RESEARCH ARTICLE

SIMULATION OF THE TRANSPORT AND DISPERSION OF AIR POLLUTANTS IN THE CITY OF BAMAKO, MALI

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ARTICLE INFO

ABSTRACT

The current rapid deterioration of air quality in most cities can be attributed mainly to ongoing urbanization. This study simulates the dispersion of atmospheric pollutants in the city of Bamako using a HYSPLIT model, taking into account a case of total suspended particulate (TSP) emission in the environment assumed to be $180\mu g / m^3$ which exceeds two times the WHO standards. Wind climatology was established using the Wind Rose Plot (WRPlot) view. The predominant wind speed on the city is 2 to 6 knots (1 to 4 m / s) and the wind direction is southwesterly with varying seasonal direction. The forward trajectory of a released pollutant in the city is generally observed to move towards the west side of the city. It is observed that the pollutant is dispersed beyond 100 km of the city, which reduces the concentration in the city. The study recommends a consultative planning process of the city that influences the characteristics of the wind on the city. Most industrial activities should be located in the extreme south of the city in order to minimize the concentration of pollutants in the city. The study further recommends that research be conducted over a longer period to determine the quality of rainwater during the rainy season. This requires accurate observation and monitoring of pollution levels in the city and other cities in the country.

INTRODUCTION

Pollutant concentration and transport vary on spatial and temporal scales depending on pollutant sources, prevailing meteorological conditions and topographical features in the surrounding area (1, 2, 3, 4). Wind, precipitation, air temperature and relative humidity are of great importance for the transport and dispersion of pollutants from one locality to another. The effects of air pollution vary according to the nature of the pollutant and its exposure. According to a report by the World Health Organization WHO (1992), most respiratory and eye diseases are closely linked to air pollution (5). The vulnerability of those exposed to pollutants varies according to a number of factors, including exposure (6). WHO (2006) points out that the most vulnerable people are the elderly, the young and those with lung and heart disease (7). Although some air pollutants enter the atmosphere through natural events such as volcanic eruptions and wind erosion of soils, emissions associated with anthropogenic activities have become a concern in the recent past (8, 9, 10, 11).The World Health Organization (WHO) report of 25 March 2014 states that air pollution is now the leading environmental health risk worldwide with 4.3 million deaths in 2012 caused by indoor air pollution, compared to 3.7 million deaths in 2012 caused by outdoor air pollution (12). Anthropogenic activities are more prevalent in developed countries than in developing countries, and are mainly concentrated in industrial and urban areas. Air pollutants, mainly particulate matter (PM), sulphides (SOx) and nitrogen oxide (NOx), cause acid rain, which can damage ecosystems and man-made structures (13). Most air pollutants occur naturally in the atmosphere and are harmless at low concentrations. Rao (1991) pointed out that pollutants become harmful when their concentrations are relatively high compared with the background value (14). According to Andreae (2001), the radiative effect of atmospheric aerosols is thought to be of the same magnitude as that of greenhouse gases (15). Similarly, other aerosol components such as black carbon (BC) are known to have a warming effect on the global climate (16). According to Schneider et al (2009), around 50% of the world's population currently lives in urban areas, despite the fact that urban areas account for less than 1% of the earth's surface (17). Unfortunately,

most developing countries, particularly in Africa, do not have air quality monitoring systems in place despite the strong growth in urban populations and industrialization. In Bamako, as in many other cities around the world, vehicle emissions are one of the main sources of air pollution. A study in India by Gupta and Kumar (2006) showed that diesel engines make a significant contribution to particulate matter and chemicals that are harmful to human health; the same observations are made by Baltrenas (2014) (18, 19). Residents of Bamako are also threatened by emissions from landfills scattered throughout the city. Commercial and industrial activities are mainly concentrated in the center of the city, although it has now been decided to move them slightly to the south (the new Banankoro-Sanankoroba industrial zone). Bamako is an example of a city that does not have a continuous and reliable air quality monitoring system. Air pollution measurements are carried out on an ad hoc basis, mainly for research purposes.

