Monitoring of persistent organic pollutants in Africa. Part 2: Design of a network to monitor the continental and intercontinental background†

G. Lammel,*ab P. Dobrovolnỳ,c A. Dvorská,a K. Chrom,c R. Brázdil,c I. Holoubekad and J. Hoškebe

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A network for the study of long-term trends of the continental background in Africa and the intercontinental background of persistent organic pollutants as resulting from long-range transport of contaminants from European, South Asian, and other potential source regions, as well as by watching supposedly pristine regions, i.e. the Southern Ocean and Antarctica is designed. The results of a pilot phase sampling programme in 2008 and meteorological and climatological information from the period 1961–2007 was used to apply objective criteria for the selection of stations for the monitoring network: out the original 26 stations six have been rejected because of suggested strong local sources of POPs and three others because of local meteorological effects, which may prevent part of the time long-range transported air to reach the sampling site. Representativeness of the meteorological patterns during the pilot phase with respect to climatology was assessed by comparison of the more local airflow situation as given by climatological vs. observed wind roses and by comparison of backward trajectories with the climatological wind (NCEP/NCAR re-analyses). With minor exceptions advection to nine inspected stations was typical for present-day climate during the pilot phase, 2008. Six to nine stations would cover satisfyingly large and densely populated regions of North-eastern, West and East Africa and its neighbouring seas, the Mediterranean, Northern and Equatorial Atlantic Ocean, the Western Indian Ocean and the Southern Ocean. Among the more densely populated areas Southern Cameroon, parts of the Abessinian plateau and most of the Great Lakes area would not be covered. The potential of the network is not hampered by on-going long-term changes of the advection to the selected stations, as these do hardly affect the coverage of target areas.

Introduction

To facilitate the evaluation of the effectiveness of the Stockholm Convention, its Article 16 stipulates that "the Conference of the Parties shall initiate the establishment of arrangements to provide itself with comparable monitoring data on the presence of the chemicals as well as their regional and global environmental transport". Air is obviously one of the environmental media to assess POPs on large spatial scales, and is also mentioned in a UNEP guidance document for a global POPs monitoring programme.

The motivation of this study is to establish a network to assess and appropriately control POP levels in air regionally, i.e. in the continental background of Africa as well as in intercontinental transport towards Africa. No such network exists. Monitoring of POPs in air in Africa was so far limited to one town in the

Environmental impact

The study is in the context of control of the levels of persistent organic pollutants (POPs) in the atmosphere over the African continent and the neighbouring seas. The objective criteria based design of a continent-wide network for air pollution, based on a pilot phase sampling programme and on climatological information is novel, probably unique, as existing continent-wide networks have mostly been developed from national activities rather than from an overarching concept. The result of the study, a suggested network of 6–9 stations across Africa, is suitable to monitor the continental and intercontinental background. Such a network is important for the global inventory of POPs, and for the development of the Global monitoring plan under the Stockholm Convention on POPs and will expectedly contribute to national implementation plans of the convention.
Republic of South Africa in 2004–05, and 3–4 stations in the Republic of South Africa, Botswana and Ghana in the frame of the GAPS network, as reported for the year 2005. The suggested network’s mission is the coverage of long-term trends and eventually episodic events. The target substances are ubiquitous substances with possible sources in Africa, i.e. dichlorodiphenyl trichloroethane (DDT) and its metabolites, hexachlorocyclohexanes (HCHs), chlorinated dioxins and furanes (PCDD/Fs), hexachlorobenzene (HCB) to some limited degree, and contaminants from sources supposedly mostly outside of Africa, i.e. polychlorinated biphenyls (PCB) and HCB. POPs have been observed over the Mediterranean, the open Atlantic and Indian oceans and Africa is receiving air pollution from other continents, i.e. Europe and South Asia, at least seasonally. Passive air samplers are simple and do not need electricity for operation, but allow only for a low time resolution. Due to economic limitations the network should be small, i.e. not comprise more than 10 stations.

