

Research

Investigating the dispersion and transport of carbon monoxide in West Africa with a focus on biomass burning and gas flaring sources

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Abstract

This study presents an in-depth analysis of the dispersion and transport of carbon monoxide (CO) in West Africa, with a specific focus on the contributions from biomass burning and gas flaring activities. Utilizing data from the Global Fire Emissions Database (GFED4s) for biomass burning and the Infrared Atmospheric Sounding Interferometer (IASI) for CO concentrations, the research examines the seasonality of air pollution. Multi-seasonal 5-day trajectories of the NAME atmospheric dispersion model were employed to trace seasonal CO sources and their movement patterns. The findings highlight the dual impact of biomass burning inland and gas flaring offshore, particularly in Angola, on CO levels. Notably, the dispersion modelling process showed that emissions from gas flaring activities affect CO concentrations along the West African coast, especially during periods of lower wind speeds and dispersion rates. The study underscores the necessity of incorporating gas flaring emissions into atmospheric models to accurately simulate air pollution in the region. This comprehensive approach enhances the understanding of CO distribution and its environmental impacts, emphasizing the critical need for improved emission inventories and modeling techniques to address air pollution in West Africa.

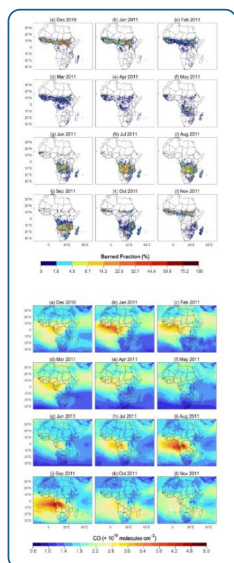
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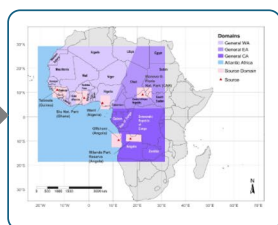
Graphical Abstract

Investigating the Dispersion and Transport of Carbon Monoxide in West Africa with a Focus on Biomass Burning and Gas Flaring Sources

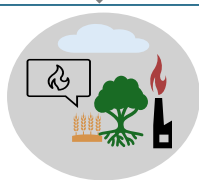
Historical CO & Biomass Burning Seasonality



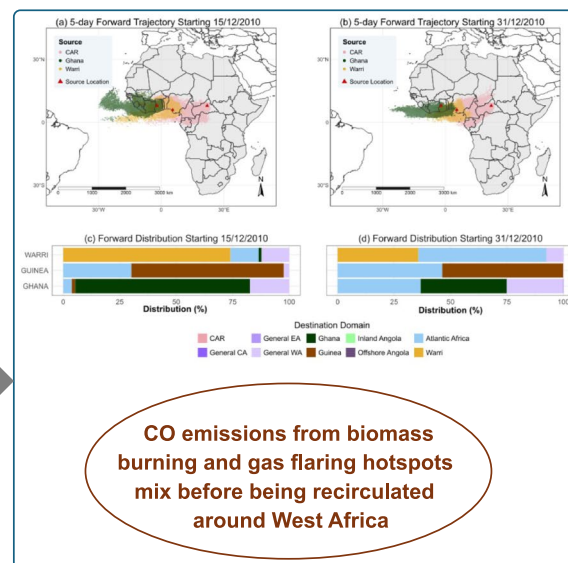
Source selection based on seasonality



NAME Multi Source Dispersion Modelling Using Selected Locations



Seasonal Outputs Showing Forward and Backward Trajectories



CO emissions from biomass burning and gas flaring hotspots mix before being recirculated around West Africa

Keywords Biomass burning · Gas flaring · Carbon monoxide · CO · Atmospheric dispersion model · Air pollution

1 Introduction

Carbon monoxide (CO) is a primary pollutant contributing to the trace composition of the lower and middle atmosphere. It is a by-product of the incomplete combustion of fuel and is typically emitted alongside other precursors essential for the formation of ozone [1]. Despite not being classified as a “greenhouse” gas [2], CO has a significant indirect impact on the radiation balance of the atmosphere due to its high reactivity with the hydroxyl radical [3, 4]. Given its tropospheric lifetime, which spans from weeks to months, and its considerable variability, CO is frequently utilized to infer the transport of polluted air masses [5, 6].

The inter-annual and seasonal variability of CO is influenced by multiple factors, including long-range transport, climate dynamics, emissions from biomass burning (BB), the combustion of fossil fuels, and gas flaring [7–11]. The seasonal movement of the Intertropical Convergence Zone (ITCZ) also influences the seasonal transport of CO in the African atmosphere [12].

Literature indicates that in addition to BB and anthropogenic emissions from fossil fuel combustion within West Africa, atmospheric CO pollution over West Africa is significantly affected by CO emissions transported from the Southern Hemisphere of Africa (SHA) during its BB season [13]. The complexities of air pollution dynamics in West Africa—a sub-region of sub-Saharan Africa—remain inadequately understood [14–16]. This lack of understanding creates gaps in the knowledge of CO’s indirect climate forcing potential within this region. Given current climate trends and the exacerbation of the effects of climate extremes such as increased wildfire frequencies [17], there is a pressing need to better understand and quantify the historical sources of ozone precursors, including CO, over West Africa.

The majority of BB in West Africa occurs in cropland areas, predominantly located between latitudes 7° N and 15° N. The West African region is also impacted by significant oil and gas emissions, particularly in the Gulf of Guinea, where extensive oil exploration and production activities, including gas flaring (GF), take place [18, 19]. Nigeria, which is estimated

to contribute 10% to global GF activities [20], is also situated in this region. The Trade deficits and other transportation issues affecting the distribution of natural gas produced in this area exacerbates the prevalence of GF, thus contributing to the release of pollutants such as CO [19, 21]. According to the Global Flaring and Methane Reduction Partnership [22], Nigeria ranked as the ninth highest GF country globally and the third highest in Africa in 2023 with a flaring intensity of 10 m³/bbl (m³ per barrel of oil). They report that the flare volume for the country was approximately 6 billion cubic meters (bcm) in 2023, which represents a reduction of at least 2 bcm compared to 2019.

The data indicates that Nigeria's flare volume in 2023 was approximately 6 billion cubic meters (bcm), reflecting a reduction of at least 2 bcm compared to 2019. Despite this decrease, the flare volume remains higher than that of other African nations with significant biomass burning, such as Angola, which recorded a flare volume of 2 bcm in 2023.

Besides evaluating satellite-based historical time series of emissions and BB, modeling offers the capacity to simulate past or future climate hazards and their resulting short- and long-term effects on air quality through mathematical equations. This study examines the seasonality of BB and CO concentrations in Africa by utilizing satellite-retrieved data from GFED4s and IASI, covering the period from December 2008 to November 2014. A subset of 1 year (December 2010–November 2011) was also taken to focus on key seasonal emission sources identified. Furthermore, we simulate the atmospheric transport of a tracer from key CO emission sources in Africa, including BB hotspots, the Niger Delta in Nigeria (a significant oil and gas production and GF region), and offshore Angola (the southernmost GF site in Atlantic Africa) to regions in West Africa.

2 Materials and methods

2.1 GFED burned area

The monthly burned area product GFED4s, provided by ORNL DAAC [23], was utilized to analyze the seasonal patterns of BB throughout Africa. The Global Fire Emissions Database (GFED) integrates satellite data on fire activity and vegetation productivity to produce globally gridded estimates of monthly burned area and fire emissions [24]. Products like GFED on a global scale are created using change detection algorithms applied to surface reflectance time series [25], obtained from spectrometers such as the Moderate Resolution Imaging Spectroradiometer (MODIS). Burned areas are detected through indicators such as charcoal and ash deposits, vegetation removal, and changes in vegetation structure [26].

The GFED4 monthly burned area dataset is specifically derived from the 500m MCD64A1 (MODIS direct broadcast burned area product) and active fire data from the Tropical Rainfall Measuring Mission (TRMM) Visible and Infrared Scanner (VIRS) and the Along-Track Scanning Radiometer (ATSR) sensor family, aggregated to a 0.25° spatial resolution monthly [27]. The version 4.1 GFED4s monthly data includes burned area fractions with small fires, rendering it a valuable resource for evaluating fires in Africa [28]. Given its coarse resolution, the GFED4s product is susceptible to errors, particularly in cropland areas situated close to tropical forests [29]. This indicates that the GFED4s data may not fully capture certain regions in Africa with significant BB. Consequently, emissions for the NHA BB season might be overestimated when compared to other higher-resolution BB products [30]. Nevertheless, the dataset remains adequate for analyzing the seasonality of biomass burning across Africa.

An assessment of the GFED4s time series, spanning from December 2008 to November 2014, was conducted to evaluate the seasonality of fires across Africa. A portion covering the period from December 2010 to November 2011 was selected to analyze fire seasonality on the continent for 1 year. The year 2010/2011 was chosen for its notable El Niño–Southern Oscillation (ENSO) activity, marked by a transition from a strong El Niño to a La Niña event globally. These extreme weather patterns had significant impacts on Africa, leading to severe droughts and floods. These climatic events resulted in unprecedented drought and famine conditions specific to different climate zones, which influenced the BB season of 2010/2011.