Like many metropolises with strong demographic growth and galloping urbanization, environmental problems, particularly air quality, are increasingly perceptible in Bamako. An analysis of the situation suggests that the city's pollution is linked to three major sources of atmospheric pollution. These are motor traffic, whether due to engine emissions or street dust, the cooking of food with wood and charcoal, and the uncontrolled burning of waste. Furthermore, according to the Scienctific and Technical Journal of Mali (JSTM), researchers have indicated that the district of Bamako is one of the cities most polluted by gases such as NO_2, benzene, SO_2, CO_2 and particles PM2.5 and PM10 (20). According to the same newspaper, researchers at the University of Science, Technology and engineering of Bamako (USTTB) have studied air pollution in the city of Bamako. They found that the main cause of the deterioration in air quality is still two-wheeled vehicles, far ahead of cars. At the end of the study, published in the Malian Journal of Science et Technology in October 2014, there was an 8.5% increase in carbon oxide emissions compared with 2006. The cause, according to the researchers, is the growth in engines, estimated at more than 10% per year. The particularly high sulphur content of the fuel imported into Mali is also responsible for the deterioration of the air in our capital. Back in 2010, a study into air quality in Bamako sounded the alarm. According to the study, pollution from volatile organic compounds, particularly benzene, is a cause for concern. This pollution is largely due to two-stroke motorcycles. Benzene is a carcinogen, and according to the results of scientific studies on the subject, benzene causes a collective excess risk of around 249 cancers per year in Bamako. Without a scientific action plan, this excess could rise to 686 cancers by 2020 (21). Dust emissions are a major source of pollution in the city. The annual average concentration of PM10 particles has been estimated at 333 µg/m3, with daily peaks exceeding 600 $µg/m^3$, whereas the WHO's daily recommendation is 50 $µg/m^3$, which should not be exceeded for more than 3 days (22). This article simulates the possible distribution of atmospheric pollutants in the event of an accident and/or emission of pollutants from the city of Bamako, considering a total suspended particulate matter (TSP) case of 180 $µg/m^3$. This simulation of the transport and dispersion of gaseous and particulate pollutants is carried out using the HYSPLIT (HYbrid Single Particle Lagrangian Integrated Trajectory) model (25).

METHODOLOGY

Geographical location of the study area: Bamako is the political and administrative capital of Mali, with geographical coordinates of 12°38' north latitude and 7°59' west longitude (Figure 1). Situated on the banks of the River Niger, the city of Bamako is built in a basin surrounded by hills. It extends 22 km from west to east and 12 km from north to south, covering an area of 267 km^2. Bamako occupies the southernmost edge of the African Sahel, corresponding to the Sudanese zone. As a result, it enjoys a fairly humid tropical climate, with a total annual rainfall of 878 millimeters, but with a distinct dry and rainy season. The driest month does not receive a single drop of rain (0 mm in December), while the wettest month is very wet (234 mm in August). The regular summer rains allow savannah trees to grow and crops such as sorghum, maize and cotton to flourish. The city's predominant winds are monsoon and harmattan, blowing in opposite directions depending on the season. The year is subdivided into two seasons: the rainy season and the dry season, which manifests itself in two stages of thermal regime known as the hot dry season and the cold dry season. There is also a transition season between the dry and wet seasons. During the wet season, the monsoon winds blow from southwest to northeast, bringing rainfall from the Atlantic Ocean for around six months. During the cold dry season, the northeast or harmattan wind, which increases in speed from November to February, brings cold, dry air to the country, causing significant drops in temperature and transporting Saharan dust to the south of the country. The same phenomenon continues from March to mid-May, but with temperature inversion and a gradual decrease in wind speed due to increased solar irradiance over the Sahara, through which the air passes, and the displacement of the inter-tropical front. Table 1 summarizes the seasons throughout the year.

