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Measurement of atmospheric gasesin the West and Central African ecosystems

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Abstract

Experimental data on gases concentrations in Great African ecosystems have been obtained under the INDAAF (**I**nternational **N**etwork to study **D**eposition and **A**tmospheric chemistry in **AF**rica) program. In this paper, data covering a complete wet and dry seasons (1998 to 2013) at three remote sites in West and Central Africa are presented. Those sites are representative of Great African ecosystems and are located along the latitudinal transect: dry savanna (Banizoumbou in Niger)-wet savanna (Lamto in Ivory Coast)-equatorial forest (Zoetele in Cameroon). For each type of these ecosystems, the monthly, seasonal and annual concentration and dry deposition variability have been determined and analyzed. Results show that at the dry savanna site, seasonal concentrations of all the five gases are higher in the wet season. In opposite, concentrations are higher during the dry season in wet savanna and in forest. The annual average concentrations of these gases measured in dry savanna are higher than those measured in wet savanna and in forest. The obtained values of annual average concentrations for the three ecosystems show the influence of the density of animal population in dry savanna and the seasonal gradient of solar radiation intensity that controls the dynamic of atmospheric air masses and photochemical reactions along the transect. We also notify the most important role that play terrigenous dust suspension, vegetation density and moisture along this transect of ecosystems. The annual average dry deposition for the five polluting gases is measured in dry savanna, wet savanna and equatorial forest. Concentrations and dry depositions of these gases depend on human activities, meteorological parameters of each ecosystem and physicochemical processes in the atmosphere.

1. Introduction

INDAAF (International Network to study Deposition and Atmospheric composition in Africa) is a programme dedicated to the long-term monitoring of the atmospheric composition and of the atmospheric deposition fluxes in Africa. It corresponds to the union of the previously labeled IDAF-DEBITS network and the "Sahelian Dust Transect" network. Within this framework studiesare carried out on gas samples (NH_3, HNO_3, O_3, SO_2 and NO_2) collected at three African ecosystems: dry savanna, wet savanna and equatorial forest. These gasesare the main precursors of aerosols responsible for acid rains, acidification of the oceans, destruction of forests, and materials of construction, etc. They strongly modify the radiative balance of the atmosphere and therefore influence climate change and human health. These effects of atmospheric pollutionhave been indicated by several stadies as follow: Nitrogen is accumulated in soils during the dry season and emitted as large pulses of NO at the beginning of the rainy season [1, 2]. Resulting emissions from these pulse events release high quantities of NO_x in the atmosphere, contributing to increase ozone formation in the troposphere and its long-range transport. "Tropospheric ozone (O_3), formed by the reaction of NO_x and volatile organic compounds (VOCs), is also a major environmental concern because of its adverse impact on human health, crops and forest ecosystems and its greenhouse gas effect responsible for climate change"[3]. Macdonald et al. (2005) [4] have

shown that soils containing partially oxidized sulfides are a source of SO_2 emission in the atmosphere and its evolution appears to be related to the evaporation of the soil surface. In addition, combustion of biomass is an important source of SO_2emission in the atmosphere [5]. "The environmental effects of SO_2 and NO_2 pollutants are the acidification of precipitations, visibility reduction, and have deleterious effects on human health and plants" [6]. Anthropogenic SO_2 is emitted during the combustion of fossil fuels containing sulfur, principally coal and heavy oils. The measurement of HNO_3 in ambient air is of great importance because of its influence in the acidification of the atmosphere and its control of the levels of photooxidants. Several studies on these gases have been made in these three tropical African ecosystems [7–12]. They haveallowed to quantify the concentrations, the drygaseous depositions and to estimate the contributions of the differentsources of gases and aérosols. These studies are supplemented by this paper which concern analysis of concentrations and dry depositionsof the five gases at Banizoumbou in dry savanna, Lamto in wet savanna and Zoetele in equatorial forest.

The main objectives of this work are to determine the variability in monthly, seasonal and annual concentrations of these five polluting gases, to compare the interannual variability of their concentrations, and to estimate the annual and seasonal dry deposits.

2. Materials and Methods

2. 1. Presentation of measurement

The INDAAF long term monitoring network is composed by 8 stations in West and Central Africa (Mali, Niger, Ivory Coast, Senegal, Benin, Congo, and Cameroun) and 5 partner sites (4 in South Africa and 1 in Tunisia) (Figure 1). These 8 West and Central African sites are located to represent a transect of ecosystems, dry savannas (Agoufou, Banizoumbou, Katibougou) - wet savannas (Djougou, Lamto) - equatorial forests (Zoetele, Bomassa).Dry savannas are characterized by a long dry season from October to May and a short-wet season from June to September.In wet savanna, wet season extends from April to Octoberand from March to November in forests;the other months represent the dry season. A detailed description of INDAAF monitoring stations can be found inAdon et al.(2010)[11]. NO_2, NH_3 and HNO_3 have been monitored since 1998, while measurementof O_3 started in 2001 and that of SO_2 in 2002.