2.2 Satellite retrieved CO

The IASI FORLI CO product, now disseminated by IASI/AERIS [31] was utilized to analyze the seasonality of carbon monoxide (CO) across Africa. The IASI instrument is sensitive to the troposphere and can retrieve CO vertical profiles in the Thermal Infrared (TIR) spectrum with a twice-daily global coverage at 9:30 am and 9:30 pm [32]. Barret et al. [33] validated total column IASI SOFRID and FORLI CO retrievals over Lagos, Nigeria and a few other cities using data from the In-service Aircraft for a Global Observing System (IAGOS). The study found an underestimation of < 8% using both

algorithms compared to IAGOS CO measurements. An assessment of IASI and IAGOS CO distribution by [34] indicated that anomalies in CO mixing ratios over Africa can be attributed to anthropogenic emissions, with significant contributions from BB. An earlier analysis by [2] revealed biases of $\leq 13\%$ compared to IAGOS-MOSAIC reference CO retrievals over airports, but concluded that IASI FORLI and SOFRID CO retrievals still accurately reproduced variability in both the lower and upper troposphere.

The IASI CO total column datasets, retrieved by LATMOS using the FORLI algorithm (version 20140922 or L2V6), were employed for the analysis of CO seasonality. These daily IASI CO datasets were aggregated into gridded monthly data at a 0.25° spatial resolution to align with the GFED4s dataset. The IASI FORLI CO time series was evaluated for the period from December 2008 to November 2014. A specific subset, spanning December 2010 to November 2011, was selected to analyze one annual cycle of CO seasonality across Africa.

A seasonal regression analysis was performed to determine the correlations between BF from GFED4s and CO from IASI, covering the period from December 2008 to November 2014. This analysis served as an additional determinant for selecting emission sources for the modeling process, alongside observed hotspots from the analysis of monthly CO and BF. The seasonal pixel-based Pearson's correlation coefficient squared (R^2) and slope of regression determined the validity of locations selected as BB hotspots in West Africa.

2.3 NAME dispersion model

The Numerical Atmospheric-dispersion Modelling Environment (NAME) is a Lagrangian particle-trajectory model [35–37] that operates by tracing the trajectories of numerous “tracer particles,” which symbolize a parcel of air mass [38]. This model is instrumental for scientific research when combined with measurements of atmospheric pollutants, facilitating the understanding of baseline background concentrations of significant gases and the geographical distribution of emission sources [39]. For the purposes of climatology and weather, the Unified Model (MetUM) meteorological fields [40, 41] were employed. Specifically, the global meteorological flow domain “UMG Mk6 L59pp” which covered the period from March 9, 2010 to April 30, 2013 was used. This domain offers an approximate spatial resolution of 25 km and is available in 3-hourly files. Version 6.5 of the NAME dispersion model was used in this analysis covering March 2010–April 2013 and was executed on the CEDA JASMIN HPC platform. There are uncertainties in the NAME model due to inaccuracies in the forecasted or historical meteorological data used and inadequate representations of atmospheric dispersion processes [42]. This limitation was accounted for by assessing several simulations of CO transport from multiple dates, times and seasons over 3 years before focusing on 2010/2011.

The use of 5-day trajectories has been extensively documented in the literature for reproducing the long-range transport of CO [43–46]. Additionally, longer trajectories have been employed to investigate the intercontinental transport of CO [47, 48]. The forward trajectory method is utilized to simulate the path taken by a tracer over a specified period following its release from a defined location. Conversely, the backward trajectory method retraces the historical path of a tracer prior to its arrival at a particular location. In this study, 1-day and 5-day trajectories were applied for forward and backward tracer transport simulations, respectively. This approach was chosen to ensure that atmospheric transport over regions with additional sources of precursor pollutants, such as the Niger Delta, was adequately considered.

This study primarily concentrated on the transport of CO over several days from its source at ground level. Therefore, the results presented focus exclusively on the 5-day trajectories commencing at ground level and including the 100 m (0–100 m) above the surface during the transport.

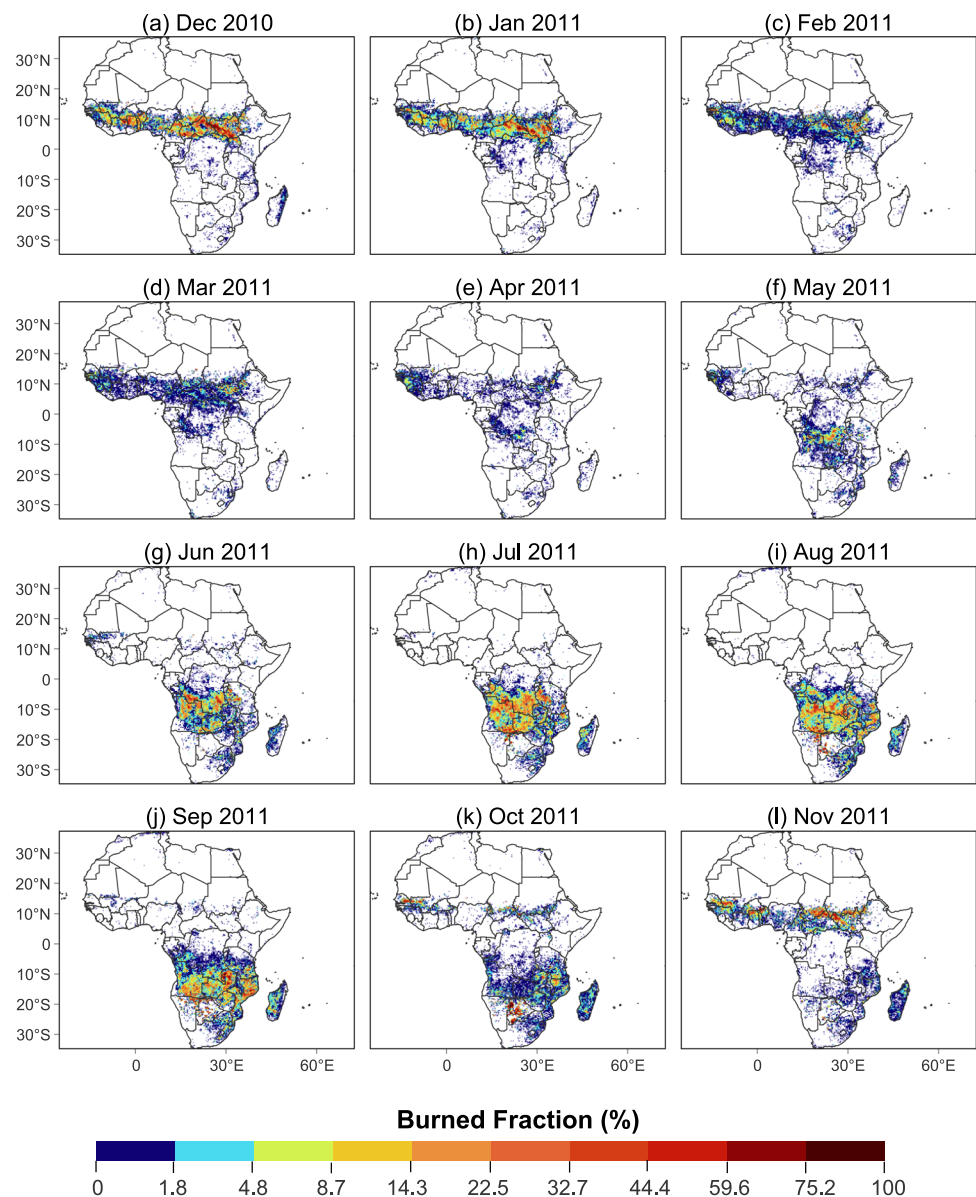
To simulate the transport of CO within the NAME model, the stable tracer option, characterized by an undefined half-life, was employed. The “chemistry” option was deliberately excluded to focus on dispersion rather than chemical reactions occurring along the transport routes. The output grid was configured with a spatial resolution of $0.25^\circ \times 0.25^\circ$ to match the resolution of the aggregated IASI CO and GFED4s burned area gridded datasets. Particle release was set at 10,000 particles per hour for each source domain, occurring at 3-h intervals, with an upper limit of 1,000,000 particles.

