through insufficient knowledge of the vertical distribution and optical  
226 properties of the particles that depend on size distribution, shape and chemical  
227 composition, while interactions between aerosol and cloud are less well understood –  
228 particularly for ice and mixed-phase clouds<sup>55,56</sup> – and remain one of the most uncertain  
229 anthropogenic forcings of the Earth’s climate<sup>57</sup>.

230 For West Africa the bulk of the aerosol-climate interaction studies look at radiative  
231 effects of dust and biomass burning aerosol. Black carbon from manmade fires during the  
232 dry season has been suggested to reduce precipitation in West Africa by changing the  
233 atmospheric circulation leading to reductions of cloud frequencies and height<sup>58</sup>. Similar  
234 impacts have been found from the radiative effects of desert dust<sup>59,60</sup>. Urban pollution can  
235 enhance downwelling radiation during clear nights and therefore cause large increases in  
236 nighttime minimum temperatures as warm air is mixed from aloft due to radiative  
237 destabilization<sup>61</sup> but this has not been investigated for the Guinea Coastal zone, where  
238 additional impacts on the nocturnal low-level jet and stratus formation can be  
239 expected<sup>26,28</sup>.

240 To the best of our knowledge, there are no studies looking into aerosol-cloud  
241 interactions over the moister southern parts of West Africa. This is partly due to a  
242 comparably sparse network of measurements for atmospheric composition and  
243 meteorological variables<sup>62</sup> and partly due to the historically low levels of industrial  
244 development. Aerosols directly affect the properties of cloud droplets and ice crystals,  
245 which then in turn affect cloud-top height, albedo, areal extent and lifetime, and the  
246 cloud’s environment, i.e. there are two-way couplings between the cloud’s microphysical  
247 and macrophysical properties<sup>63–67</sup>. As a result, effects of aerosols on single clouds can be

248 quite different from when a system of clouds evolving through many cloud lifetimes is  
249 considered. Such aerosol effects have barely been considered for the meteorological  
250 environment of the West African monsoon.

251 Previous research in regions affected by biomass burning<sup>68</sup> has shown that the size  
252 distribution and number concentration of the aerosol particles are the main predictor of  
253 the cloud condensation nuclei (CCN) concentration, while composition and  
254 hygroscopicity are less important. However, secondary organic aerosols may play a role  
255 in complicating predictions of CCN concentration<sup>69</sup>. Studies on the extensive marine  
256 stratus decks in subtropical high-pressure regions show that an increase in aerosol can  
257 lead to changes of up to 40% of the reflected shortwave radiation<sup>70</sup> and can inhibit rainfall  
258 with lightly precipitating clouds affected most severely<sup>71</sup>. In summertime West Africa,  
259 the nocturnal low-level jet carries pollution from the coastal belt inland, where  
260 interactions with biogenic emissions from fields and forests may lead to the formation of  
261 secondary aerosol particles as discussed above. These aerosols are likely to be mixed into  
262 the extensive low stratus decks over the region (see Fig. 2). It would therefore be  
263 interesting to investigate possible changes to the clouds' radiative effects<sup>72</sup>, which in turn  
264 could change the evolution of the boundary layer and consequently the diurnal cycle of  
265 convection<sup>73</sup>. Changes to the areal cover, longevity or brightness of the West African  
266 stratus clouds could then have an effect on surface radiation due to the contrast in albedo  
267 to the underlying dark forest areas<sup>27</sup>. This may ultimately affect larger parts of the West  
268 African monsoon system through changes to the regional circulation. Unfortunately,  
269 current climate models appear to struggle with realistically representing both low- and  
270 mid-level clouds in this region, resulting in a spread of up to  $90 \text{ W m}^{-2}$  in the regional

271 mean daily surface solar irradiance<sup>27,74</sup>. Couvreux et al.<sup>75</sup> show that the cloud radiative  
272 errors are already established after a few days simulation time and appear to be related to  
273 the complex local energy balances and boundary-layer processes rather than large-scale  
274 advection<sup>18</sup>. These errors may therefore be related to problems with the model  
275 parameterisations of convection and the boundary layer and demonstrate the challenge of  
276 realistically representing cloud-aerosol effects in this region in models.