2. 2. Principle of operation of the passive samplers

The operating principle of the passive samplers is based on the following two phenomena:

-the physical phenomenon of molecular diffusion;

- the chemical reaction between the molecules of the gas studied and those of the substance of which the cellulose filter is impregnated.

The gas which concentration is to be determined is carried passively into the passive sampler by molecular diffusion. It is chemically trapped on a filter impregnated with a substance dissolved in a volatile solvent (methanol). The product of the reaction is recovered by extraction in a small volume of milli-Q water (deionized water) before being analyzed by ion chromatography (ammonium, nitrates, and sulfates).

The dose thus measured is proportional to the concentration of the gas in the ambient air determined by the formula(1):

$$C = (L/A.\ X.\ R.\ T) / (t.\ D.\ P) \quad (1)$$ with:

C: concentration of the gas considered in the air in ppb.

X: the quantity of molecules collected on the cellulose filter in µmol (corrected with the white).

R: the perfect gas constant ($R = 0.08206\ L.atm.K^{-1}.mol^{-1}$).

T: the average ambient temperature during the exposure period in Kelvin (K).

P: the mean atmospheric pressure during the exposure period of the passive samplers (atm).

D: the molecular diffusion coefficient of the gas in the air ($m^2.s^{-1}$).

t: the exposure time of the passive samplers in second (s).

$L / A = 47.5\ m^{-1}$, coefficient of air resistance[7]. A is the section of the sampler and L its

The passivesamplers are differentiated by a color code: gray for NO_2, white for NH_3, black for both SO_2 and HNO_3, and gray and black plume for O_3. Before and after exposure (one month), passivesamplers are stored in the refrigerator in the laboratory or on the site, trying to minimize the time between exposure and analysis. All passive samplers (including "blanks"), after sampling on the sites, are sent back to the Laboratory of Aerologyat Toulouse for analysis.

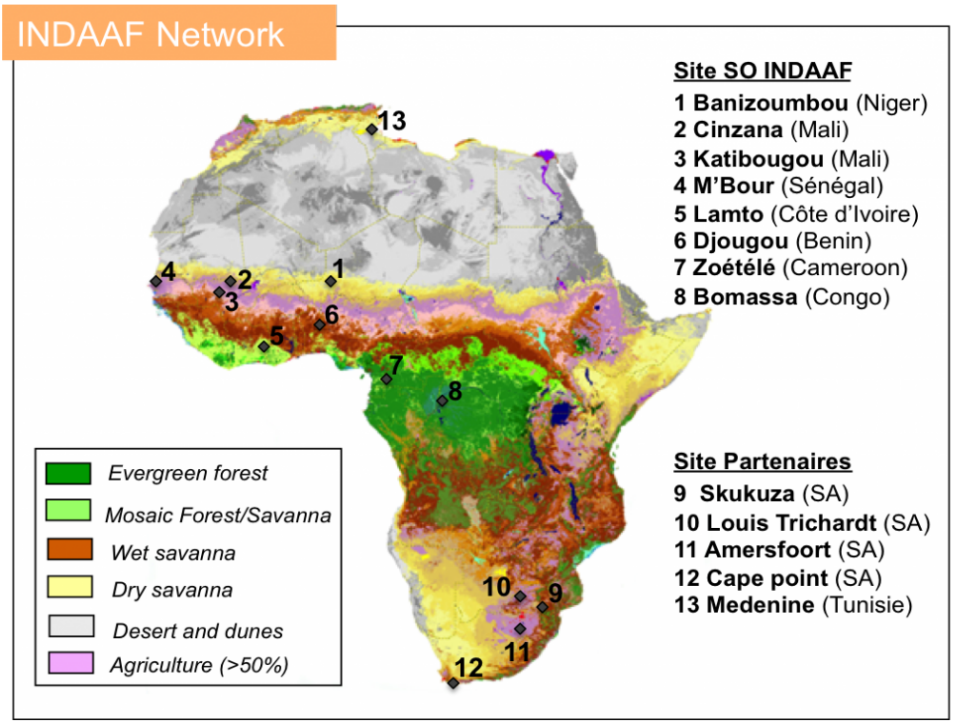

Figure 1: The 13 INDAAF measurement stations

2. 3. Analysis technique for passive samplers

In the passive samplers, the impregnated filter which traps the gas must have a complete reactive efficiency. For the different gases studied, the chemical capture is carried out by reactions. The product of the reaction is recovered by ultrasonic extraction in a small volume of milli-Q water (deionized water). The desorption volume is 10 ml for the black and gray passive samplers filters and 5 ml for the white one. The solution obtained is analyzed by ion chromatography for the trapped ions: NO_2^- (for NO_2), NO_3^- (for HNO_3 and O_3), NH_4^+ (for NH_3) and SO_4^{2-} (for SO_2).

3. Results and Discussion

3. 1. Monthly average concentrations of the gases measured atBanizoumbou, Lamto and Zoetele

Figure 2(a-c) presenting variations in monthly average concentrations of gases allow us to identify periods of high concentrations and, therefore, to deduce favorable conditions for emission and physicochemical processes of transformation of these gasesinthethree ecosystems studied.