3 Results and discussions

3.1 Seasonality of biomass burning and CO over Africa

Figure 1 illustrates the seasonality of BB across Africa from December 2010 to November 2011, as observed from the GFED4s burned area product. In December, BB primarily occurred between latitudes 7° N and 15° N, encompassing

Fig. 1 Mean monthly burned area fraction over Africa between December 2010 and November 2011



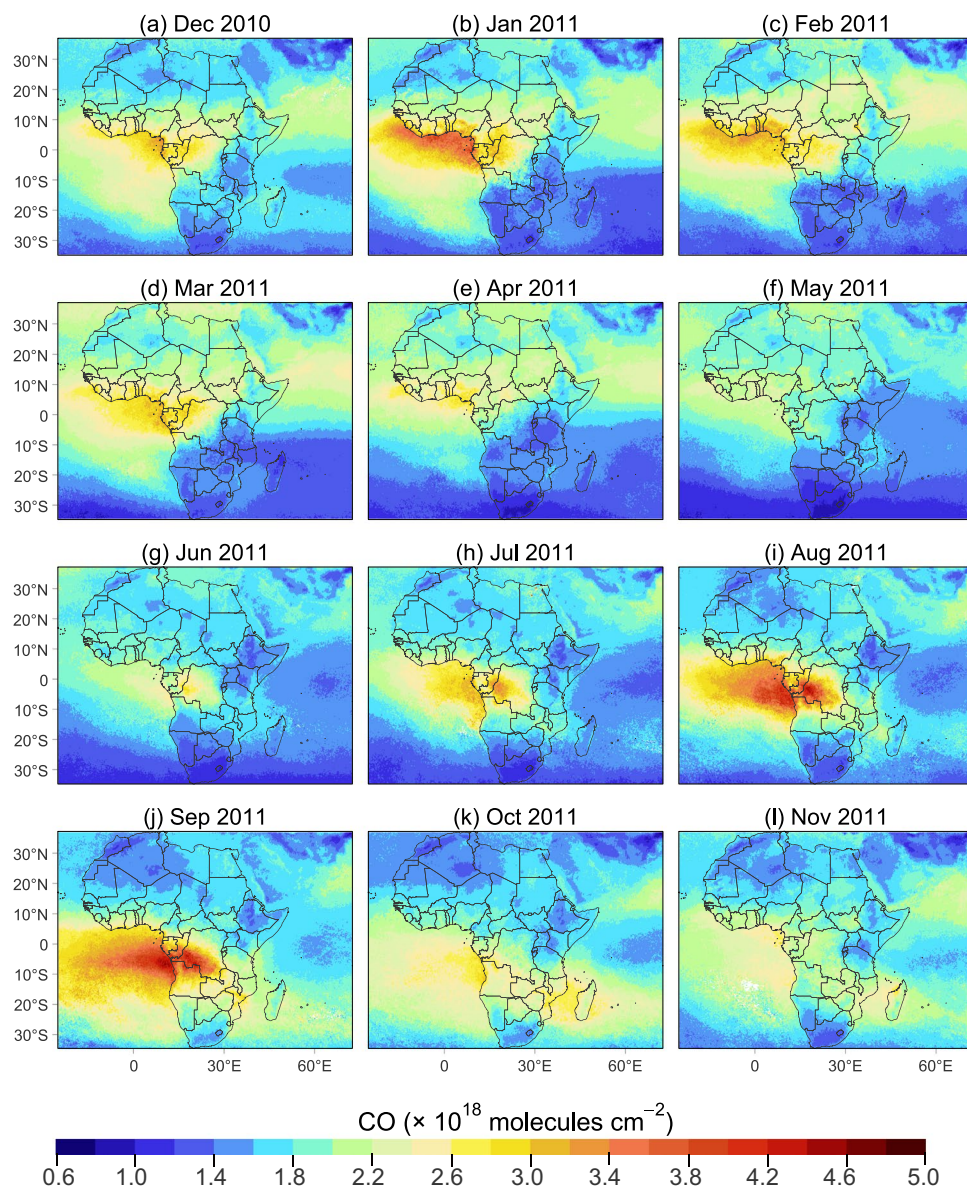
regions of Central and West Africa. While many areas exhibited burned areas of less than 20%, certain regions in North-Central/East Africa and West Africa had areas with Burned Fraction (BF) > 60%. Similar BF values were particularly widespread around northern Central African Republic (CAR) and southern South Sudan, which lie within the equatorial monsoon climate zone. Boundary regions between northeast Côte d'Ivoire and northwest Ghana exhibited sign of BB with BF > 50% in West Africa. In January, a greater spatial extent of BB (BF ≥ 20%) was observed across west, north central, and east Africa. Regions in central Africa that had BF > 60% in December showed a reduction in the percentage of burned area by January. By February, most of the BF per pixel in the NHA had declined to < 20%, except for small areas in South Sudan and northern CAR. In March, fewer areas in the NHA showed signs of BB compared to February except around the inland Niger Delta in Mali (> 5%).

In April, a rise in BB was observed in parts of Guinea, Sierra Leone, and southern Democratic Republic of Congo (DRC), with BF reaching up to 15%. In May, the areas showing BB further expanded in the southern DRC and northern Angola, exceeding 20%. By June, most regions in the southern DRC and northern Angola exhibited significant BB activity. In July, there was no evidence of BB in the NHA, while extensive BB (BF > 20%) was observed in south-central Africa, particularly in Angola, the southern DRC, and Zambia in southern Africa. In August, northeast Angola in the SHA experienced the highest widespread percentage of burned areas, exceeding 50% per grid.

By September, BB began to decline in most parts of south-central Africa but increased in regions further south, including Botswana and South Africa. In October, BB in Botswana reached as high as $BF > 80\%$ per grid, and there were prominent indications of the onset of the BB season in the NHA around Senegal and southwestern Mali. By November, BB had ceased in most of the SHA but continued to rise in the NHA.

Figure 2 demonstrates the 12-month cycle of atmospheric CO over Africa from December 2010 to November 2011, aggregated from the IASI FORLI CO product. In December, a high concentration of CO ($\geq 3.0 \times 10^{18}$ molecules cm^{-2}) is observed offshore in the Gulf of Guinea, particularly around the east equatorial monsoon climate zone of West Africa, where significant oil exploration and GF activities occur. This increased to $\geq 3.6 \times 10^{18}$ molecules cm^{-2} in January, extending along the land–ocean boundary of West Africa and the Gulf of Guinea, with the highest CO values observed offshore of Côte d'Ivoire and Ghana. Inland concentrations of CO in some regions of southern Nigeria, central Ghana, Cameroon, and the Central African Republic (CAR) also reached $\geq 3.4 \times 10^{18}$ molecules cm^{-2} in January. By February, a slight decline in concentrations around the Gulf of Guinea offshore West Africa and Cameroon to levels $\leq 3.4 \times 10^{18}$ molecules cm^{-2} was observed, with more areas in the southern parts of Ghana, Togo, Benin, and Nigeria exhibiting concentrations $\leq 3.2 \times 10^{18}$ molecules cm^{-2} . By March, inland CO levels had decreased in most areas of West Africa, while some regions in the Congo and CAR maintained CO levels like those in February. CO concentrations in the Gulf of Guinea also declined to $\leq 3.0 \times 10^{18}$ molecules cm^{-2} in March. In April, two distinct sources of CO are identified over West Africa: BB in the west equatorial

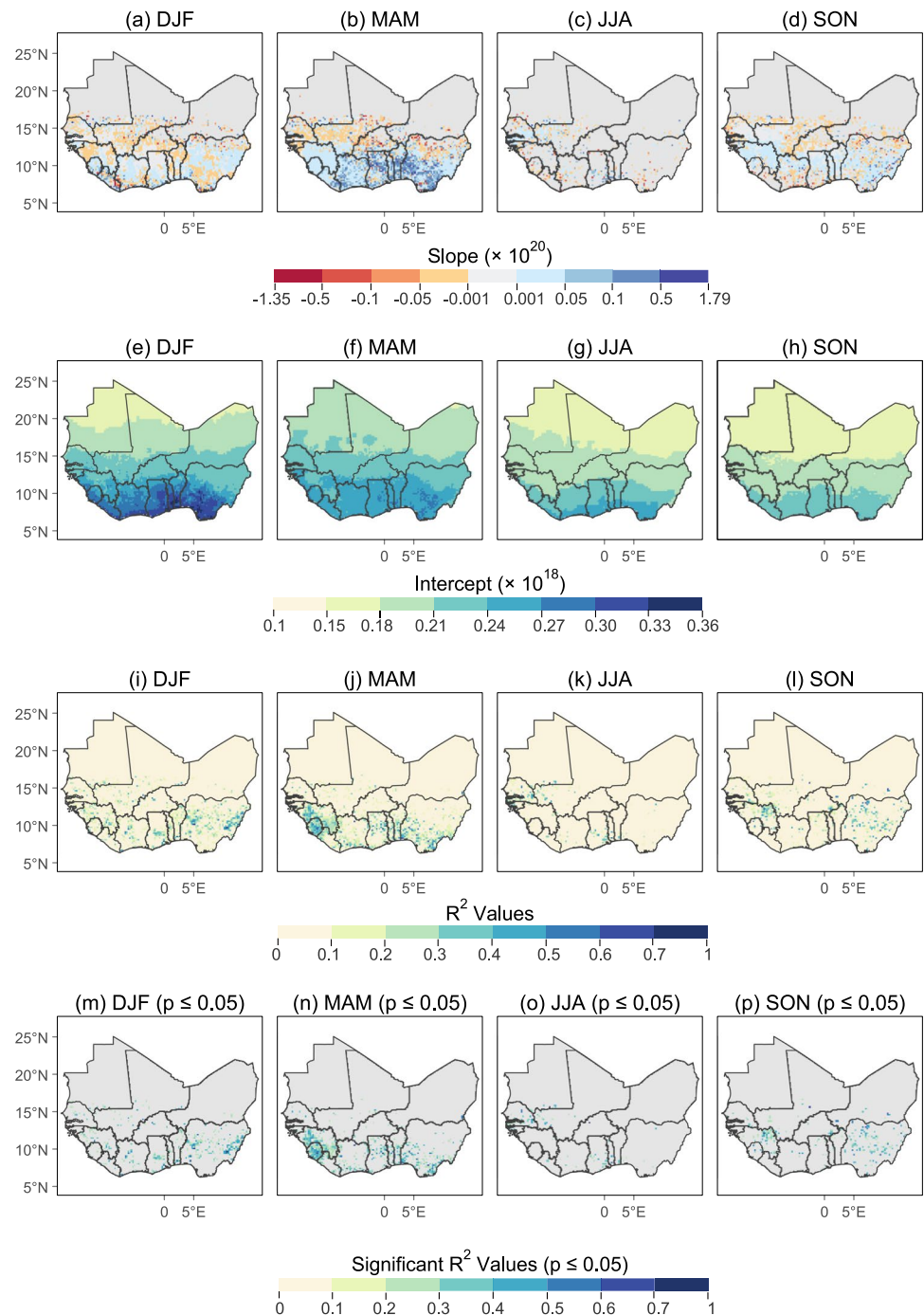
Fig. 2 Mean monthly CO column concentrations over Africa between December 2010 and November 2011



monsoon climate zone and around GF sites in the Gulf of Guinea. By May, CO levels across Africa became more homogenous, reaching $\geq 2.4 \times 10^{18}$ molecules cm^{-2} .