Continent-wide air monitoring networks exist under the umbrellas of the World Meteorological Organization and conventions for environmental protection. Address conventional air pollutants, ozone-depleting substances and greenhouse gases. They combine stations of various history and conventional air pollutants, ozone-depleting substances and contaminants from sources supposedly mostly outside of Africa, i.e. polychlorinated biphenyls (PCB) and HCB. POPs have been observed over the Mediterranean, the open Atlantic and Indian oceans and Africa is receiving air pollution from other continents, i.e. Europe and South Asia, at least seasonally. Passive air samplers are simple and do not need electricity for operation, but allow only for a low time resolution. Due to economic limitations the network should be small, i.e. not comprise more than 10 stations.

The defined target regions of the aimed network are the major populated geographic regions of Africa, i.e. equatorial Africa, the savannah regions to the north and south of it and the populated coastal areas, and four sea regions, covering in three cases airflow from potential overseas source regions beyond these sea regions, i.e. the Central Atlantic (with Central and South America), the Mediterranean (with Europe), the western Indian Ocean (with South Asia) and the Southern Ocean. The emission sources in Africa themselves, however, are not aimed to be controlled by this network, as a much higher network density would be needed for this purpose.

This study describes a pilot phase POPs sampling programme and the application of objective criteria to select a short list of suitable network stations based on a combination of the pilot phase sampling programme results, meteorological and climatological information. The potential of the network is characterised and discussed taking into account.

Methodology

Sampling and chemical analyses

Passive air samples were collected as 28-day means (with some exceptions in the range 25–33 days) except for PCDDs/Fs which were exposed over three months. The samplers were equipped with a polyurethane foam disk. Sampling time was chosen such that saturation of the compounds could be excluded. The sampling method and its validation had been published elsewhere.

Samples were analyzed for seven indicator PCBs, DDT and its metabolites, PeCB and HCB, PCDD/Fs and 16 priority PAHs (according to US EPA; see Klánová et al. for a list of individual substances). Limits of quantification of <0.1–0.5 pg m⁻³ resulted for PCBs and OCPs and of <1.0 pg m⁻³ for PAHs. The sampling and analytical methods and QA/QC data were reported in the companion paper.

During the pilot phase samples were collected at 26 stations in 15 countries throughout the continent (Fig. 1).

Back-trajectories

The regional provenance of advected air was determined by three-dimensional 96 h-back-trajectories during the year 2008 (every 4 hours, 200 m above ground arrival height, HYSPLIT model). This level ensures that the trajectory starts in the mixing layer of the atmosphere. Additional control on this condition was conducted and only sporadic trajectories were found to have their starting height above the mixing layer height during night. During previous days, the starting heights of all trajectories were well within the mixing layer. Therefore, no whole trajectory was excluded from the data set.

![Fig. 1](https://example.com/fi1.jpg) Sites of the pilot phase sampling programme, January–June 2008. IA = international airport, IS = industrial site.
Trajectories were generated for one station in each of the 15 countries (Fig. 1). In countries with multiple sites, trajectories were generated for two stations, with background character, and as distant as possible from each other.

Climatological analysis

Wind directions of individual sites have been characterized using NCEP/NCAR re-analysis data. The four closest grid points for each station were extracted from the database that comprises six-hourly data with 2.5° × 2.5° spatial resolution. Data from the pressure level which was vertically closest to the arrival height of the calculated back-trajectory were used. Bi-linear interpolation was used to compute monthly mean wind directions for the sites in the period 1961–2007.

Since there is a lack of observed data, re-analysis data can give a reasonable approximation of the wind climatology. However, it must be stressed, that due to the spatial resolution of the gridded data general circulation patterns prevailing at the study sites can be characterized, but local topographic effects can be hardly addressed. We use monthly mean wind roses to characterize wind direction frequencies, their seasonality and temporal stability. However, the characteristics derived simply from wind roses can be problematic, when two or more different directions with comparable high frequency occur.

Wind direction patterns can be more precisely characterized by means of the prevailing wind direction (PWD) and its frequency (PWF). In comparison with characteristics computed directly from wind roses, PWD and PWF values consider patterns with two or more frequent winds of similar frequencies. PWD (in degrees) and PWF (in %) were expressed for each month and year. If $n_1, ..., n_4$ are relative frequencies (%) of neighbouring wind directions which have to fulfil the conditions $n_3 > n_1$ and $n_2 > n_4$ (i.e. the most frequent directions must be $n_2$ or $n_3$), prevailing wind direction, PWD, is calculated as an angle (in degrees) added to the wind direction with the frequency equal $n_1$ (towards $n_2$ and $n_3$).\(^{24}\)

$$PWD = n_1 + 45\cdot \left[1 + \frac{n_3 - n_1}{(n_3 - n_1) + (n_2 - n_4)} \right]$$