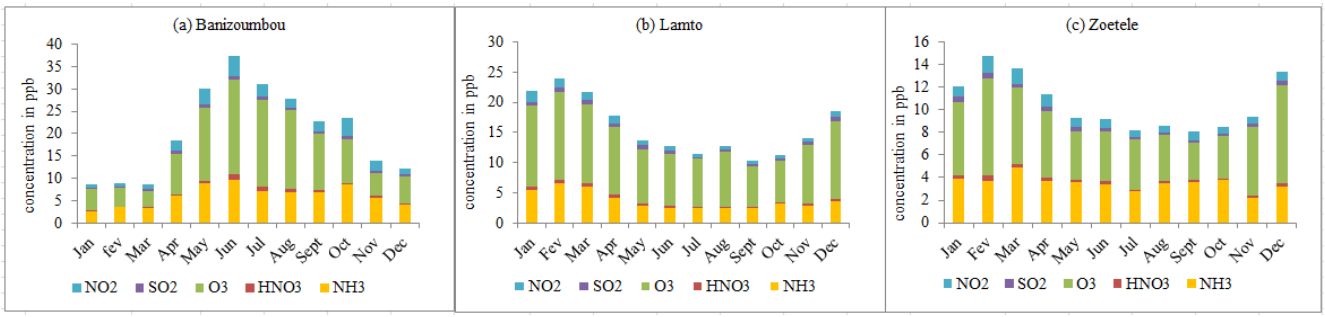

Figure 2 (a-c): Variation in monthly mean concentrations of gases at the three INDAAF sites

In dry savanna (Figure 2a) we notice a period of high concentrationsof gases from April to October with a peak in June which is the first month of the wet season. This peak of gases concentrations is due to the change in meteorological and ecologicalparameters. These parameters include soil pH, temperature, moisture and texture, wind speed, plant cover, floristic composition and N input fertilization [13 – 17]. Soil moisture in tropical regions is the principal driver of NO emission with most intensity when the first rains fall on the very dry soils[2, 10, 14, 18, 19]. Therefore the concentrations of NO_x, HNO_3 and O_3 increase by photochemical reactions in the atmosphere.

NH_3 and NO_2 have high concentrations again in October which is the beginning of the dry season. This result could be explained by the emission formfertilized soils, biomass fires, crop residues decomposition,vegetation and domestic fuelwood burning [20- 22].

From June to Otober (wet season), the concentration of gases is relatively high although reduced by the leaching of the atmosphere by more regular precipitations in July, August and September.This result is with agreement to Galy-Lacaux and Modi (1998) affirmation [23]. In the Sahelian region,hydrolysis of urea from animal urine deposited in pasture grazing areas is a considerable source of nitrogenous compounds because high densities of domestic animals are concentrated on the fresh natural pastures greening.

This high concentration of gases during the rainy season clearly shows the influence of humidity in bacterial decomposition of urea in animal excreta very active in the wet season, emissions from natural soils and vegetation[24 - 26, 10] leading to the increase of NH_3, NO_x ($NO + NO_2$) concentrations.Also lightning[27],solar radiation intensity and atmospheric stability are favorable for atmospheric photochemical reactions that increase the formation of secondary pollutant gases such as O_3, NO_x, SO_2 and HNO_3.

The high O_3concentration formed in the atmosphere during the wet season can be explained by the reaction between NO_x, volatile organic compounds andoxydising radicals (OH, H_2O_2, RO_2) through photochemical activity. The nitric acid (HNO_3) and sulfuric acid (H_2SO_4)formations follow the same mecanismof photochemical oxidation which is active in tropical regions with high humidityand temperature [28, 29].

We notice that in March the concentration of gases starts to increase. This month marks the beginning of the hottest period of the region when the solar radiation is intensified. This high intensity of solar radiation creates the Saharan Thermal Depression in the North. This situation weakened the Harmattan andreduced the terrigenous aerosols [30]. In the same time, the monsoon which flow from the south-west to the nord-east increases the relative humidity in the atmosphere andcarriesconsiderable quantities of volatile organic compounds, oxidizing radicals and other gases emitted by fertilized soils and vegetation of the southernwet savanna and forest watered rather. Even more intense solar radiation during this period, the low suspension of dust in the atmosphererereduising the heterogenousprocesses[31] lead to high concentration of gases in the atmosphere. The senescence of the vegetation and biomass burning are possible additional sources [31].

In November, the concentration of gases becomes low again.This month marks the beginning of the cold period and then the very changes in meteorological parameters and physicochemical processes that governthe transformation and the transport ofthese gaseous pollutants. This mainly involves reduction of relative humidity, temperature, solar radiation intensity andthe increase in dust suspension by Harmattan favorable for the heterogenous processes [30, 31].

The low fluctuation in NH_3 concentration would be attributed to the complementarity of its sources between the two seasons. These sources are senescence of the vegetation and biomass fires during the dry season and soil emission, hydrolysis of animal excretaand fertilizer use in the rainy season [9].