By September, atmospheric CO inland and offshore in Angola, Gabon, the Democratic Republic of Congo (DRC), and Congo had reached $\leq 4.5 \times 10^{18}$ molecules cm^{-2} , concentrations up to 4.8×10^{18} molecules cm^{-2} observed offshore around the Angola/DRC/Congo/Gabon boundary. Two distinct CO peaks were detected offshore and inland around the Angola/Congo/DRC/Gabon border of Africa between July and September. By October, CO in the SHA had decreased to $\leq 2.5 \times 10^{18}$ molecules cm^{-2} and further reduced to $\leq 2.2 \times 10^{18}$ molecules cm^{-2} by November.

Fig. 3 Seasonal relationships between burned area fraction and CO concentrations over West Africa between December 2008 and November 2014



3.2 Seasonal relationships between biomass burning and CO concentrations

Figure 3 illustrates the seasonal linear regression models between BF and CO concentrations across West Africa for the period from December 2008 to November 2014. The seasons are categorized as December, January, and February (DJF), March, April, and May (MAM), June, July, and August (JJA), and September, October, and November (SON) to align with the seasonal meteorological and BB patterns of West Africa. Many regions except around the Sahel exhibited weak positive slopes (0.001 to 0.05×10^{20}) during the DJF, MAM, and SON seasons, which coincide with significant BB in many parts of West Africa. However, the slope was negligible ($< 0.001 \times 10^{20}$) during the JJA season, corresponding to the SHA BB season. This finding indicates that high CO concentrations over West Africa during this time of year are not correlated with local BB events.

Observed positive slope ($> 0.1 \times 10^{20}$) in parts of Nigeria, Togo and Ghana during the DJF season (Fig. 3a, e, i, and m) and significant correlations ($R^2 \geq 0.5$, $p \leq 0.05$) suggest that specific conditions, such as agricultural burning or other human activities, might be contributing to the observed CO levels. Similarly, in central Ghana, Sierra Leone, and western Guinea during the MAM season (Fig. 3b, j, and n), the positive slope and observed significant correlations ($R^2 \geq 0.5$, $p \leq 0.05$) imply that seasonal agricultural practices or natural vegetation cycles could be influencing local CO emissions. Overall, the low level of association between CO and burned area fraction for some seasons suggests that other sources or meteorological factors not considered in the linear model may also affect CO concentrations over West Africa differently throughout the year.

3.3 Simulation of atmospheric dispersion

The objective of the numerical modeling using NAME was to simulate the travel paths of emissions from the primary CO pollution hotspots, identified through observed seasonality of monthly CO concentrations and BB. Six source locations were selected for running the dispersion model based on criteria such as atmospheric CO concentrations/seasonality, high burned area fractions, and significant GF. The GF locations were chosen according to the United States Energy Information Administration (USEIA) statistics on oil/gas production in West Africa, and the locations of gas flares in Africa as identified by [49, 50]. These GF hotspots are also well documented as being distributed along the African coast between Nigeria and Angola [22].

Sample sites for dispersion modeling were selected from various regions across Africa. In West Africa, the sample locations were in western Ghana (where the BF exceeded 40% in December and January), Guinea (where BB continued in April), and near Warri, Nigeria (a major GF hotspot where CO levels exceeded 3.0×10^{18} molecules cm^{-2} from December to March). Two sample sites were selected around Angola: an inland location with high CO levels (approximately 4.0×10^{18} molecules cm^{-2}) and prevalent BB during the SHA BB season (May to September), and an offshore location with prevalent GF and CO levels exceeding 4.6×10^{18} molecules cm^{-2} . The location selected in the Central African Republic (CAR) showed a BF > 40% between December and February. The analysis indicated significant BB in Congo (Central Africa), with a BF > 40% during the JJA season. Despite this, the location was not chosen for the modeling process because research demonstrated that the primary transport pathway for emissions from Congo in July was predominantly towards the northeast. [18].

Figure 4 presents the locations of the selected emission sites across Africa. The geographic coordinates of the source domains were defined using the WGS 84 system. To facilitate analysis in NAME, unique local domains were established around these sample locations. Additionally, four supplementary domains were created around the general dispersion boundary: Atlantic Africa (covering the Atlantic/Gulf of Guinea to the west), General CA (encompassing central Africa and the areas around Angola), General EA (including regions surrounding CAR), and General WA (covering the majority of West Africa). The primary domains were excluded from the supplementary domains to ensure a complete summation of air distribution from each source.

Table 1 provides a summary of the selected locations, their unique identifiers in the model, and the types of trajectories modeled for these locations for specific months. Figure 10 (Appendix) shows a MODIS landcover map based on the International Geosphere-Biosphere Programme (IGBP) classification for reference purposes. Manovo Gounda Floris National Park (a UNESCO heritage site in CAR) is known for its ecological diversity and importance but is threatened by human activities including conflict, deforestation and poaching [51, 52]. The occurrence of fires within the park is attributed to both natural and anthropogenic factors. Naturally, seasonal dryness and droughts contribute to the ignition of fires. However, human activities such as land clearing for agriculture and efforts to enhance grazing conditions also play

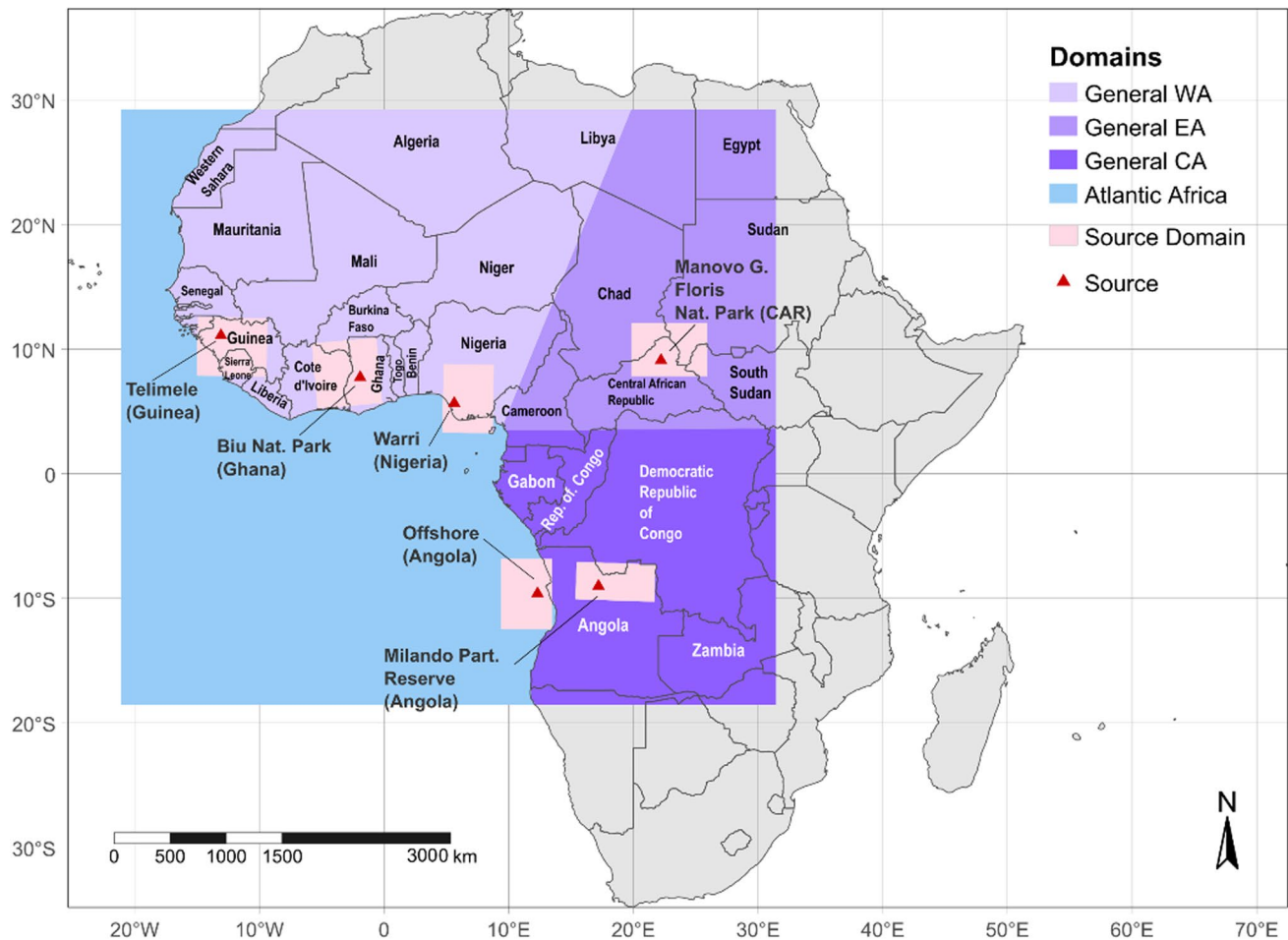


Fig. 4 Approximate locations of sources selected for dispersion modelling across Africa between December 2010 and November 2011 and their domains