Table 1. Seasons and their duration in Bamako

Seasons	Months
Rainyseason	June-July-August (JJA)
Early dry season	September-October-November (SON)
Cold dry season	December-January-February (DJF)
Hot dry season	March-April-May (MAM)

Bamako's demographic growth is impressive. This uncontrolled growth is causing major problems in terms of traffic, hygiene (access to drinking water, sanitation) and pollution. Between 1998 and 2009, the population multiplied by almost 1.8, an average annual growth rate of 4.8%, to reach 3.5 million inhabitants at a density of 1,115 inhabitants per km^2 in 2016. This growth is essentially due to the rural exodus, administration and education. Most of the country's economic activities, such as trade, transport and industry, are more developed in Bamako than in other cities.

Wind Rose Plot view: Wind climatology was established using the Wind Rose Plot (WRPlot) view, taking into account hourly wind speed and direction for over 12 years; 2001- 2012. The software is a program that runs in the Windows environment on a PC to generate wind statistics and plots for a given weather station within a specified timeframe (Lakes Environmental, 2000) (23). It has a frequency number that displays the number of wind occurrences in tabular form in each of sixteen direction sectors and 6
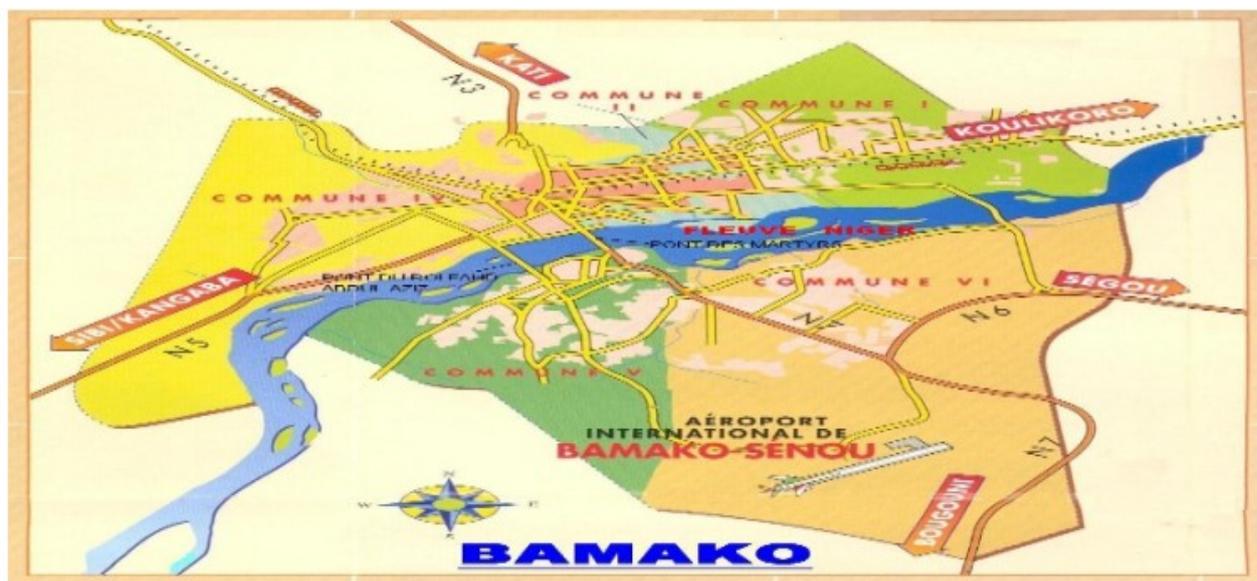

Figure 1. Bamako's city map (Source: MAT-Mali)

wind speed classes for a given location and time period. It also has a frequency distribution tab which gives a table displaying the frequency of wind occurrences in each compass direction and six wind speed classes (23).