277 For convective clouds, modelling studies have shown that aerosol effects are  
278 typically more important in situations with relatively low Convective Available Potential  
279 Energy<sup>76</sup>, as often the case along the Guinea Coast. Detailed mechanisms have been  
280 proposed for single clouds such as the concept of convective invigoration<sup>64</sup> that links  
281 increased aerosol loading to deeper more vigorous convection by chaining together a  
282 number of physical processes. However, breaks in that chain or differences introduced by  
283 considering additional physical processes such as entrainment, downdraft production and  
284 aerosol radiative interactions can even lead to suppression of convection<sup>77</sup>. Again, ideas  
285 and results based on single clouds may not translate to results for cloud fields, since the  
286 evolution of the thermodynamics and aerosol environments is more complex and allows  
287 for interactions between clouds to occur<sup>66</sup>. For example, some recent studies have shown  
288 that precipitation rates can be quite robust to aerosol changes in some situations, even  
289 though the aerosols may still affect the microphysical and radiative properties of the  
290 clouds<sup>78,79</sup>. Nevertheless, changes to deep convective clouds from increased aerosol over  
291 West Africa have some potential to affect the distribution and intensity of precipitation,  
292 on which the population rely, and to modify the monsoon circulation through changes to  
293 tropospheric heating and by modifying upper and mid-level clouds that are formed via

294 detrainment<sup>80,81</sup>. Effects are likely to change as the character and organisation of  
295 convection changes through the monsoon. None of these ideas have ever been tested for  
296 the polluted parts of West Africa.

297

## 298 **Future perspectives**

299 In many ways the atmosphere above West Africa is still one of the least studied and  
300 understood on the planet, yet it plays a central role in determining the health and  
301 economic wellbeing of a large and increasing population. Based on experiences in other  
302 densely populated monsoon areas in India and East Asia, we argue in this Perspective that  
303 more effort is needed to improve our understanding of the impact of air pollution on  
304 climate in West Africa and its importance relative to regional effects of global climate  
305 change as well as effects of land-use and land-cover changes. Progress is currently  
306 hampered by a lack of appropriate meteorological and compositional observations and  
307 statistical information on emission patterns to research the complex interplay between  
308 pollutants, their secondary chemistry and changes to meteorology and climate across a  
309 range of spatial and temporal scales.

310 Fully coupled chemistry-aerosol-climate models are needed to advance our process  
311 understanding, to estimate the importance of air pollution relative to other climate drivers  
312 and to assess impacts of different future scenarios and mitigation pathways. However,  
313 substantial model errors still exist with respect to key features of the West African  
314 monsoon<sup>82-84</sup>, leading to a lack of skill in seasonal prediction<sup>85,86</sup> and large inter-model  
315 spread and low confidence in climate projections, especially for precipitation<sup>87,88,89</sup>.  
316 Despite significant advances, for example as part of the AMMA<sup>30</sup> project<sup>84,90,91</sup>, some

317 well-known model errors remain, such as those associated with the radiative imbalance in  
318 the area of the summertime Saharan heat low over Mali and Mauritania<sup>92</sup>, the  
319 representation of deep convection in the Sahel and its effects on the monsoon<sup>80,81,93</sup>, air-  
320 sea interactions over the tropical eastern Atlantic Ocean<sup>94</sup> and low- and midlevel  
321 cloudiness in southern West Africa<sup>27,74</sup>. Deficits in the meteorological models influence  
322 the simulated distribution of pollutants through transport, mixing and removal processes  
323 and therefore contribute to uncertainties in the coupled meteorology-chemistry system<sup>31</sup>.  
324 To overcome these difficulties, several important steps are proposed:

- 325 1) Refine emission inventories and scenarios. This requires a targeted source  
326 specification and key emission factor measurements, particularly for unique sectors  
327 like West African oil exploration, traffic or waste burning. Better statistical data on  
328 aspects such as fuel consumption (vehicles, wood, charcoal etc.) are also needed to  
329 scale the measurements up to national level. Together these data should be fed into  
330 emission inventories and for the development of future scenarios.
- 331 2) Monitor air pollution. An extension of the existing network of long-term parallel  
332 observations of air pollution (with key atmospheric composition parameters in both  
333 the gas and aerosol phase) and epidemiological and biological studies at the source  
334 level in selected urban sites is needed for an assessment of health issues related to air  
335 pollution in addition to, for example, the rural IDAF network. Results from such  
336 assessments can demonstrate potential benefits from emission regulations on both  
337 health and climate.
- 338 3) Improve availability of meteorological observations. This requires that observations  
339 of standard meteorological parameters (precipitation, cloud cover, temperature,