The frequency of prevailing wind direction PWF is calculated as:\(^{24}\)

$$PWF = n_2 + n_3 + \frac{(n_1 - m_1) + (n_2 - n_4)}{2}$$

$$\left(3 - \frac{3}{2} - \frac{n_3 - n_1}{(n_3 - n_1) + (n_2 - n_4)} \right)^2$$

Two PWDs and PWFs are calculated for those stations where patterns with two prevailing winds from different directions but similar frequency are found. The criterion for similarity of frequencies is $n_2 + n_3 \approx 25\%$ for the second most frequent wind.

PWD is also reflected in PWD time series. Particularly those stations with temporarily stable PWD and those with high PWF are candidates for the network (see section ‘Long-term stability of airflow’). Finally, we compare wind roses derived from reanalysis data with those derived from the back-trajectories in order to assess to what extent the advection and circulation patterns during the pilot phase, in 2008, reflected the advection and circulation based on climatology. As for the frequency of calms in observing terms at the individual stations, it is negligible. Most calms, only 0.2% of all observations, occurred at the Reduit station. Calms were 0.1% at Mt. Kenya, Lusaka IA and Tunis and 0.01–0.04% at the other stations.

The climatological analysis was conducted for 9 pre-selected stations (see below).

Towards a selection of suitable network stations

In the following section we apply a number of criteria with the aim to come up with a reasonably small number of stations for the continental monitoring network.

Absence of source influence and suitability to address long-range transport

A summary statistics of the pilot phase sampling programme including meteorological information is given in Table ESI 1. The latter is mostly taken from reports of weather stations in the area\(^{25}\) and only partly based on the on-site measurements. This is due to the fact that most of the on-site measurements were discontinuous and corresponding data largely incomplete. Precipitation was below mean during the greater part of the pilot phase period throughout most of the continent. The chemical results are presented in detail in the companion paper by Klánová et al.\(^{18}\)

The stations had been categorized before and during the pilot phase programme by allocation to one of four types of sites, i.e. pristine environment, continental background site, moderately polluted (rural or residential) and heavily polluted (urban or industrial) environment (with respect to individual contaminants). The stations of the latter category for which the results of the pilot phase sampling programme (Table ESI 1) suggests strong local sources of more than one POP (i.e. groups of individual substances) were rejected. Suggested strong local sources of just one pollutant group were not considered sufficient for rejection. Due to this criterion Cairo (PCB, HCH, PCDD/F, PAH), Dakar (PCB, DDT, PCDD/F, PAH), Bamako (DDT, PAH), Kitengela (HCH, DDT), Nairobi IS (PCB, PAH) and Kinshasa (PCB, PAH) were removed from the candidate list.

Local meteorological features may prevent for part of the time long-range transported air to reach the sampling site: if low laying, persistent cloud cover was frequent, advected air could not be mixed down to the ground. If the local precipitation frequency was very high, pollutants would be removed efficiently from air advected to the site. If the site was placed most of the time within a local wind system, such as land-sea breeze circulation or mountain slope circulation, air re-distributed within the area would be collected rather than air of regional provenance. This leads to the decline of the Kwabenya and East Legon (local wind system) and Brazzaville (precipitation frequency) stations. Moreover, precipitation in Brazzaville (the same for Kinshasa), throughout October–May, is accompanied by thunderstorms some 150 days per year.\(^{26}\)

Coverage of target regions

The long-term expectancy of provenance of advected air was determined with the aim to come to a selection of stations which are located in such a way that they can cover the continental
background in as many parts of Africa as possible and the intercontinental background from neighbouring continents and across neighbouring seas. This is done in three steps: (a) the candidate list of stations is shortened by removing stations which would only little add to the network performance; (b) the long-term stability of air flow at the remaining stations is assessed (more local scale); (c) the provenance of air as received there in 2008 is described (regional scale) and discussed in the context of the climatological airflow. Finally, the regions expectedly covered are identified (d).