The HYSPLIT model: Pollutant trajectories, concentration and distribution were performed using HYSPLIT, described in detail by Draxler and Rolph 2017 (24). HYSPLIT is a computer-based air pollution modeling package used for modeling and can provide an accurate representation of air pollution levels (25, 26). According to Draxler and Rolph (2017), the model calculates simple and complex air parcel trajectories and dispersion. The system also simulates pollutant deposition. In this case, a hybrid between Lagrangian and Eulerian approaches is used (24). Pollutant concentration is calculated on a fixed grid. The results of the simulation are complex profiles for the concentration of atmospheric pollutants. Calculations are performed on archival meteorological data from the Global Data Assimilation System (GDAS) operated by the US National Centers for Environmental Prediction (NCEP).GDAS is run four times a day; 00:00, 06:00, 12:00 and 18:00 Coordinated Universal Time (UTC). NCEP post-processing converts spectral coefficient shape data into 1 degree latitude-longitude grids (360 by 181) and sigma levels to mandatory pressure levels (24).

The model output is in GRIB (GRidded Information in Binary) format. The data finally archived is in synoptic order and has no missing records. It is therefore possible to position any location in a data file without order. Air circulation diagrams determine the transport and dilution of atmospheric pollutants. The representation dates for each season were chosen according to the corresponding wind frequency patterns calculated using wind roses. Table 1 shows the four climatic seasons over the city of Bamako. Pollutant concentrations are calculated on a fixed network. The results of the simulation output are complex air concentration contour models. Calculations are performed on archival GDAS (Global Data Assimilation System) meteorological data of 1 degree resolution. Simulation dates must be representative of the seasons of the year. Table 1 shows the simulation dates deemed representative of the city's different seasons. The dates of the representative seasons should be chosen on the fifteenth day of the second month of the season (27).

Table 2. Representative simulation dates for the seasons

Season	Representative dates
Early dry season	Novemberfrom15 to 16, 2016
Cold dry season	Januaryfrom15 to 16, 2017
Hot Dry Season	April from 15 to 16, 2016
Rainyseason August	August from15 to 16, 2016

RESULTS AND DISCUSSION

Wind diagrams: The dominant wind over the city is the Harmattan, with a northeast-southeast direction from November to May in the dry season, and the Monsoon in the rainy season, with a south-southwest direction from mid-May to October. Figure 2 shows the wind rose frequencies representing the four defined seasonal periods of 2016, displaying wind speed and direction

during each of the seasons defined above. During the warm dry season (March-April-May), the prevailing wind is from the north-east, but of low average intensity (Figure 2-a), with pollutants dispersing in almost all directions.

In the rainy season, strong to moderate south-westerly winds tend to direct pollutants towards the north-east (Figure 2-b). At the end of the rainy season and the start of the cold season (September-October-November), coinciding with a transition period between the rainy season and the cold season, northeasterly and southwesterly winds blow intermittently, with a tendency towards the former as time progresses (Figure 2-c).

This tendency disperses pollutants to the south of the city. During the cold dry season, the prevailing wind is the harmattan, which disperses pollutants southward (Figure 2-d).
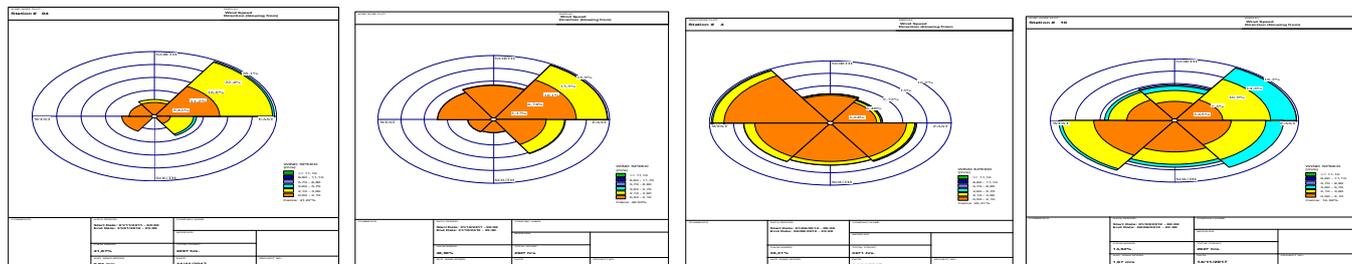

Figure 2. Frequencies of seasonal wind roses for (a) March-April-May (b) June-July-August (c) September-October-November (d) December-January-February.