340 humidity, wind and radiation) from existing networks, usually operated by national  
341 weather services, are made available to the research community more systematically  
342 and if possible in real time. This should also include upper-air information from  
343 radiosondes and pilot balloons<sup>95</sup> and would ideally be accompanied by an  
344 enhancement of existing measuring capabilities, particularly of radiation,  
345 precipitation and clouds. Digitisation of observational records only existing on paper  
346 would further enhance the data availability for long-term studies.

347 4) Conduct targeted international field campaigns in West Africa using sophisticated  
348 ground-based and airborne instrumentation for atmospheric dynamics (particularly  
349 diurnal evolution of the boundary layer and associated cloudiness), composition  
350 (particularly secondary aerosol formation from anthropogenic and biogenic  
351 emissions), cloud microphysics (characteristics of low-level liquid clouds and  
352 transition to deeper clouds) and radiation (both aerosol direct and cloud effects). The  
353 data, together with models, should be used to reduce uncertainty in our  
354 understanding of the complex interplay between meteorology, atmospheric  
355 chemistry and clouds. Such a campaign is currently planned for June-July 2016 as  
356 part of the EU-funded “Dynamics-Aerosol-Chemistry-Cloud Interactions over West  
357 Africa” (DACCIWA) project<sup>96</sup>.

358 5) Enhance reliability of satellite data. Every remote sensing product needs ground  
359 truth to assess its reliability. The lack of adequate surface-based observations in  
360 West Africa currently impedes a rigorous assessment of the quality of satellite  
361 products. The steps outlined above, together with an enhanced network of ground-  
362 based sunphotometers, would greatly enhance the possibility to generate West Africa

363 specific evaluations of satellite products and to improve existing and future  
364 retrievals. This should include both meteorological (e.g. the new Global Precipitation  
365 Mission) and compositional (e.g. the new high-resolution sensors on the European  
366 Space Agency's Global Monitoring for Environment and Security, Sentinel series)  
367 parameters.

368 6) Improve the representation of the West African monsoon system in numerical  
369 models. New and better observations should be used to evaluate and further develop  
370 coupled meteorological-atmospheric chemistry models used for predictions of air-  
371 quality, weather, seasonal and climate signals. This will require coordinated efforts  
372 from both academic and operational institutions, e.g. the IMPALA (Improving  
373 Model Processes for African cLimAte) project within the 'Future Climate for Africa  
374 (FCFA) programme. Recent developments in computing power are now enabling  
375 high-resolution simulations (~km scales) to be performed over relatively large  
376 spatial domains for long periods. This allows all processes from city-scale emissions  
377 of pollutants, to their chemistry, explicit resolving of cloud processes and the  
378 resultant impacts on meteorology, health, ecosystems and climate to be examined  
379 seamlessly within a single model<sup>81</sup>. New developments in data assimilation including  
380 aerosol parameters also contribute to the identification and reduction of model  
381 errors. It is hoped that such studies can in the long run improve the representation of  
382 salient features of the West African monsoon. A specific target for southern West  
383 Africa should be the summertime low-level stratus and warm rain showers that we  
384 hypothesise here to be susceptible to aerosol effects.

385 7) Assess future impacts and mitigation pathways. New and improved models should  
386 be used to investigate possible future changes in the West African environment  
387 related to global climate change, regional land-use and land-cover change and local  
388 to regional anthropogenic emissions in an integrated way. These models should also  
389 be used to explore mitigation pathways, e.g. through West-Africa specific emission  
390 regulations.

391 8) Build local capacity. This requires the training of the next generation of African  
392 climate scientists that understand the complex interplay between natural and  
393 manmade, global and regional factors that affect the West African climate as well as  
394 linkages to socio-economic and political implications. A notable initiative in this  
395 direction, in addition to FCFA mentioned above, is The West African Science  
396 Service Center on Climate Change and Adapted Land Use (WASCAL,  
397 [www.wascal.org](http://www.wascal.org)).