In addition to the participation of nitrogen dioxides in the formation of ozone, they are also removed from the troposphere by oxidation to nitric acid (HNO_3), particularly by the reaction $NO_2 + OH \rightarrow HNO_3$. This acid dissociates in the aqueous phase of the clouds to nitrate (in wet season) or is caught by the mineral particlesthroughout heterogenous processes [31]. Sulfur dioxide follows the same processes as nitrogen dioxide and leadsto the formation of sulfuric acid (H_2SO_4). These two inorganicacids react with NH_3andpass to aerosol phase in ammonium sulfate ($(NH_4)_2SO_4$) and ammonium nitrate (NH_4NO_3) forms[28]. It is obviously these multiple reactions and processes affecting NO_2, SO_2 and HNO_3 that explain their low concentrations throughout the year in all the three ecosystems.

Inthe wet savanna of Lamto(Figure 2b) and inthe equatorial forest of Zoetele (Figure 2c), two peaks of gases concentrations are observed. The first peakobtained in February and the second in December during the dry season would be due to intense solar radiation, vegetation and biomass fires emissions. This result is confirmed by Galanter et al. (2000) [32] who found that more than 75 % of the NO_x at the surface near equatorial Africa is biomass burningemission that occurs from December to February.

Between these two peaks, the concentration of gases is relatively low. This could be attributed to clouds cover which considerably reduces the intensity of incident solar radiation and then reduces the photochemical reactions, the adsorption of gases on plants, and mainly the leaching of the atmosphere by permanent precipitations. It is then evident that much of these gases are chemically transformed into the aqueous phase by multiphasic processes and certainly removed from the atmosphere as wet deposition in the forms SO_4^{2-}, NO_3^- and NH_4^+ [28]. The absorption of certain gases directly by the leaves of plants with moistured surfaces also constitutes a no less important phenomenon contributing to decrease their concentrations. Tsai et al. (2010) [33] show that the canopy resistance (*R*c) is the main factor determining the deposition rate in vegetative zones because surface deposition (cuticle) and stomatal uptake become important. BothNO_3^- and NH_4^+ were considered to be taken up by plants in nitrogen-limited ecosystems [34].

At Zoetele in the equatorial forest, ozone concentration follows a marked decrease and becomes lower than that of ammonia in September and October.This result shows the role of the tropical forests which appear to be a major O_3 sink through ground and foliage deposits, chemical reactions with hydrocarbons and nitrogen oxides [35 - 38].

3. 2. Seasonal average concentrations of gases measured in Banizoumbou, LamtoetZoetele

An analysis according to the seasons could clearly elucidate the favorable conditions to the emissions and the physicochemical transformations of these five gases as well as the evolution of their concentrations according to the ecosystems. Figure 3 (a-c) shows the gases concentrations during dry season and wet season estimated as percentages.

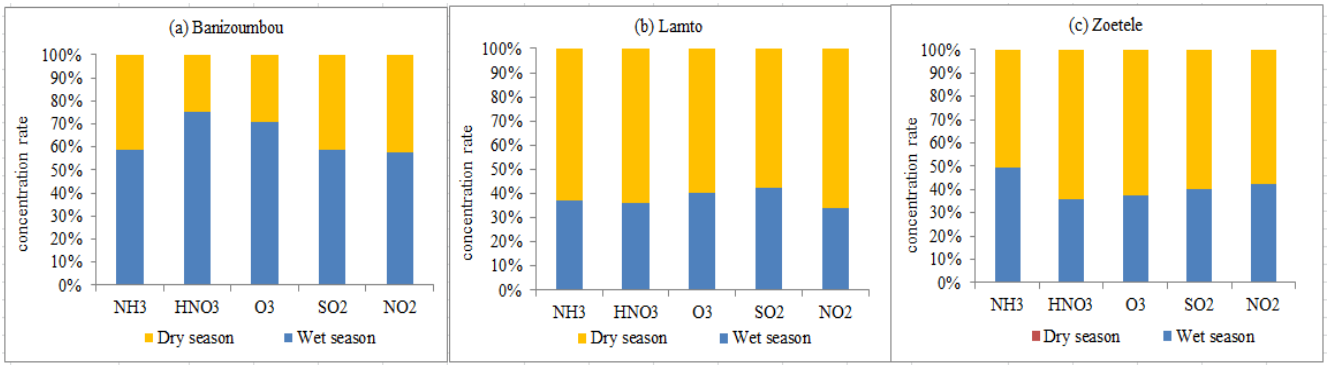

Figure 3 (a-c): Seasonal mean concentrations of gases in percentages at the three sites

For thedry savanna of Banizoumbou (Figure 3a) and for all the gases, the wet season concentrationsare higher than those during the dry season despite the leaching of the atmosphere by precipitations and the short duration of this period. The figure 3a shows the following result: HNO_3 (75%, 25%), O_3 (71%, 29%), $NH_3$and SO_2 (59%, 41%) andNO_2 (58%, 42%)during wet season and dry season respectively.We report that the gases concentration rates during the wet season are greater than 50%.