Table 3. Seasonal wind climatology observed in Bamako

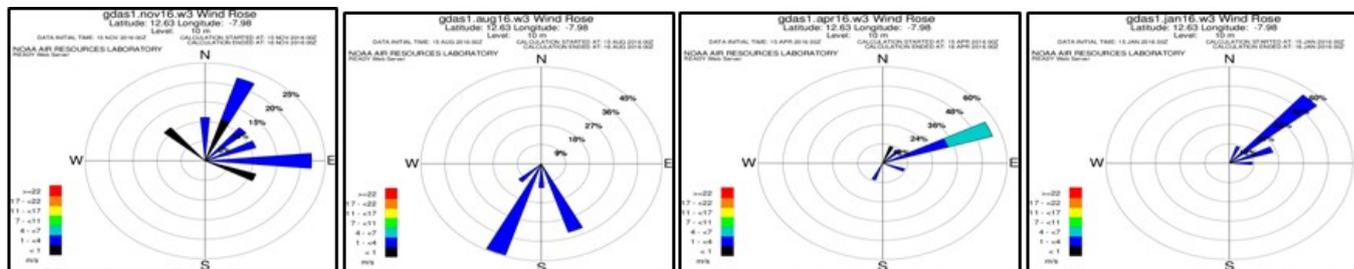| Season	Wind direction (Frequency)	Wind speed (m/s)
Early dry season	East-North-East (ENE)	2.10- 3.8
Cold dry season	East-North-East (ENE)	2.60- 4.0
Warm dry season	East-North-East (ENE)	3.60–5.70
Rainyseason	West-South-West (WSW)	1.0– 4.0

Figure 3. Wind diagrams for: (a) January 15, 2016; (b) April 15, 2016 (c) August 15, 2016; (d) November 15, 2016

Wind speeds also vary from 4 to 10 knots, consistent with the wind climatology (Table 1). Figure 1 shows the wind roses calculated from the grid model data for Bamako in the meteorological model domain. The four wind roses show that the pollutant introduced into the atmosphere over the city is transported and dispersed to the southwest and northwest of the city. Wind speeds over the city range from 4 to 11 knots. However, most studies indicate that urbanization is likely to reduce wind speeds over cities (e.g., Ongoma et al., 2013; Shepherd, 2005) (28, 29). This poses a threat to the future of air quality over cities. . Table 2 shows the wind speed and direction calculated by HYSPLIT on the simulation dates. The model predictions are in full agreement with the WRPLOT view.

Table 4. Seasonal representation of wind speed and direction by HYSPLIT over Bamako in 2013

Season	Wind direction (Frequency)	Wind speed (m/s)
Early dry season	East-North-East (ENE)	1- 4
Cold dry season	East-North-East (ENE)	1- 4
Warm dry season	East-North-East (ENE)	4 - 7
Rainyseason	West-South-West (OSW)	1 - 4

Wind meteorologicalfields: The meteorological fields over the study area show the different variations in wind direction over the city. Figure 3 shows the meteorological wind fields over the study area, plotted by the HYSPLIT model on simulation dates.
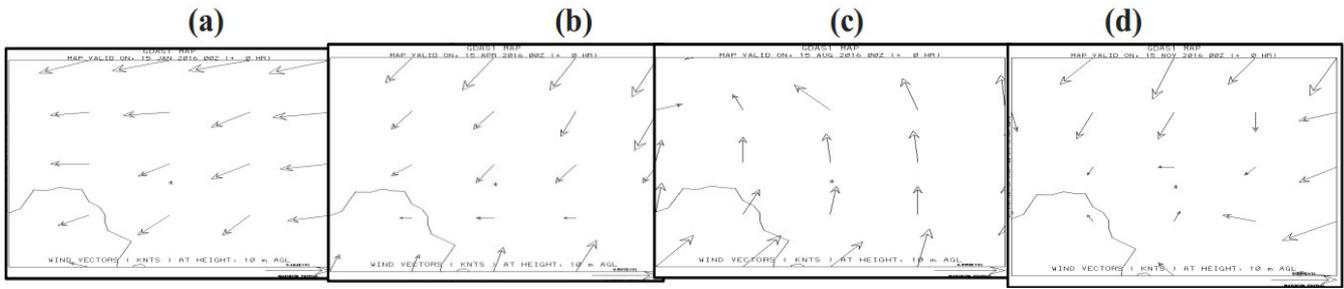
Figure 4. Meteorological wind fields over Bamako by HYSPLIT for simulation dates: (a) January 15, 2016, (b) April 15, 2016, (c) August 15, 2016 and (d) November 15, 2016