Table 1 Selected emission sources around Africa, trajectories and corresponding dates

Source location	Id	Source type	Trajectory	Dates
Warri, Nigeria	Warri	Oil & gas/gas flaring	Forwards/backwards	10/12/2010–11/01/2011
			Forwards/backwards	11/07/2011–11/08/2011
Manovo Gounda Floris National Park, CAR	CAR	Biomass burning	Forwards	10/12/2010–11/01/2011
Bui National Park, Ghana	Ghana	Biomass burning	Forwards	10/12/2010–11/01/2011
Telimele, Guinea	Guinea	Biomass burning	Backwards	10/12/2010–11/01/2011
			Forwards	11/05/2011–11/06/2011
			Backwards	11/07/2011–11/08/2011
Angola Offshore	Offshore Angola	Oil & gas/gas flaring	Forwards	11/07/2011–11/08/2011
Milando Partial Reserve, Angola	Inland Angola	Biomass burning	Forwards	11/07/2011–11/08/2011

a significant role. The Manovo Gounda Floris Park was selected because it exhibited strong BB signals ($BF > 44\%$) in the DJF season. The source location chosen here is covered by grasslands and savannahs See (Fig. 10, Appendix).

Research indicates that many fires around savannahs in Ghana and in reserves can be attributed to anthropogenic activities, particularly land clearing for agricultural purposes and fuelwood generation [53]. An assessment of BB in western Ghana revealed that 19% of these fires were associated with farming practices, while an additional 10% were linked to charcoal production [54]. Bui National Park was selected because of the strong BB signals during the DJF season. This location is covered by a mix of croplands, woody savannahs, savannahs and grasslands (see Fig. 10).

Telimele, Guinea was chosen as an emission source due to evidence of significant BB ($BF > 30\%$) during the MAM season, a time when other West African areas showed minimal BB. This location also showed strong correlation between CO and BB in the MAM season ($R^2 \geq 0.5$, $p \leq 0.05$). The landcover over Telimele is dominated by savannahs, croplands and forests. Milando Partial Reserve located in Malange, Angola, a region known for having a high annual fire frequency was also selected [55]. This location was chosen because was near the southernmost areas with significant burning ($BF > 30\%$) in the JJA season. It is covered mainly croplands, savannahs and forests.

The NAME model was executed in both forward and backward modes for durations of 1 day and 5 days (Table 1). All dispersion model runs spanned from the 10th or 11th day of the starting month to the same day in the subsequent month, covering a full month with eight runs per day at 3-h intervals. Following a meticulous review, it was determined that two dates at 9:00am (closest to the MetOp/IASI overpass time of 9:30am) during the peak BB seasons in the NHA, Guinea, and SHA regions were most representative of each season. CO possesses a lifetime ranging from weeks to months under various atmospheric conditions [56]. Consequently, incorporating a 5-day trajectory into the model ensured that dispersion patterns were adequately captured prior to full dissemination from source and other chemical reactions in the atmosphere. The selected vertical maximum height was 15 km, which corresponds to the average altitude of the troposphere in tropical regions [57]. The trajectory analysis was confined within the domain boundaries depicted in Fig. 4.

3.4 Pollution transport in December and January (NHA/BB dry season)

The results illustrate the air mass history from multiple source locations, combined into a single plot. Figure 5 displays the forward trajectories for tracers released from Ghana, Warri, and the Central African Republic (CAR). The 5-day forward trajectories initiated on the 15th and 31st of December 2010 at 9:00 am, respectively. Atmospheric circulation from the three source domains predominantly moved westwards and southwestwards on the 15th and 31st of December, with notable southwestern transport (Fig. 5a and b). The air masses originating from Ghana, CAR, and Warri exhibit a tendency to converge over the Atlantic Ocean. However, emissions from Ghana seldom returned to the Warri domain. The backward trajectory from Warri on the 20th of December indicated that air masses originated from regions as far south as the

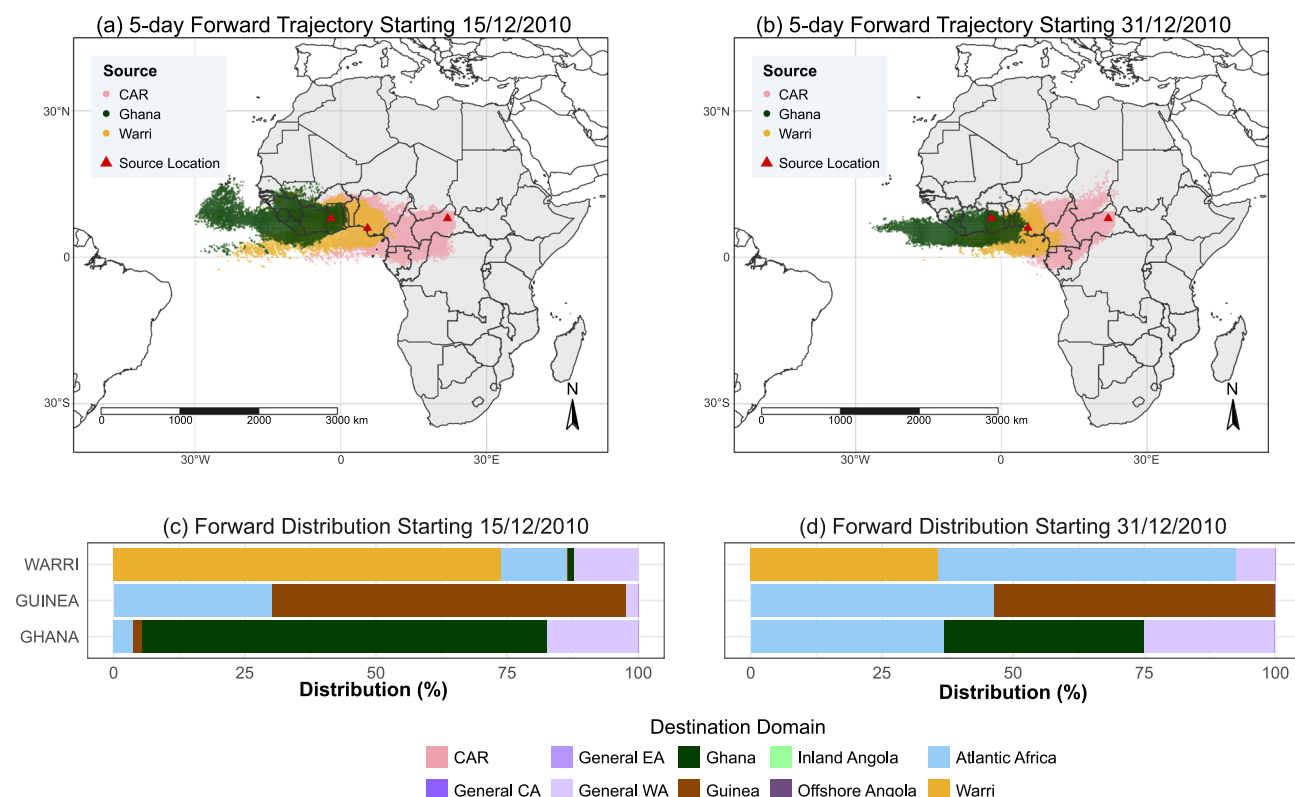


Fig. 5 5-day forward trajectories of a tracer released at 9:00 a.m. on the 15th and 31st of December 2010 from CAR, Ghana and Warri (a and b) with their distribution into domains (c and d)

equator and extended northeastward as far as Sudan. Figure 5c and d illustrates the dispersion of air masses from their sources in CAR, Ghana, and Warri into adjacent domains during the NHA BB season. Approximately 75% of the air mass originating from the Central African Republic (CAR), a BB hotspot, was transported towards the neighbouring General EA. About 15% of this air mass was distributed towards General CA, while roughly 10% remained within the CAR domain.

On December 15, most of the air mass from Ghana remained within the Ghana domain, accounting for 70% of the total air mass distributed. The General WA domain received ~ 18% of the distributed air mass (Fig. 5c, d). Smaller fractions, specifically less than 2% and 4%, were circulated towards Guinea and Atlantic Africa, respectively from December 15th. However, a shift was observed on December 31, where approximately 37% of the air mass remained within the Ghana domain, another 37% was transported towards Atlantic Africa, and 25% moved into the General CA domain. In contrast, 75% of the air mass originating from Warri on December 15 remained within the Warri domain but declined to 37% by the 31st. Approximately equal portions of the air mass leaving the Warri domain (about 12% each), were transported to the Atlantic Africa and General WA domains on December 15. By the 31st, a significant shift in circulation patterns was observed, with most of the air mass from the Warri domain, at least 55%, being directed towards the Atlantic Africa domain, while less than 10% reached the General WA domain.