398 The steps outlined above require increased efforts from the global climate research  
399 community to advance the understanding of the multiple facets of the challenging  
400 problem of regional climate change in one of the most rapidly evolving regions of the  
401 world. An advanced understanding should help to clarify the question if the steeply  
402 increasing short-lived anthropogenic constituents need to be considered for the more  
403 policy relevant mid-term climate projection until the middle of the 21<sup>st</sup> century. The next  
404 significant challenge will then be to translate enhanced scientific understanding into  
405 policy reform on the city, regional, national and international levels. This can only work  
406 in collaboration with African partners such as academic researchers, national weather  
407 services and government organisations.

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665

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671

### 672 **Author contributions**

673 P.K. led the drafting of the text with input from the other authors on specific aspects. All  
674 authors contributed to the intellectual content.

675

### 676 **Competing financial interests**

677 The authors declare no competing financial interests.

678 **Figure legends**

679

680 **Figure 1 | Sea breeze, clouds and pollution.** MODIS visible image at 1335 UTC on 12  
681 October 2013 over southern West Africa showing a well defined land-sea breeze, small-  
682 scale cumulus inland and enhanced air pollution along the coast and over the Gulf of  
683 Guinea, particularly in the vicinity of the coastal cities marked in white. MODIS aerosol  
684 optical depth at 0.55  $\mu\text{m}$  wavelength is overlaid as colour shading in areas where the  
685 retrieval algorithm<sup>97</sup> determines the image to be sufficiently cloud-free.

686

687 **Figure 2 | Clouds and the West African monsoon.** (a) Schematic meridional-pressure  
688 section illustrating the West African monsoon circulation, main cloud types (dark grey for  
689 frequent and light grey for less frequent occurrence), moist monsoonal layer  
690 characterised by southwesterly winds (red shading) and the African Easterly jet (AEJ,  
691 blue shading). Grey lines are isentropic surfaces; the 0°C isotherm is marked. (b) Zoom  
692 into the processes involved in the formation and maintenance of low-level stratus decks  
693 over southern West Africa. Vectors show a typical vertical profile of horizontal wind;  
694 NLLJ indicates the nocturnal low-level jet. This figure is derived from high-resolution  
695 modelling<sup>28</sup>.

696

697 **Figure 3 | Trends in West African population and settlement patterns.** Dashed  
698 black line: estimates and growth projections of the region's total population between  
699 1950 and 2020 (ECOWAS member states plus Mauritania) taken from United Nations  
700 (UN) data. Red line: Urban population according to the Africapolis study based on  
701 analysis of satellite/ aerial images and census data. Green line: Rural population  
702 according to official estimates. Solid black line: Sum of red and green lines, showing  
703 possible disagreement with UN estimates. Grey lines give ratios of urban versus rural

704 population for the two different estimates. (Figure taken from 98 with permission from the  
705 authors).

706

707 **Figure 4 | Emission inventories and scenarios.** (a) West African emissions of black  
708 carbon (BC), organic carbon (OC), oxides of nitrogen (NO<sub>x</sub>) and sulphur (SO<sub>2</sub>), non-  
709 methane volatile organic compounds (NMVOC) and carbon monoxide (CO) in 2005 and  
710 2030 for a reference (REF) scenario and a “carbon constraint case” (CCC) scenario  
711 assuming Africa-specific regulations implemented to obtain a strong reduction of  
712 emissions resulting from incomplete combustion. Sector-activity relative abundances  
713 (traffic, domestic fires, industries and power plants) are indicated in each case. Data are  
714 based on 14. (b) A typical source of pollution in West African cities: two-wheel taxis  
715 (photo courtesy of Benjamin Guinot).

716

717 **Figure 5 | Atmospheric chemistry and its impacts over West Africa.** The schematic  
718 shows the main emission sources of atmospheric trace gases and secondary aerosol in  
719 a north–south transect through West Africa including elements of long-range transport  
720 depicted as red boxes. Boxes below the main diagram show the different pressures on  
721 this system from on-going changes as well as their potential impacts on the regional  
722 scale.