Remove redundant sites

First stations of the same type of site and with the same regional provenance of advected air were removed from the candidate list, because these would be redundant in the network. For this purpose, provenance of advected air during one year, 2008, was used based on back-trajectories for all 17 stations remaining from the previous criteria, except when located in the direct vicinity and comparable orography (i.e. pairs of stations in Mali, Ghana, Kenya, Republic of South Africa). Furthermore, indicated local pollution sources, else than dealt with for urban sites (see above, section ‘Remove redundant sites’), are an additional argument for exclusion at this stage of the selection process.

These considerations combined lead to the decline of the Niono, Bamako IA and Kouitila (as close to Tombouctou), Koumakonda (as close to Sheda), Dandora and Kabete (as close to Mt. Kenya) and Vanderbijl Park and Barberspan (as close to Molopo) stations. Tombouctou is more suitable than Niono, Bamako IA or Kouitila, because of its rather isolated location at the very margin of the Sahara desert, receiving air from each wide sectors of either agricultural land (S) or the desert (N). Furthermore, PAH levels in air at Bamako IA suggest at least significant local sources of this pollutant, most likely from road and air traffic. Sheda is more suitable than Koumakonda, because it is located more to the east, which allows to receive air from a larger sector which is not covered by Tombouctou. Furthermore, very high HCH levels in 2008 might indicate local sources of this pollutant in Koumakonda. Mt. Kenya station is more suitable than Dandora or Kabete, because it is on the top of an isolated mountain, while these are situated in the plain and eventually influenced by local industrial, traffic or agricultural sources in the Nairobi metropolitan area. Furthermore, Dandora is a waste dumping site and the high PAH levels there suggest at least significant local sources of this pollutant. Molopo is more suitable than the Vanderbijl Park and Barberspan stations, because of its rather isolated location at the very margin of the Kalahari desert. Furthermore, PAH levels at Vanderbijl Park suggest at least significant local sources of this pollutant, most likely from traffic or industrial combustion. Nine stations are remaining, namely Tunis, Khartoum, Tombouctou, Sheda, Asela, Mt. Kenya, Lusaka IA, Reduit and Molopo.

Long-term stability of airflow

Monthly wind roses, PWD and PWF for the period 1961–2007 at each remaining station are used to characterize the long-term inter-annual stability of the airflow patterns. Table 1 summarizes the most frequent wind directions on the monthly level derived from wind roses of individual stations.

The interannual variability based on climatological data was quantified by the frequency of the prevailing wind direction on the monthly basis (Table 1). Hereby, ‘W + NW (66 + 17)’ means that in 66% of the years of the period 1961–2007 the prevailing wind in the respective month was from west and in 17% from north-west. As can be seen from Table 1, the long-term stability of the wind patterns is very high for some stations. However, it can vary for individual months due to, for example, general atmospheric circulation of the region in question. For instance, at Lusaka IA for eastern direction between April and October and at Sheda for the south-west direction between May and July it is even 100%. This dominance is not so evident for the other months. A high long-term stability of airflow is found for all months at Reduit. Even though there are two main prevailing directions with comparable and relatively high frequency for some months, the stability of wind patterns is usually very high, because these two directions are adjacent. For instance, a period from November to March is typical with very frequent western and north-western winds at the Tunis station. Conversely, for May and June there are two markedly different directions (NW and E) at the same station. However, such cases of high variability of wind patterns occur at the selected stations rather exceptionally over the 1961–2007 period (see e.g. November for Molopo).