Trajectories: The trajectories for the respective seasons are shown in Figures 3a, 3b, 3c and 3d. The transfer of pollutants emitted over the city is generally observed on the western side of the city, with the exception of the rainy season, during which the flow in the city is directed to the north and northeast.
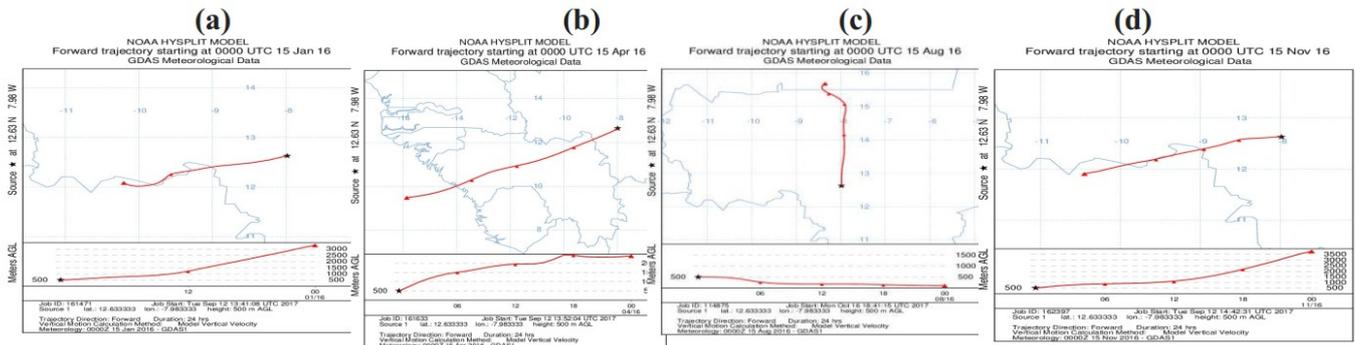

Figure 5. 24-hour trajectories of pollutant-laden air masses starting at 00:00 for: (a) January 15, 2016; (b) April 15, 2016 (c) August 15, 2016; (d) November 15, 2016