The backward trajectory analysis (see Fig. 6), initiated on December 20 and January 5, revealed that the predominant source of air masses in the Warri domain during December and January originated from the Atlantic Africa region, contributing 85% and 65% respectively for both dates. Additionally, air masses originating from the Warri domain itself accounted for 15% and 30% on these days. A minor percentage (< 4%) of the air mass in Warri for both days was traced back to the General EA domain. In the Guinea domain, most of the air mass was recirculated locally, approximately 55% on December 20 and January 5. On December 20, a minimal proportion of the air mass reaching Guinea (~ 1%) originated from the Ghana domain. The primary external source of air mass in Guinea was identified as the General WA region, contributing approximately 30% on both days, while a minor portion (15%) originated from Atlantic Africa.

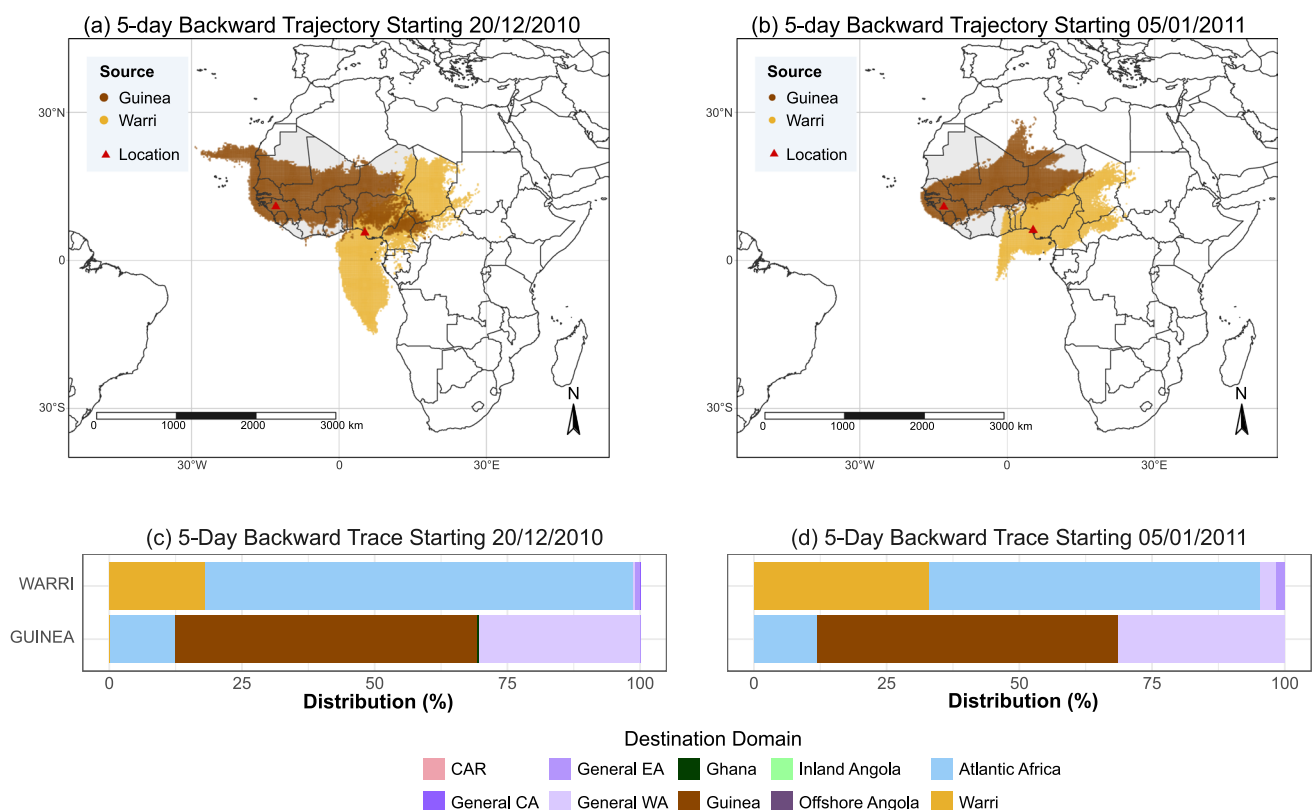


Fig. 6 5-day back trajectories of a tracer released at 9:00 a.m. on the 15th and 31st of December 2010 from Guinea and Warri (a and b) with their source domains (c and d)

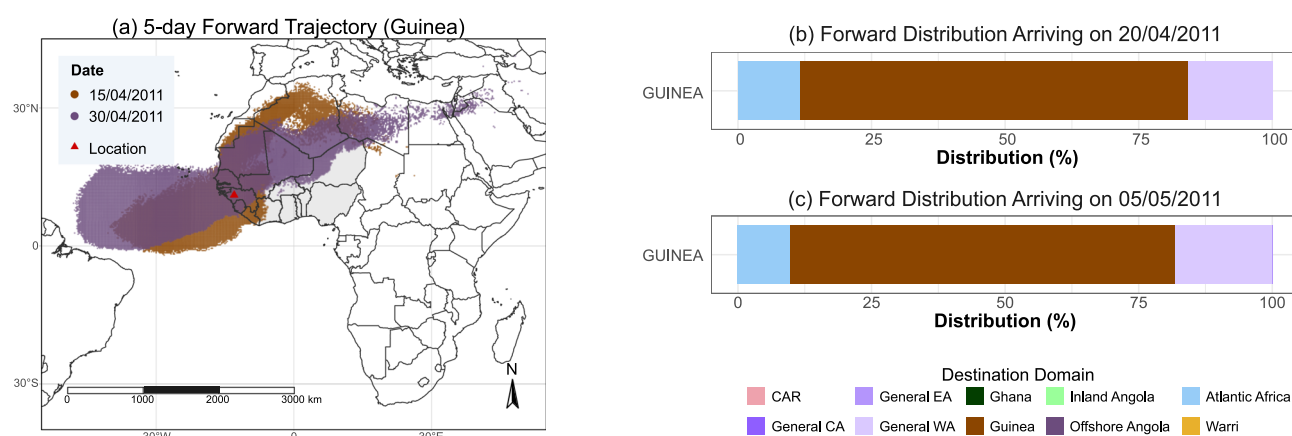


Fig. 7 5-day forward trajectories of a tracer released at 9:00 a.m. on the 15th and 30th of April 2011 from Guinea (a) with their corresponding distribution into domains (b and c)

3.5 Pollution transport from Guinea (BB season) in April/May

The dispersion directions for the tracers released from Guinea at 9:00 a.m. on April 15th and 30th, 2011, and their positions after 5 days are depicted in Fig. 7a. The travel paths for both days were similar. In April, when BB persists in the Guinea domain (Fig. 1), most of the air mass is recirculated locally within the Guinea region (Fig. 7c). The visualization of the tracer particles released on these dates showed trajectories southwestwards, into the Atlantic (as far as south American waters), the General WA domain, and North Africa. At this time of year, the only area with active BB intersected by the dispersed tracers was in central Mali (Fig. 1). A substantial portion of the air mass from Guinea, at least 70%, remained within the Guinea domain. 15–20% of the air mass reached the General WA domain, and another $\leq 15\%$ dispersed into the Atlantic Africa domain. The observed particle transport patterns suggest that there was no back flow of the tracer towards the GF hotspots. These findings suggest that the concentrations of CO detected around the Gulf of Guinea in April and May are more likely attributed to GF activities rather than BB.

In examining the dispersion directions of tracers released from Guinea at 9:00am on April 15th and 30th, 2011, Fig. 7a illustrates their positions after 5 days. For both days, the travel paths remained similar. In April, when BB persists within the Guinea domain (Fig. 1), most of the air mass is recirculated locally within the Guinea region (Fig. 7b and c). The visualization of tracer particles for these dates showed trajectories extending southwest into the Atlantic Ocean, the General WA domain, and North Africa. At this time of year, the only active BB area intersected by the dispersed tracers was in central Mali (Fig. 1). A significant portion of the air mass from Guinea ($\sim 70\%$), remained within the Guinea domain, while 15–20% reached the General WA domain. Another $\leq 15\%$ dispersed into the Atlantic Africa domain. The observed particle transport patterns suggest that there was no backflow of the tracer toward the GF hotspots. These findings imply that the concentrations of CO detected around the Gulf of Guinea in April and May are more likely attributed to GF activities rather than BB.

3.6 Pollution transport in July and August (SHA dry/BB season)

The 5-day forward trajectories, initiated on July 15th and 31st, 2011 at 9:00 a.m., during the SHA dry/BB season, had tracers released from inland Angola, offshore Angola, and Warri (Fig. 8a and b). The maps show that air masses from both inland and offshore Angola mixed over the Atlantic Ocean before spreading out. Figure 8c and d show that most of these air masses traveled northeast to the General CA domain, making up 50.8% and 67.6%, respectively. Air masses from inland Angola, a BB hotspot, had about 13% going towards Atlantic Africa, while offshore Angola had more influence on the General CA domain, with rates between 60 and 65% on both dates. Only a small fraction of the air mass from inland Angola on July 31 ($\sim 2\%$) reached the Warri domain.