Regional provenance of the air in 2008

The regional provenance of the air in 2008 is shown as four-day back trajectories (Fig. 2, selected months). The Tunis station received the air advected across central and western Europe (albeit rarely across the Iberian Peninsula) and almost the entire Mediterranean. The coastal areas of the Maghreb countries were covered by advection during October–January. Tombouctou received air from all parts of the western and central Sahara throughout October–April and from SW-S in the remaining months (SW trade winds). Monitoring northward located areas, however, did not address Maghreb, i.e. beyond the Atlas Mountains. Sheda, located ca. 1200 km SE of Tombouctou, receives air from the Gulf of Guinea (SW-S, trade winds) and from the central and eastern Sahara during roughly December–February (NE trade winds, harmattan season). Khartoum received air from N to NE (covering Egypt, besides other areas, but not across the Red Sea, because of the strong convection over the Arabian peninsula) throughout the year and from SW-S during July–September. Monitoring southward from Khartoum, however, did not reach the Congo basin or the Great Lakes area. The dominant flow is from SW-S for the stations Tombouctou, Sheda, Khartoum and Asela where these are placed northerly of the axis of intertropical trough (intertropical convergence zone, southern trade winds), while N-NE prevails when placed southerly of it by its seasonal migration (northern trade winds; Leroux, 2001). Similarly, Asela, located ca. 1000 km southeast of Khartoum on the Abessinian plateau, received air from the same directions, which is dominated from the Gulf of Aden, from south during April–September. The sectors covered by the station Asela were, however, less wide than those covered by Khartoum. At the Mt. Kenya station air was received from NE-E during November–April (NE monsoon season) and from...
The most frequent monthly wind directions derived from wind roses over the 1961–2007 period. Numbers in brackets express relative frequencies (%) of the occurrence of individual wind directions. Arrows indicate statistically significant ($\alpha = 0.05$) positive (counter-clockwise) trends in PWD values (see text for explanations).

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Note: for comparison in Fig. 3 heights above the ground are not the same (the closest level out of 1000, 925 or 850 hPa— for Mt. Kenya 600 hPa—to 200 m above ground vs. 200 m above ground) and wind direction is derived from different spatial resolutions (interpolated in a $2.5^\circ \times 2.5^\circ$ grid or given as the direction from the location of the back-trajectory endpoint 1 h before arrival to the location of the station, respectively). Results are in general good agreement, especially for Lusaka IA, Reduit and Tombouctou for all months. The compared wind roses agree both in the prevailing wind direction and also in the overall pattern of wind roses. Thus we can argue that the airflow patterns during the pilot phase of the programme were very similar to climatology at these stations. Less agreement can be observed for the rest of the stations. However, they mostly preserve very similar overall patterns and they differ only in some individual months. For example, at the Molopo station the most frequent long-term mean wind directions are those from the north while they were from the northeast according to backward trajectories. As can be seen from Fig. 3, such differences relate mostly to adjacent directions and can be considered as random since we use back-trajectories from one year only. The comparison of trajectories in 2008 with the climatological boundary layer wind confirms the good agreement. The airflow at the selected stations in 2008 were in close to perfect agreement with the climatological situation with only few exceptions: While the re-analysis data indicate E-S to be the most frequent directions in Asela during January–June, the airflow during these months in

Table 1 The most frequent monthly wind directions derived from wind roses over the 1961–2007 period. Numbers in brackets express relative frequencies (%) of the occurrence of individual wind directions. Arrows indicate statistically significant ($\alpha = 0.05$) positive (counter-clockwise) trends in PWD values (see text for explanations).
Fig. 2  Back-trajectories at selected stations during selected months of 2008 (120 h, every 4 hours, 200 m above ground arrival height, HYSPLIT model).
2008 reflects a di-pole pattern with NE-E during January–May and SW in June. Mt. Kenya received from SE in May–June which was unusual previously, but has occurred more frequently in recent years (Table 1). Lusaka IA was exposed to the westerly flow less than usual, namely not earlier than December, although this flow is expected to set one-two months earlier.

This was obviously related to an unusual late south-eastward movement of the trade-wind inversion in this part of southern Africa (and, at the same time, of the wet season) in 2008.

In summary, this analysis suggests no rejection of stations from a monitoring network.

Regions expectedly covered by monitoring from the remaining stations

Most of the remaining stations cover satisfyingly large and important (i.e., densely populated) regions of Northeast (Egypt), West (Senegal, Ivory Coast, Ghana, Nigeria) and East (Kenya, Tanzania) Africa and its neighbouring seas, i.e. the Mediterranean, Northern and Equatorial Atlantic Ocean, the West Indian Ocean and the Southern Ocean. Besides some less populated areas, notably in Central and South-west Africa, also some more or highly populated areas of Africa, Southern Cameroon, parts of the Abessinian plateau and most of the Great Lakes area would not be covered. The reason for the latter limitation is that this area is located beyond the intertropical trough throughout the year as seen from Khartoum and never placed upwind to one of the other stations. The Reduit station would allow to monitor the South Indian Ocean. With regard to POPs this sea region is almost pristine and certainly a net-receptor region, but could be turned into a secondary source region as was found for the Bering and Chukchi Seas earlier (HCH). But the other regions which can be addressed from Reduit could be covered by the Mt. Kenya and Molopo stations. Asela would add unique, but rather limited (by area) regions to the network, namely the Gulf of Aden, parts of northern and southern Ethiopia and northern