This result shows the importance of the secondary pollutants (HNO_3, O_3) formation by photochimical reactions in the atmosphere during the wet season. These gases are obtained by oxidation of primary NO_xmostly emitteddurin the wet season [2, 3]. The large solar radiation that reaches the lower layers of the leached atmosphere, the high NO_x emissions and the monsoon transports of additional volatile organic compounds increase the formation of HNO_3 and O_3 during the wet season.

It is evident that the emission of NH_3 is also favored by temperature and moisture[39]through the hydrolysis and the bacterial decomposition of urea in animal excreta and the emission by natural or fertilized soils [25]. Its small percentage would be due to the so important role that it plays in the process of neutralizing atmospheric acidity by its transformation into particulate forms as NH_4NO_3, $(NH_4)_2SO_4$ [40].

In the other hand, the capture of HNO_3 and H_2SO_4 by the alkaline terrigenous particles explains the low percentagesof NO_2 and SO_2obtained during the dry season[40].

Inthe wet savanna of Lamto (Figure 3b) andin theequatorial forest of Zoetele (Figure 3c), an antagonistic situation to that found at the dry savanna of Banizoumbou is obtained. The concentrations of the gases during the dry season are higher than those obtained during the wet season despite its long duration. The gases concentration rates are: SO_2 (42%, 58%), O_3 (40%, 60%), NH_3 (37%, 63%), HNO_3 (36%, 64%), NO_2 (34%, 66%) at Lamtoand NH_3 (49%, 51%), NO_2 (43%, 57%), SO_2 (40%, 60%), O_3 (38%, 62%), HNO_3 (36%, 64%) at Zoetele during wet season and dry season respectively. We notice that the concentration rates of gases during the dry season are less than 50% in both sites.Thisresult would be due tothe reduction of solar radiation by cloud cover, leaching of the atmosphere by quasi-permanenteprecipitations during the wet season and the nucleation and condensationprocesseswhich convert these gases intoparticulateform.The high concentrations of gases in the wet savanna and the equatorial forest during the dry season would be due to the biomass fires and the use of wood and charcoal as source of energy [11, 12]. Table 1 and 2 summarizes the values of annual and seasonal concentrations of gases at the three sites.

The NO_2, SO_2, HNO_3 concentrations (Table 1) which lead to NO_3^- and SO_4^{2-}responsibles for rainfall acidity [40] suggest that precipitations would appear more acidic in dry savanna than in wet savanna and equatorial forest.

Table 1: Values of annual mean concentrations of gases in ppb at Banizoumbou, Lamto and Zoetele with min is use for minimum and max for maximum values

Concentration (ppb)	NH_3		HNO_3		O_3		SO_2		NO_2	
Annual mean value	min - max	meam	min - max	mean	min - max	mean	min - max	meam	min - max	mean
Banizoumbou	2.58 - 9.06	6.22	0.18 - 0.72	0.45	11.11 - 15.09	11.10	0.23 - 0.85	0.55	1.73 - 2.29	2.38
Lamto	2.39 - 5.37	3.42	0.27 - 0.56	0.37	7.22 - 12.44	10.77	0.15 - 0.88	0.57	0.63 - 1.53	0.91
Zoetele	1.50 - 5.47	3.70	0.13 - 0.36	0.25	3.58 - 9.25	5.66	0,.14 - 0.51	0.30	0.63 - 1.28	0.87

Table 2: Values of seasonal mean concentrations of gases in ppb at Banizoumbou, Lamto and Zoetele

Seasonnal value	dry season	wet season	dry season	wet season	dry season	wet season	dry season	wet season	dry season	wet season
Banizoumbou	5.33	7.59	0.29	0.88	7.40	17.76	0.47	0.67	2.07	2.85
Lamto	4.89	2.86	0.50	0.28	12.73	8.51	0.65	0.48	1.27	0.65
Zoetele	3.59	3.49	0.37	0.21	7.94	4.81	0.42	0.28	1.08	0.80

Studies on the physicochemical characterizations of precipitations carried out on the transect of ecosystems: dry savanna-wet savanna-equatorial forest [23, 31, 41–45] have shown an opposit result. Rainfall at dry savanna is basic, while atwet savanna and equatorial forest it is acidic. It is true that the area with dense vegetation (wet savanna and forest) is subjected to an important emission of organic acids but that would not explain this situation. Ammonia and terrigenous particles which concentrations are higherin dry savanna play an important role in the neutralization of atmospheric acidity. Therefore, NH_3reacts with acidic gases (HNO_3 and H_2SO_4) and leads to the salts of ammonium which explains their basic character. The capture of these acidic gases by terrigenous particles is also another reason of this rain alkalinity in dry savanna[31].

3. 3. Annual averageconcentrations of gases measured at Banizoumbou, Lamto and Zoetele

The analysis of the annual averageconcentrations of gases will allow us to understand the interannual evolution of their concentrations.