These findings suggest that air masses from BB and GF in and around Angola significantly impact the Atlantic Africa region. On both dates, air masses from Warri either stayed local ($\sim 60\%$ and 30%) or moved into the General WA domain

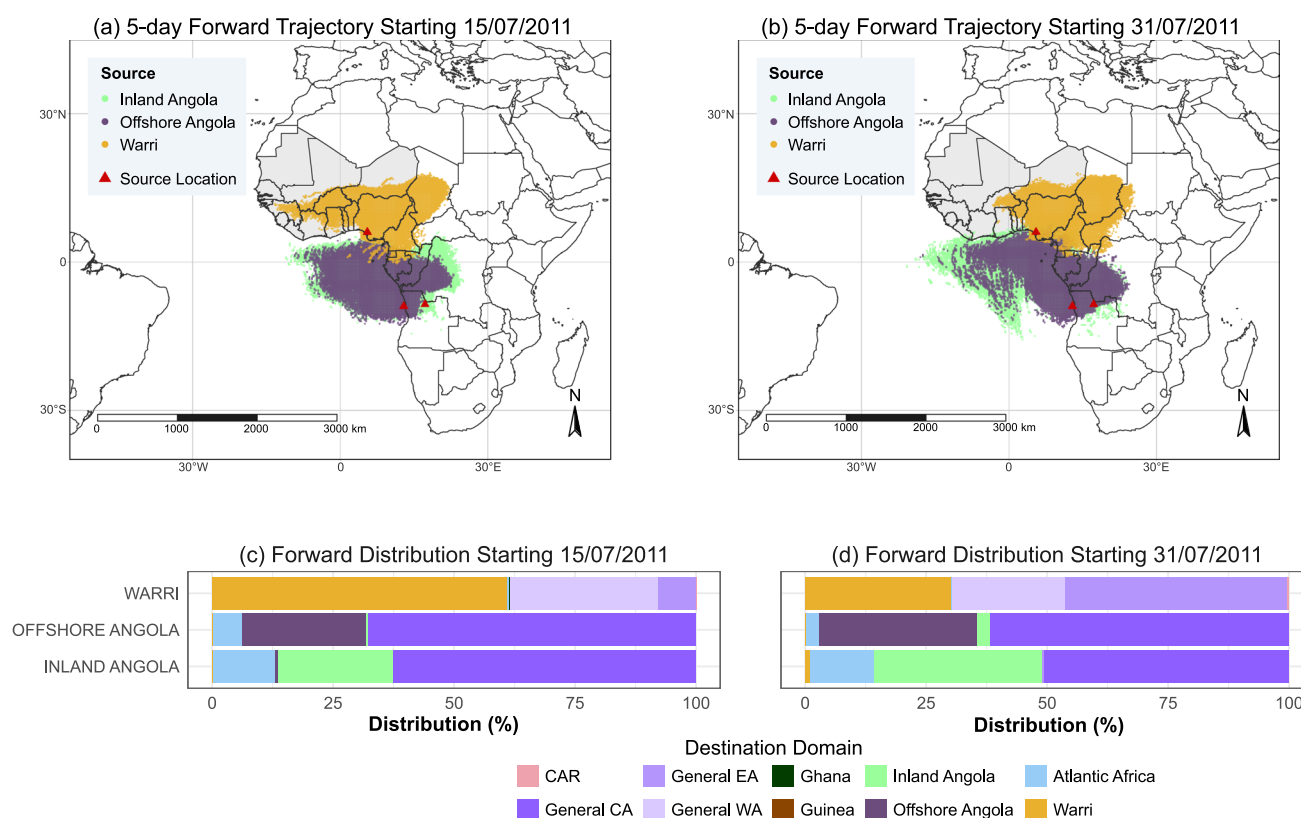


Fig. 8 5-day forward trajectories of a tracer released at 9:00am on the 15th and 31st of July 2011 from CAR, Ghana and Warri (a and b) with their distribution into domains (c and d)

(30.7% and 23.4%) and the General EA domain (7.8% and 45.8%). A tiny portion of this air mass (0.13%) was recirculated into the Atlantic Africa domain on July 15th.

The backward trajectory analysis for Warri on the 20th of July and the 5th of August (Fig. 9c and d) indicated that air masses predominantly originated from the Atlantic Africa domain, contributing to $\geq 85\%$, with $\leq 15\%$ sourced from the local Warri domain. In contrast, the air mass history for Guinea on these dates revealed that the major source for the trace-back on 20th of July was local with external influence from the Atlantic Africa domain, accounting for 45%. This changed on the 5th of August with the Atlantic Africa domain accounting for 75%. Considering map showing the 5-day forward and backward trajectories from the 15th of July to the 5th of August (Fig. 9a and b), it was observed that emissions from both inland and offshore Angola traversed into the Atlantic Africa domain. While the distribution only showed Atlantic Africa as the major external source in Warri and Guinea (Fig. 9c and d), the observed mixing over the Atlantic observed in Fig. 8 suggests a dual source effect of BB and GF over CO emissions being redistributed from the Atlantic Africa domain.

The backward trajectory analysis for Warri on July 20th and August 5th (Fig. 9c and d) showed that air masses mainly came from the Atlantic Africa domain, contributing $\geq 85\%$, with $\leq 15\%$ from the local Warri domain. In contrast, the air mass history for Guinea on these dates revealed that the major source on July 20th was local, with an external influence from the Atlantic Africa domain accounting for 45%. This changed on August 5th, with the Atlantic Africa domain contributing 75%. Considering the maps showing the 5-day forward and backward trajectories from July 15th to August 5th (Figs. 8a, b, 9a and b), it was observed that emissions from both inland and offshore Angola moved into the Atlantic Africa domain. The distribution only identified the Atlantic Africa domain as the major external source in Warri and Guinea (Fig. 9c and d). However, the observed mixing over the Atlantic (Fig. 8) suggests a dual-source effect of BB and GF on CO emissions being redistributed from the Atlantic Africa domain.

3.7 Drivers of CO concentrations and its dispersion

Climatic processes, including variations in wind speed, vertical circulation, and seasonal dispersion patterns, likely contribute to the observed CO concentrations. Analyzing CO data from IASI shows that CO levels decrease westward from the

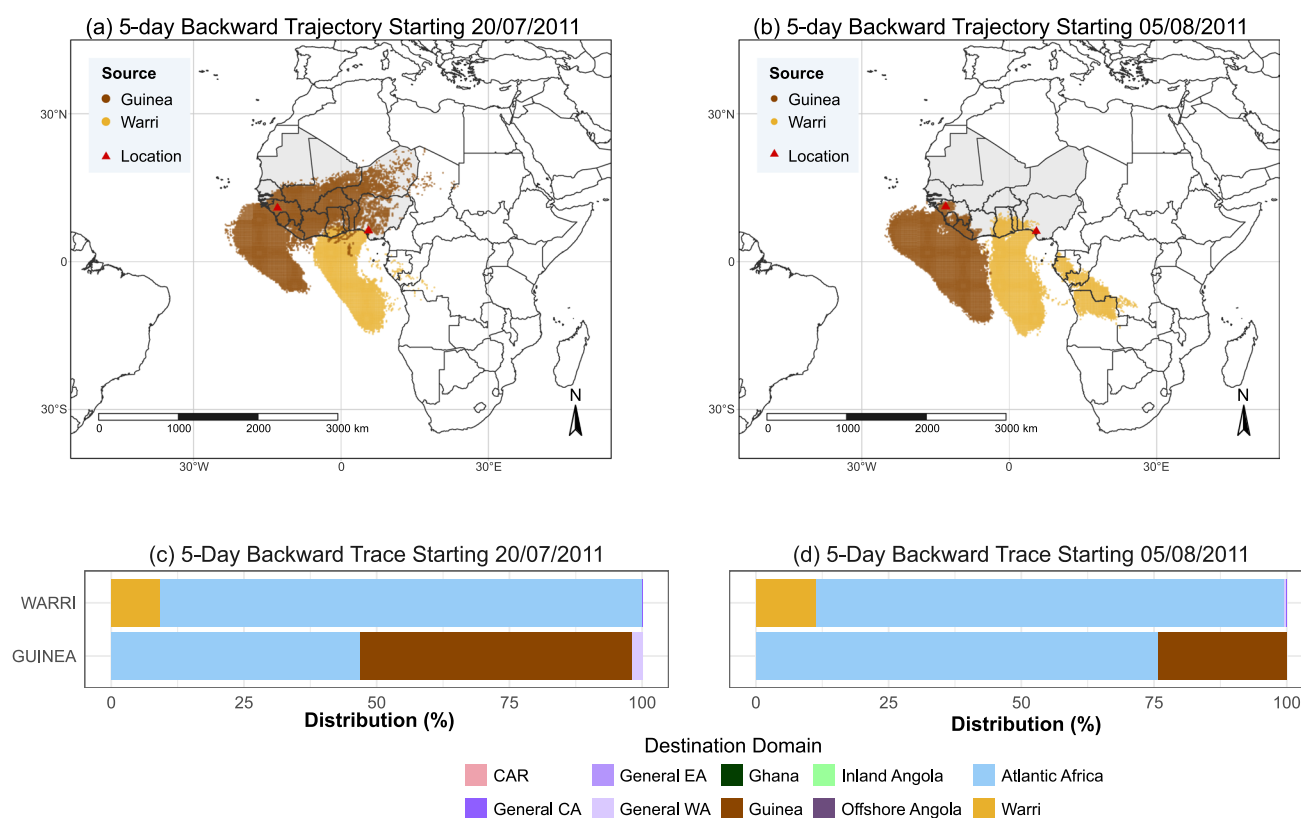


Fig. 9 5-day back trajectories of a tracer released at 9:00am on the 15th and 31st of July 2011 from Guinea and Warri (a and b) with their source domains (c and d)

Niger Delta in January and northwestward/westward from Angola around August. CO molecules, which are long-lived, can persist in the areas to which they are transported. Although emissions from oil exploration and GF along the African Atlantic coast from the Niger Delta to Angola occur year-round, they are most noticeable during periods of lower wind speeds and slower dispersion rates.