Fig. 3 Comparisons of mean January–June (July) wind roses calculated from NCEP/NCAR data for the period 1961–2007 (standard pressure level closest to 200 m above the ground; left) and from back-trajectories in 2008 (last hour prior arrival, i.e. $\Delta t \leq 1$ h, 200 m above the ground; right).
Kenya. It cannot cover the potential source region of the Abersian plateau as a whole. The same, but to a lesser extent applies for Lusaka IA: Monitoring from there cannot cover northern parts of Zambia and most parts of the Congo basin, nor the savannah and desert belt (south Angola, Namibia, Botswana), but it allows to monitor the lower Congo basin at least seasonally. Based on these considerations we come up with a list of six indispensable stations, i.e. Tunis, Tombouctou, Sheda, Khartoum, Mt. Kenya and Molopo, and a list of three somewhat less efficient stations in terms of spatial and temporal monitoring, i.e. Lusaka IA, Asela and Reduit, with decreasing significance for the performance of the network.

Long-term trends

Airflow. Prevailing wind directions have been used to address long-term changes in airflow patterns in the reference period 1961–2007. A linear trend was fitted to time series of PWD values and the significance of the slope parameter was evaluated (Table 1). A significant positive trend indicates a tendency of the wind to turn towards higher azimuth values (i.e. clockwise), while a negative trend implies counterclockwise changes. A significant long-term trend in PWD indicates that changes in prevailing wind direction can be expected in the near future and this fact must be considered with respect to geographical coverage of potential POPs source areas by a suggested monitoring network.

Only Tombouctou is a station without significant change in wind direction during 1961–2007. Tunis and Reduit can be considered as localities with very stable airflow patterns over the last 47 years since only two not-adjacent months indicate a significant trend. A higher number of months with a significant trend was found at other stations. At Sheda, there is a tendency of airflow veering from the SW to the S for all months from January to June. This long-term trend would increase the potential as a monitoring station as the Gulf of Guinea eastern coastal area could come into reach. A similar pattern is found for Khartoum (from the N to the NW during January–May). At the Asela station five months from July to December (except October) show a significant tendency of change of PWD from S-SW or E in clockwise direction. Besides relatively stable and highly frequent eastern winds at Lusaka IA, there is a tendency to shift to more northerly directions in 7 months. Also these latter three changes would not create a significant reduction of the regions monitored by the stations. At the Molopo station, similar to Asela, seven months show a tendency of change of the PWD from the N and NE in clockwise direction. This long-term trend would increase the potential as a monitoring station as parts of Zimbabwe and Botswana could come into reach while Transvaal would still be covered.

Possible droughts. To be robust, network design should also consider current trends and near-future projections in African climate. The observed climate trends\(^{29}\) include a strong decline in precipitation in the Sahel region, especially from the 1960s to 1980s.\(^{30}\) A decrease of precipitation is expected for most parts of the continent. An increase in annual mean rainfall is likely in East Africa. It is unclear how rainfall in the southern Sahara, the Sahel and the Guinea Gulf regions will evolve with some models projecting increases and others decreases in sub-Saharan Africa.\(^{31}\) Desertification, however, is under way in large parts of the African continent (which has also reasons in land use change). More frequent droughts are likely for some regions including the Sahel and parts of southern Africa.\(^{29}\)

Volatilization of pesticides from dry soils has been found to be suppressed as a consequence of extreme adsorption.\(^{32}\) In response, levels of pesticides in air could decrease. This behaviour was confirmed by simulations using a non-steady state multimedia box model.\(^{33}\) The model results suggest that for sites in a Sahel-like climate under drought conditions the atmospheric levels for various substances would be half of the levels under the present climate.