Concentrations: Simulation of pollutant concentration and dispersion was carried out taking into account a case of TSP (Total Suspended Particulates). Pollution levels were assumed to be high in relation to the average value recommended by the WHO. The average value of 90 μg/m^3 recommended by the WHO is exceeded by more than a factor of 2. The amount of pollutants was 180 μg/m^3 from 00:00 UTC for a duration of 1 hour. The average integration period of the pollutants was 1 hour. The dry deposition rate was 0.01 cm / s, while the clearance height was 10 m. The pollutant is transported beyond 100 m throughout the year (Figure 4). Figure 4 shows pollutant dispersion, while Table 3 summarizes the results. In line with the cold season trajectories (Fig.3), pollutants are dispersed in a north-easterly direction.
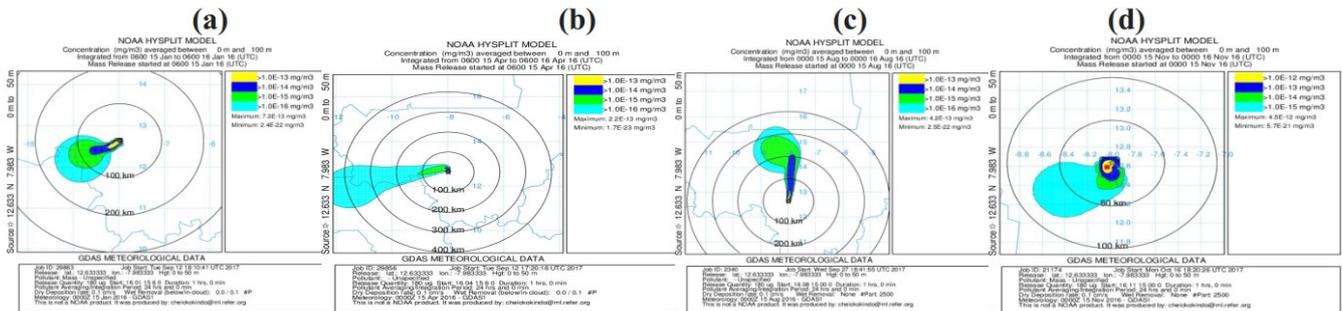

Figure 6. Pollutant concentrations: (a) January 15, 2016; (b) April 15, 2016 (c) August 15, 2016; (d) November 15, 2016

Table 5. Pollutant dispersion and concentration simulations

Season	Centerline concentration (in mg / m3) at ground level downwind at various distances.					
	10 km	20km	30km	40km	50 km	60km
Early dry season	1×10^{-13}	1×10^{-13}	1×10^{-13}	1×10^{-13}	1×10^{-14}	1×10^{-13}
Mid-dry season	1×10^{-13}	1×10^{-13}	1×10^{-13}	1×10^{-14}	1×10^{-14}	1×10^{-14}
Hot season	1×10^{-14}	1×10^{-14}	1×10^{-14}	1×10^{-14}	1×10^{-14}	1×10^{-16}
Rainyseason	1×10^{-13}	1×10^{-13}	1×10^{-14}	1×10^{-13}	1×10^{-13}	1×10^{-14}

Deposit: Wet deposition due to precipitation during the rainy season is likely to reduce atmospheric pollutants in the locality (30). However, rainwater that is collected by a very large number of households for consumption presents a great health risk due to the dissolution of certain pollutants. Quality control of this water is therefore recommended before authorizing its consumption by the population.
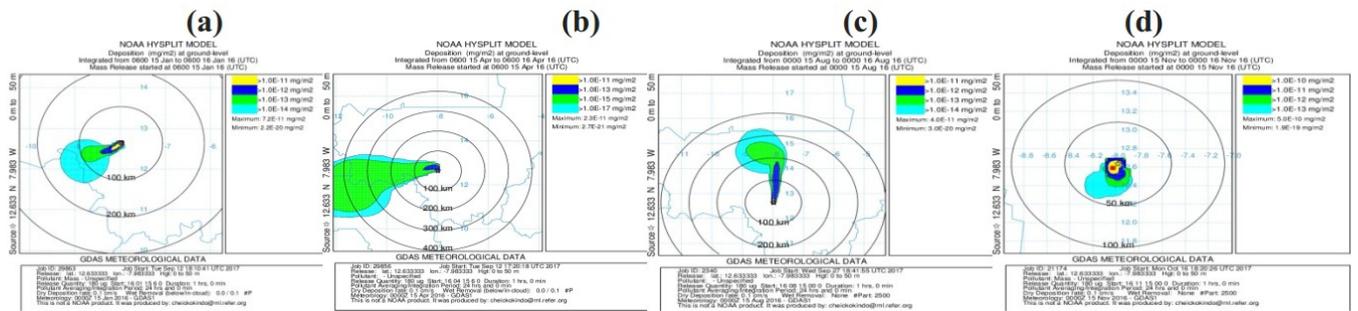
Figure 7. Deposits for the dates (a) January 15, 2016; (b) April 15, 2016 (c) August 15, 2016; (d) November 15, 2016