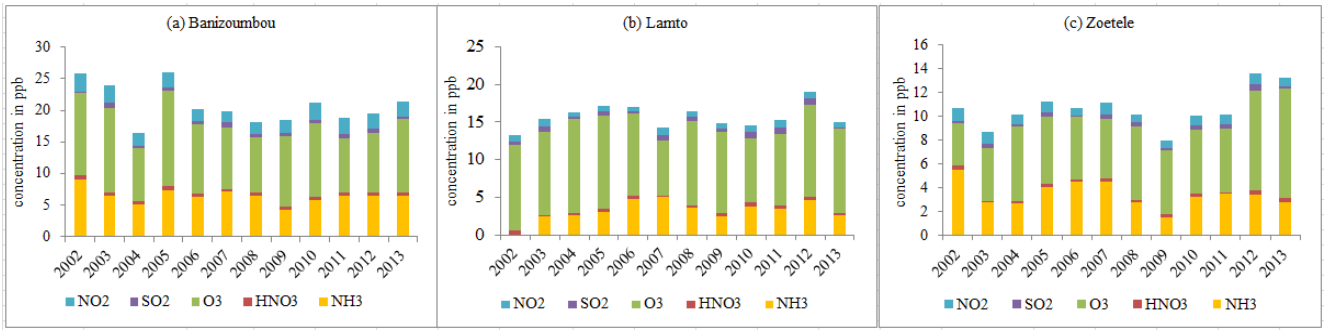

Figure 4 (a-c): Annual average concentration variations of gases at the three IDAF sites

At Zoetele in equatorial forest, the concentration of ozone which is lower than that of ammonia, grows by the year and becomes greater (Figure4c). This result shows that the equatorial forest is losing its ozone sinking power due to the human pressure through deforestation.

For the rest,no trend of interannual evolution of concentrations is observed. Nevertheless, there are years of significant concentrations and others of lower concentrations of gases(figure 4 (a-c)). Table 1 shows the mean, minimum and maximum concentrations values of each gas studied at the threesites. Analysis of thesevalues shows that ozone and nitric acid have negative gradients of concentration on the transect: drysavanna-wet savanna-equatorial forest.

The annual mean concentrations of gases (O_3 + NH_3 + NO_2 + SO_2 + HNO_3)load are 26.9, 16.04, and 10.78 ppb atBanizoumbou, Lamto and Zoetele respectively. These values show a negative gradient of total gases concentration along this transect ofmajor African ecosystems. The factors responsible for this negative gradient of gases concentration on the transect: dry savanna - wet savanna - equatorial forest would be likely the following:

- the negative gradient of aridity which favors the capture of acid gases (H_2SO_4, HNO_3) by large predominantly terrigenous particles especially during the dry season leading to the formation of aerosols. Carmichael et al. (1997) [46] and Dentener et al. (1996) [47] have inferred that desert particles can significantly influence the atmospheric cycles of trace gases, particularly in tropical areas;

- the positive gradient of vegetation density [48] which favors the emission of gases by senescence of the vegetation and biomass burning during the dry season but also their elimination by adsorption and absorption. Its effects increase when goying from North to South;
- the seasonal solar radiation gradient which favors the photochemical reactions from March to November in dry savanna and from December to February in wet savanna and equatorial forest and leading to the formation of secondary gaseous pollutants (HNO_3 SO_2, and O_3).
- the positive gradient of humidity [49] which promote the emission of nitrogen gases by nitrification and denitrification and also the emission of sulfur compounds through the development of phytoplankton and algae. Apparently, this may result in a greater accumulation of gases in wet savanna and forest, which are the wetter environments. But the leaching of the atmosphere by permanent precipitations in these ecosystems considerably reduces the gases concentrations by solublisation in the aqueous phase and their transformation into particulate species such as NH_4^+, NO_3^-, and SO_4^{2-}[28].
- the presence of an important animal population, especially in dry savanna promotes the emission of ammonia and NO_x by the decomposition of urea and animal excreta. This explains the high concentration of ammonia at Banizoumbou in dry savanna;
- during the West African Monsoon, the southwesterly wind could also carries a significant amount of gases produced in the South at wet savanna and equatorial forest and then increase their concentrations in dry savanna. Hao and Liu, 1994 [50] and Cooke et al., 1996 [51] have indicated that African fires have a well known seasonality with a northern fire belt in November–February and a southern fire belt in June–October.

3. 4. Impacts of the gases

The figure 5(a-c) expresses clearly the low concentration value of SO_2 (2.81-3.79%) and HNO_3 (2.12-2.28%). Although the concentrations of these gases are low, their environmental impacts are considerable.They are the main causes of rains, soils and surface waters acidity [40]. NO_2, SO_2, O_3 and HNO_3 also have an impact on the radiative balance of the atmosphere because they are able to absorb and diffuse the solar radiation or even to cause the formation of clouds when they are associated with other substances like terrigenous particles. Mineral dust populations can also affect indirectly cloud condensation nuclei populations through physical processes by altering gas-particle partitioning, or coagulating with existing cloud condensation nuclei (active particles)[52].
Other pollutants also have direct and indirect effects with a wide range of impacts on human health, ecosystems, agriculture and materials. For example, nitric acid (HNO_3) is an important transformation product of NO_x and has the potential to cause adverse respiratory effects through both acidification and oxidation reactions [53].NH_3, although involved in soil enrichment and neutralization of atmospheric acidity, deposition of nitrogen compounds contributes to eutrophisation. Depositions of large amounts of nitrogen also affect the viability of forests, can negatively affect crop quality, reduce biodiversity and contribute to surface and groundwater pollution [6].