Main outcomes and conclusions

By applying a number of objective criteria, a small number of stations (6–9 stations) is suggested for the continental monitoring network. These would cover most and essential parts of the continent and of neighbouring sea regions, but would also exclude some parts. The network should welcome additional stations addressing the not covered areas, in case these would become available. E.g., the Izana station, Canary Islands, Spain, located in the trade winds zone, would cover the SW outflows from Western and South-western Europe\(^{34}\) which is, at least partly, directed towards the Maghreb countries. The Western Africa coastal region’s coverage could be improved by a coastal rural or remote station in Ghana or Ivory Coast and in Congo, respectively. Also the Equatorial Atlantic background would be addressed. A station in the central Southern Africa, between Lusaka IA and Molopo, could monitor areas in Namibia, Botswana and Southern Angola which are so far excluded from coverage. Because of the location and movement of the trade-wind inversion a coastal station in this region would be of lower potential.

Furthermore, logistic factors, such as accessibility of location, availability of trained local site operators etc., may influence the network design and help prioritize stations. E.g., in one case a recommended station could be replaced by an other without any significant loss of coverage: Because of similar airflow climatology Barberspan could replace Molopo, which is not easily accessible.

As far as major air pollutants are measurable, e.g. ozone, by passive methods, these should be included in the network to enhance the network potential.

The criteria applied for the design of a monitoring network in this work reflect the present climatology and results of measurements during a 6-month pilot phase sampling programme in 2008. The analysis of airflows for nine stations across the continent during the 1961–2007 period demonstrated a low inter-annual variability but indicated on-going changes of the airflow. The results of this study suggest that an increased frequency of droughts would suppress contamination of the atmospheric environment in affected regions of Africa. Changes in the atmospheric circulation might be caused by changes in temperature distribution as a critical forcing factor. Generally, it is expected that drier subtropical regions will be exposed to warming more than the more humid tropics. Moreover, a different rate of warming is expected in costal areas and inner continental regions.\(^{29}\) For instance, according to Freiman and...
Tyson\textsuperscript{48} warming in the Indian Ocean and Pacific has been linked with the warming of the troposphere in southern Africa and a subsequent increase in number of days with stable inversion layers in the late 20th century. Wang\textsuperscript{46} concludes that the African–Asian monsoon circulation weakened since the end of the 1970s. On-going changes of the circulation over Africa identified in this study (Table 1) could partly change the long-range transport and detectable sources of air contamination at the selected monitoring stations. However, no significant losses of regions covered are likely as far as indicated by now.

Acknowledgements

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References


20 NOAA Air Resources Laboratory, Silver Springs, USA.


Electronic Supplementary Information

Table ESI 1: Statistics of POPs measurements during the pilot phase sampling programme as 6-month mean mass (ng/sample), for PCDDs and PCDFs I-TEQ (pg I-TEQ/sample), together with meteorological data (min-max monthly mean, sum) and site classification. IA = international airport, IS = industrial site.

<table>
<thead>
<tr>
<th>Station</th>
<th>Site type</th>
<th>Meteorological characteristics</th>
<th>Pollution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Air temperature (°C)</td>
<td>Relative air humidity (%)</td>
</tr>
<tr>
<td>Tunis (Tunisia)</td>
<td>Residential</td>
<td>12.8-24.9</td>
<td>65-83</td>
</tr>
<tr>
<td>Cairo (Egypt)</td>
<td>Urban</td>
<td>12.6-29.3</td>
<td>41-60</td>
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<tr>
<td>Khartoum (Sudan)</td>
<td>Urban</td>
<td>23.1-35.1</td>
<td>18-57</td>
</tr>
<tr>
<td>Tombouctou (Mali)</td>
<td>Residential</td>
<td>19.1-35.7</td>
<td>16-33</td>
</tr>
<tr>
<td>Location</td>
<td>Type</td>
<td>Temperature Range</td>
<td>Pollution Level</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------</td>
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<td>-----------------</td>
</tr>
<tr>
<td>Dakar (Senegal)</td>
<td>Urban industrial</td>
<td>22.7-26.2</td>
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<tr>
<td>Niono (Mali)</td>
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<td>20-32</td>
<td>0-8</td>
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<tr>
<td>Bamako Centre (Mali)</td>
<td>Urban¹</td>
<td>22.8-31.4</td>
<td>0-111 / 0-9</td>
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<td>Bamako IA (Mali)</td>
<td>Urban</td>
<td>6)</td>
<td>- / 0-7</td>
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<tr>
<td>Koutiala (Mali)</td>
<td>Agricultural</td>
<td>22.3-32.5</td>
<td>0-174 / 0-10</td>
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<td>Sheda (Nigeria)</td>
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<td>Koumakonda (Togo)</td>
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<td>26.4-29.4¹⁰</td>
<td>0-246 / 0-13¹⁰</td>
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<td>Kwabenya (Ghana)</td>
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<td>0-19-31¹²</td>
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<td>East Legon (Ghana)</td>
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<td>0-19-31¹²</td>
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<tr>
<td>Asela (Ethiopia)</td>
<td>Residential</td>
<td>16.8-18.9⁴</td>
<td>0-94 / 0-17⁴</td>
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<tr>
<td>Mt Kenya (Kenya)</td>
<td>Remote</td>
<td>-</td>
<td>-</td>
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</table>