Particle position: The position of particles is calculated at least 24 hours after the emission of gaseous precursors into the atmosphere. In addition, particles are formed by gas-particle transformation a little further away from the source of emission of the gaseous pollutants carried by the wind (24).
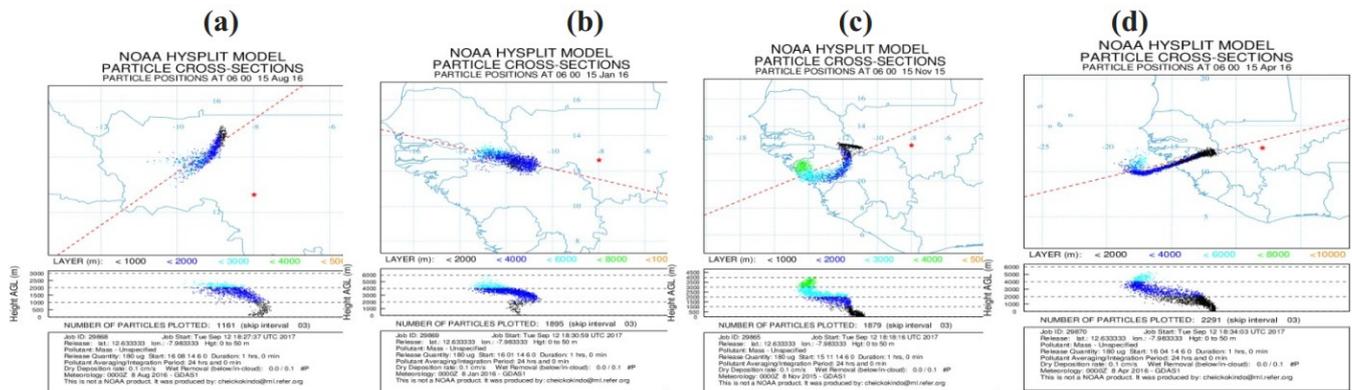

Figure 8. Particle positions on dates (a) January 15, 2016; (b) April 15, 2016 (c) August 15, 2016; (d) November 15, 2016

CONCLUSION

The prevailing winds in the city of Bamako are mainly from the north-east, which means that pollutants will be transported mainly to the south-west of the city. Trajectories generally show a south-westerly flow of pollutants emitted in the city throughout the year, except in the middle of the rainy season due to the monsoon season. Pollutants are dispersed over 100 km in less than an hour, with the least dispersion during the rainy season. However, interactions between different spatial and temporal scales play a major role in determining the flow pattern over the urban rooftop in a densely built-up environment. Intense surface inhomogeneities also generate intense temporal inhomogeneities, requiring specific spatial and temporal monitoring of pollutant concentration and flow. Particle deposition and position were assessed to take into account the case of wet deposition during the rainy season, and the gas-particle transformation process. The study therefore recommends a consultative city planning process that explains the wind characteristics observed over the city.

For example, most industrial activities should be located to the extreme south or south-west of the city to minimize the concentration of pollutants in the city.The study also recommends that more research, particularly over a longer period, be carried out to determine the concentration of pollutants and the quality of rainwater during the rainy season. This requires accurate observation and monitoring of pollution levels in Bamako and other cities across the country. With a young population particularly sensitive to the effects of pollution, our country is characterized by respiratory diseases, notably tuberculosis. As a solution, we recommend acquiring a laboratory, reinforcing legislation and standardization, and raising public awareness. In addition, professional drivers should be trained to drive minibuses and cabs economically, in order to reduce fuel consumption and the corresponding pollutant emissions, and dirt roads should be surfaced to reduce particulate levels, which account for 40% of district emissions. Other recommendations include improving traffic flow in the city and developing the use of improved fireplaces, as well as creating a waste treatment center to reduce individual burning (sorting, composting, burying certain types of waste and incineration with energy recovery).

ACKNOWLEDGMENT

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