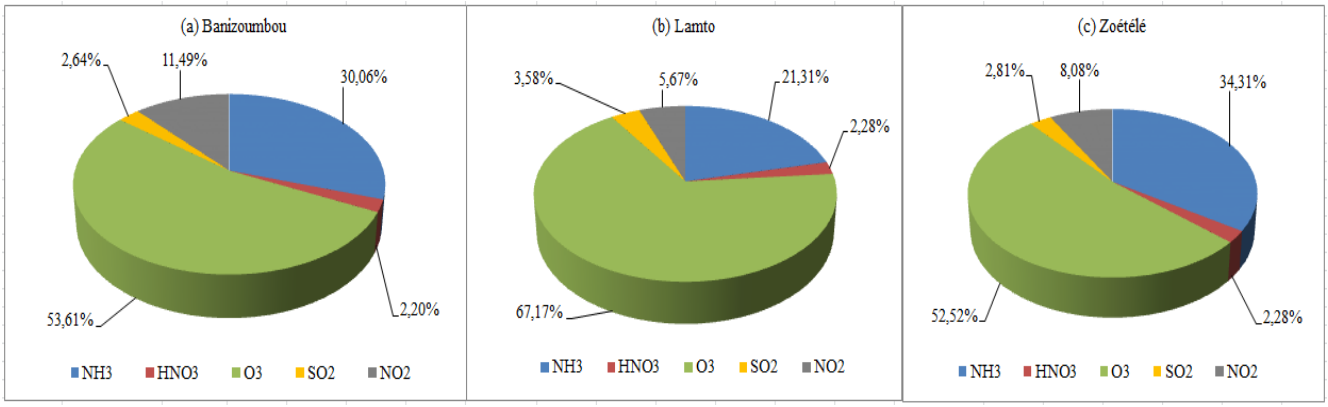

Figure 5 (a-c): Gas centesimal composition at INDAAF sitesstudied

3. 5. Estimation of gaseous dry deposition at Banizoumbou, Lamto and Zoetele

The dry deposition fluxes of NH_3, HNO_3, O_3, SO_2 and NO_2 are calculated on a seasonal and annual basis. These fluxes were estimated using the inferential method, that is, the product of the ambient concentrations of gases measured at a specific height and their dry deposition velocities for each site. The value of the dry deposit flow is calculated from the formula 2:

$$Ds = C_x . V_d \qquad (2)$$

$D_S$is the dry deposition of gas ($\mu g.m^{-2}.s^{-1}$),C_x the atmospheric concentration (monthly mean) of the measured gas ($\mu g.m^{-3}$) and$V_d$its dry deposition velocity ($m.s^{-1}$). Accordingly, the dry deposition of a gas is controlled by its concentration in ambient air and its dry deposition velocity. We will use the mean annual and seasonal dry deposition velocities of gases obtained by Adon et al., (2010)[11].

3. 5. 1. Estimation of annual mean dry deposition of gases at Banizoumbou, Lamto and Zoetele

The dry deposition of the gases on the three studied siteshas been influenced by the physicochemical characteristics and climatic conditions of each ecosystem, but also by the characteristics of each gas, which profoundly affect its dry deposition velocity. It should be reported that the annual meandry deposition velocity of gases is more importantwhenthe ecosystem is wet enough[11]. The annual mean dry depositions are given by the table 3.

Table 3: Annual average dry deposition of the gases at Banizoumbou, Lamto et Zoetele

dépôt ($Kg.ha^{-1}.year^{-1}$)	NH_3	HNO_3	O_3	SO_2	NO_2	Total
Banizoumbou	3.14	2.62	10.99	0.99	2.12	19.86
Lamto	3.82	3.47	19.34	1.99	1.51	30.13
Zoetele	6.81	4.39	12.27	1.72	1.65	26.84

This table shows the annual average deposits of each gas on the threesites staded and therefore the order of the total dry deposition magnitude of the five gases according to the ecosystems. Thus, dry gaseous depositions are greater in wet savanna, then in equatorial forest and less important in dry savanna. The dry deposits of gases is accentuated by the high deposition velocities of gases in forest and wet savanna[11].It is clearly observable that the largest total dry deposition at Lamto in wet savanna is due to the role of the tropical forests as major O_3 sink.

3. 5. 2. Seasonal average deposition of gases at Banizoumbou, Lamto and Zoetele

In the dry savanna, dry depositions of all gases are higher during the wet season than during the dry season. This situation is due to the fact of concentrations and dry deposition velocitiesof gases are high together during this period. For wet savanna and equatorial forest, although dry deposition velocities are higher during the wet season, dry deposition of all gases is less than 50% because of low gases concentrations during this period (Figure. 7 (a-c)).