Note: 
¹: Data from 1988
⁴: Data from 1994
¹⁰: Data from 1990
¹²: Data from 1992
¹¹: Data from 1991
<table>
<thead>
<tr>
<th>Location</th>
<th>Type</th>
<th>Temperature (°C)</th>
<th>Humidity (%)</th>
<th>CO₂ Emissions (ppm)</th>
<th>NO₂ Emissions (ppm)</th>
<th>SO₂ Emissions (ppm)</th>
<th>PM₁₀ Emissions (ppm)</th>
<th>PM₂·₅ Emissions (ppm)</th>
<th>PM₁₀ Emissions (ppm)</th>
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<tbody>
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<td>Kitengela (Kenya)</td>
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<td>18.7-20.9⁵</td>
<td>0-48</td>
<td>2-193 / 1-12⁵</td>
<td>4.8</td>
<td>4517</td>
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<tr>
<td>Dandora (Kenya)</td>
<td>Agricultural²</td>
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<tr>
<td>Nairobi IS (Kenya)</td>
<td>Industrial</td>
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<tr>
<td>Kabete (Kenya)</td>
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<td>Orstom de Brazzville (Congo)</td>
<td>Urban</td>
<td>23.6-26.7³</td>
<td>88-93⁴</td>
<td>0-125 / 0-10³</td>
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<td>-</td>
<td>-</td>
<td>39.1</td>
<td>12.6</td>
<td>44.7</td>
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<td>16.9-27.3</td>
<td>-</td>
<td>-</td>
<td>3.5</td>
<td>4.2</td>
<td>36.5</td>
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<td>1.7¹¹</td>
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<td>Reduit (Mauritius)</td>
<td>Remote</td>
<td>24.3-27.9⁷</td>
<td>79-84</td>
<td>66-338 / 8-18</td>
<td>1.8</td>
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<td>Vanderbijl Park (RSA)</td>
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<td>13.2-23.3⁹</td>
<td>47-60⁹</td>
<td>8-247 / 2-5⁹</td>
<td>3.1</td>
<td>23.4</td>
<td>3.5</td>
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<td>29-38⁸</td>
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</table>
PCBs = sum of PCB 28, PCB 52, PCB 101, PCB 118, PCB 153, PCB 138, and PCB 180, HCHs = sum of α-, β-, γ-, and δ-hexachlorocyclohexane isomers, DDTs = sum of o,p’- and p,p’-DDT, -DDE and DDD, HCBs = sum of hexachlorobenzene (HCB) and pentachlorobenzene (PeCB), PCDDs and PCDFs = 11 and 14 species, respectively, PAHs = sum of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(123cd)pyrene, dibenz(ah)anthracene and benzo(ghi)perylene (= 16 EPA PAHs).


1 obsolete pesticide dumping site
2 waste dumping site
3 data reported from two stations combined
4 data from Addis Abeba station, 8°59’N/38°48’E, 2324 m a.s.l.
6 data from Nairobi station, 1°19’N/36°55’E, 1624 m a.s.l.
6 no data, cf. station in line above
7 data from St.Brandon station, 16°27’N/59°37’E, 3 m a.s.l.
8 data from Upington station 28°24’S/21°16’E, 836 m a.s.l.
9 data from Pretoria station 25°44’S/28°11’E, 1330 m a.s.l.
10 data from Atakpame station 7°35’N/1°07’E, 402 m a.s.l.
11 April-June covered only
12 January-March covered only
estimated based on relative humidity measurements (daily maximum > 98%)

data from Carthago station, 36°52'N/10°20'E

dates do not match with months, but deviate by 3-7 days

no data, cf. station in line below