In August and September 2011, CO concentrations around Angola reveal two main sources: BB activities inland and GF/oil exploration offshore. BB hotspots had over 40% BF in the JJA season when deforestation and land clearing for agricultural purposes or grazing are high [55]. The GF hotspots recorded CO concentrations exceeding 4.6×10^{18} molecules cm^{-2} in August and September. These findings were validated by dispersion modeling using 5-day forward and backward trajectories. This dual-source scenario corroborates the hypothesis that the elevated CO column concentrations observed in December and January along the West African coast are not solely attributed to BB. Emissions from GF also play a significant role. Air mass distributions from the dispersion model demonstrate that emissions from offshore Angola, where GF occurs, and inland Angola, where BB is prevalent, converge during atmospheric transport in the SHA BB season. Consequently, CO transported to West Africa at that time of the year is not exclusively derived from BB in the Southern Hemisphere Africa (SHA) region. The transport of tracers from offshore sources near Angola suggests that emissions from other GF sites in Equatorial Guinea, the Republic of Congo, and Gabon may also contribute to CO levels in West Africa during the SHA BB season.

Furthermore, tagged simulations from the GEOS-Chem Chemical Transport Model (CTM) identify BB but exclude biofuel as a significant source of CO pollution in Africa specifically [58]. Africa's biofuel emissions are only accounted for under the global tracers in this CTM. Black Carbon (BC) has a shorter lifetime in the atmosphere compared to CO and is not dispersed as far away as CO from source. Stohl et al. [59] observed improvements in the ECLIPSE model for the Arctic when GF was accounted for as a source of BC. Similarly, Fawole et al. [19] reviewed the impact of GF on air pollution, noting that few emission inventories, such as EDGAR and ECLIPSE, include GF emissions. They highlighted the critical need to incorporate GF emissions in atmospheric transport models, particularly in regions like Nigeria in West Africa that are prone to such emissions. The results of this study underscore the critical importance of incorporating CO emissions from GF into atmospheric models that aim to accurately simulate air pollution in the troposphere for West Africa.

4 Conclusion

This study provides a comprehensive analysis of the dispersion and transport of CO in West Africa, with a specific focus on the contributions of BB and GF. In addition to linear regression, the forward and backward trajectories of air masses highlight significant seasonal variations influenced by wind speed, vertical circulation, and emission sources. The detected CO concentrations around the Gulf of Guinea in April and May 2011 suggest a stronger attribution to GF activities rather than BB.

During the SHA dry season in July and August 2011, air masses originating from both inland and offshore Angola demonstrated significant mixing over the Atlantic Ocean, leading to substantial transport toward the General CA domain. The backward trajectory analysis indicated that emissions from Angola played a crucial role in influencing CO levels in the Warri and Guinea domains, in addition to local contributions. This phenomenon is attributed to the geographical proximity of these locations to the Atlantic, where emissions from Angola are transported and subsequently recirculated westward. Moreover, the seasonal variation in CO concentrations observed around Angola in August and September 2011 highlights the dual impact of biomass burning inland and oil exploration/GF offshore. This dual-source scenario corroborates the hypothesis that the elevated CO levels detected along the West African coast in December and January are not only due to biomass burning but are also significantly affected by GF and other anthropogenic activities.

The findings from this study emphasize the need to incorporate gas flaring emissions into atmospheric models to accurately simulate air pollution in West Africa. The review by Fawole et al. [21] reinforces this necessity, highlighting the limited inclusion of gas flaring emissions in existing CO inventories for West Africa.

In conclusion, this study underscores the critical importance of accounting for both biomass burning and gas flaring emissions in atmospheric models to enhance the accuracy of air pollution simulations in the troposphere over West Africa. Addressing these dual sources will provide a more comprehensive understanding of CO distribution and its environmental impacts in the region.

Author contributions A.O.: conceptualization, analysis of biomass burning and CO datasets, writing, review and editing of the manuscript. Z.F.: setting up and running the NAME numerical model, writing review and editing of the manuscript. M.P.: updated runs of the NAME numerical model, manuscript edits. H.B.: supervision, conceptualization and review of first manuscript. P.M.: supervision, conceptualization and review of first manuscript.

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Data availability The IASO CO data set used in this study is available at <https://iasi.aeris-data.fr/catalog/?currentSelection=6299d624-a8ca-4f77-ae1d-bd54a4af6bbf>. The GFED4s monthly burned area product with small fires is available at https://daac.ornl.gov/VEGETATION/guides/fire_emissions_v4_R1.html. More information on the NAME dispersion model by the UK Met Office can be found here: <https://www.metoffice.gov.uk/research/approach/modelling-systems/dispersion-model>.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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Appendix

See Fig. 10.

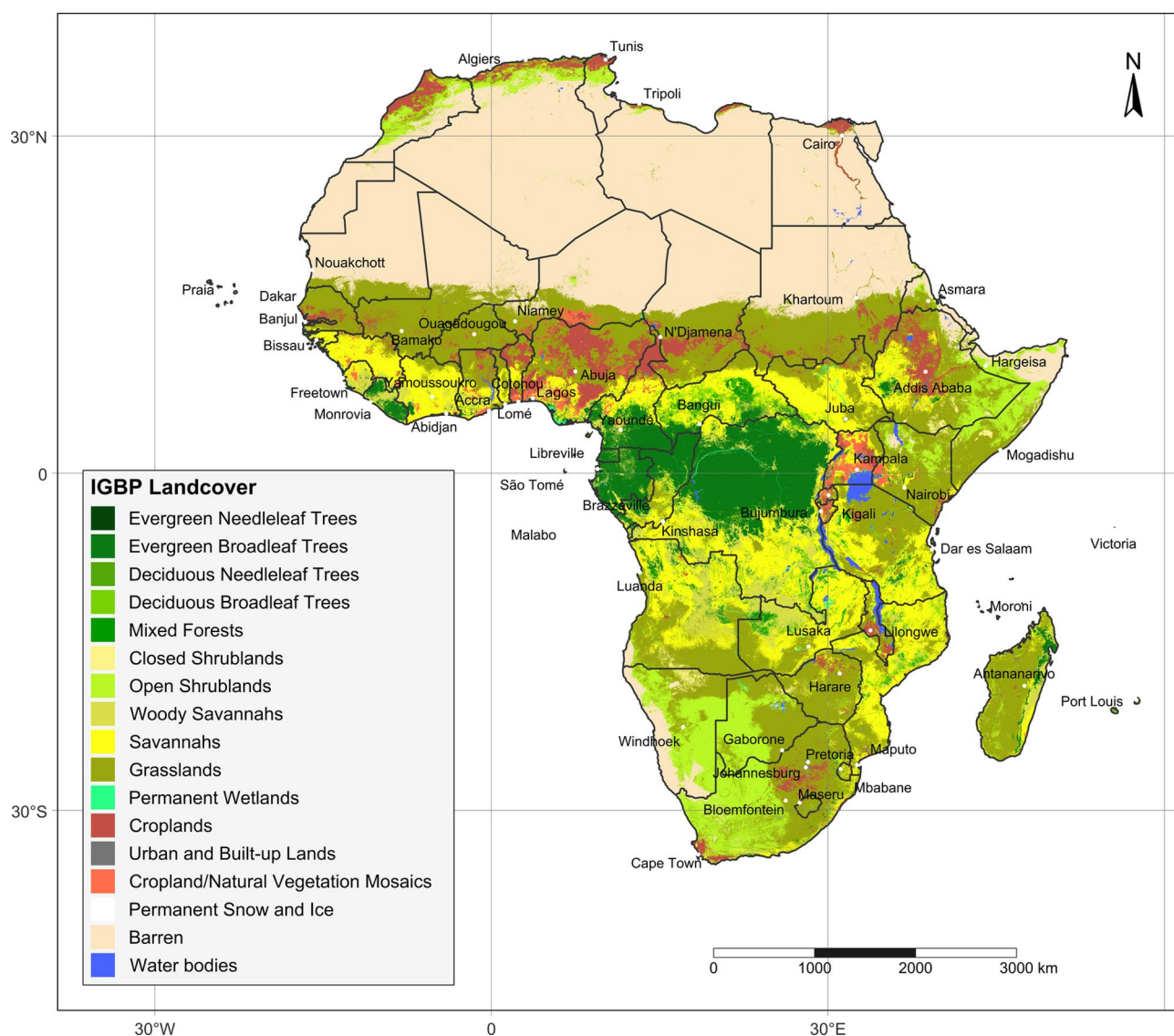


Fig. 10 MODIS landcover classes over Africa based on the Annual International Geosphere-Biosphere Programme (IGBP) classification [60]

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