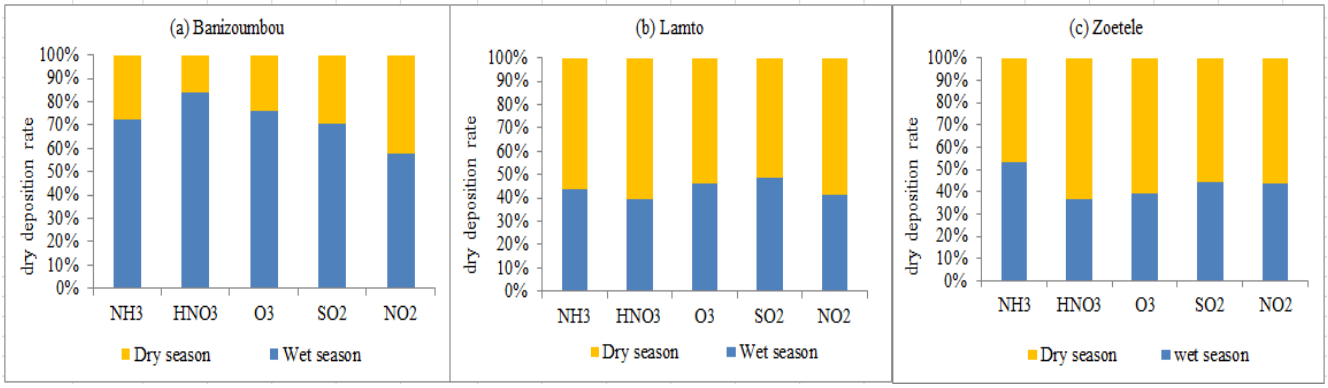

Figure:7 (a-c): Seasonal mean deposition of gases measured at the three INDAAF sites

4. Conclusion

The present study reportson measurementsof gases NH_3, HNO_3, O_3, SO_2 and NO_2at threeremote sites in West and Central Africa within the frameworkof the INDAAF network. The monthly, seasonal, and annual analysis of the concentrations of these gases allowed us to obtain the following results.

For all the gases measured, their seasonal concentrations were the highest in the dry savanna during the wet season. In contrary, these concentrations were higher in the wet savanna andequatorial forest during the dry season.

Higher concentrations of HNO_3 in the drysavanna during the wet season (0.7–1.05 ppb) can be explained by the increase in production of HNO_3 from gaseous precursors (NO_x)through photochemical activity.

The concentration of O_3 in the dry savanna duringthe wet season is 17.76 ppb (Banizoumbou) and 12.73 ppb in the wetsavanna during the dry season. Biogenicemissions likely are the main contributor to ozone

production,through the emission of NO_x as precursors during the wetseason in the dry savanna and by biomass burning during the dry season in the wet savanna.
At Zoetele, the lowest O_3concentrations measured (7.74 and 4.81 ppb)duringdryand wet seasonsrespectively indicate that tropical forestappears to be a major O_3 sink.In parallel, the analysis of annual mean concentrations of gases shows that the equatorial forest is losing its ozone sinking power because of human pressure.
For NH_3, the higher concentrations measured during the wet season over dry savanna 7.59 ppb is mainly related to the hydrolysis of urea fromanimal excreta deposited in grazing areas.
Annualaverage concentrations of gases in ppb are O_3 (11.09; 10.77; 5.66), NH_3 (6.22; 3.42; 3.70), NO_2 (2.38; 0.91; 0.87), SO_2 (0.55;0.57; 0.30), and HNO_3 (0.45; 0.37; 0.25) at Banizoumbou, Lamto andZoetele, respectively.
The INDAAF remote sites are not yet impacted by anthropogenic sources of gases and particlesbut an interaction between large ecosystems that is assured by the dynamic of the atmosphere through movement of air masses including Harmatan and monsoon.
Physicochemical processes, meteorological parameters,and therefor, gaseous concentrationvaluesand dry deposition velocities control the importance of gaseous dry depositions. The values of annual average dry deposition in $kg.ha^{-1}.yr^{-1}$ are: O_3 (10.99 ± 0.69, 19.34 ± 0.67, 12.27 ± 0.35), NH_3 (3.14 ± 0.14, 3.82 ± 0.15, 6.81 ± 0.16), HNO_3 (2.62 ± 0.18, 3.47 ± 0.18, 4.39 ± 0.24), NO_2 (2.12 ± 0.14, 1.51 ± 0.05, 1.65 ± 0.05), SO_2 (0.99 ± 0.05, 1.99 ± 0.09, 1.72 ± 0.05) in dry savanna, wet savanna and equatorial forest, respectively. Additional observations in the tropics with simultaneous measurements of gases, aerosols and precipitation chemistrywill allowanalyzing the temporal evolution of tropospheric chemistry linked to climate variability and anthropogenic actions on tropical ecosystems. This is our project through the INDAAF program for Africa to provide data on long term evolution trends, essential to identify the main factors that regulate the tropical atmospheric chemistry.

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