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RESEARCH ARTICLE

SIMULATION OF THE AEROSOL DEPOSITION OF BIOMASS FIRES IN THE BAOULÉ LOOP IN MALI USING HYSPLIT

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ABSTRACT

In this study, the HYbrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model is used to simulate the deposition of $PM_{2.5}$ aerosol particles emitted by biomass fires in the Baoulé loop, from the locality of Neguela in Mali. This simulation is done through the calculation and the analysis of backward trajectories maps in height configuration for the attribution of the sources as well as the deposition maps. The sources are located along the backward trajectoires. The activities of biomass fires in the zone are observed mainly in the dry season with maximum frequency at the end of the dry season and early wintering. This period is also a period of dry deposition of $PM_{2.5}$ particles. The end of the dry season and early wintering is the period of burning of growing spaces. This practice has a positive aspect in the case of a supply of phosphate, nitrogenous and potash nutrients. At the end of the dry season, the backward trajectoires show the origin of the particles emitted by the bush fires of Guinea, the Ivory Coast and the surroundings of Néguéla. In dry seasons, dust storms bring $PM_{2.5}$ particles from the North. In winter, air masses are transported south and south-west from the Atlantic Ocean. This promotes precipitation, which in turn results in the wet deposition of $PM_{2.5}$ particles that are removed from the atmosphere. During the rainy season, there is no major emission of particles except those of domestic combustion. Deposition calculations by HYSPLIT model are in good agreement with in situ measurements

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INTRODUCTION

Biomass fires and mineral dusts are important sources of atmospheric airborne particulate matter known as aerosols and are present for at least several hours (Doumbia, 2012). Aerosols from biomass fires are considered particulate matter (Particulate Matter) and are characterized by their size or diameter which is less than 2.5 μm, hence the name $PM_{2.5}$ (Wen Kuoa, 2010). The chemical composition and concentration of these aerosols are dependent on geographical location and weather conditions (Diarra, 2014). To improve knowledge of these types of aerosols, several methods of study and observations such as in situ measurements, remote sensing from the ground or from space and modeling are used (Bencharif-Madani *et al*., 2015).

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Biomass fires in sub-Saharan Africa are most often considered as harmful to the environment (Devineau *et al*., 2010; Kanvaly *et al*., 2011). Uncontrolled fires can also induce a loss of plant biomass (Toriyama *et al*., 2014). In tropical savannas in particular, iterative fire has been shown to have a detrimental effect on the sustainability of ecological resources and services (Sawadogo, 2011). Fires expose the soil to erosion and increase the atmospheric load of greenhouse gases and pollutants of all kinds (Vieira *et al*., 2015). However, it is now proven that these same fires participate, in these tropical spaces, in the structuring of savanna vegetation (Ghebrehiwot *et al*., 2011). Far from being random, these fires are even integrated into the rhythm of the social and cultural life of the populations (Sow *et al*., 2013; Kamau, 2014). Although biomass fires have negative climatic and health impacts, they may have positive impacts on agriculture in the case of nitrate and phosphate nutrient inputs (Cometta, 2014). Potassium is found in wood ash, which may also contain heavy metals, or radionuclides in some areas (http://creativecommons.org/licenses/by-sa/3.0/deed.fr). Indeed, fires regulate in time and space the production and availability of plant biomass, a basic resource for human and wildlife needs and populations (Bareremna, 2010 ; Kwon *et al*., 2013; Kamau, 2014). In the West African region, the concentration of smoke particles is increased by the transport of mineral dust by the wind in the dry season (El Hadj Thierno Doumbia, 2012). In the Baoulé loop, Prihodko *et al*., 2012 in studies based on in situ measurements revealed the presence of levoglucosan, two types of gas (NO2 and NH4) and $PM_{2.5}$ particles whose analyzes of their Chemical compositions have shown the presence of some carbohydrates, nitrogenous and phosphatic substances (PO4, NO2, NH4, NH3) and calcium (Ca) (Prihodko Lara, 2012). Levoglucosan ($C_6H_{10}O_5$) is used as a chemical tracer for the combustion of any fraction of biomass when it comes to studying the chemical composition of the atmosphere, in particular its PM2.5 particulate matter content in suspension (Aiken *et al*., 2010). Like other tracers such as potassium, oxalate and methyl cyanide in gaseous form, the levoglucosan level has been found to be very strongly correlated with the presence of plant fires, since the gases resulting from pyrolysis wood contains levoglucosan in a significant amount (Kehrwald *et al*., 2012). Calcium is on the other hand considered a tracer of mineral substance like the Saharan dust. Thus, these studies proved a Saharan provenance of some $PM_{2.5}$ particles in the Baoulé loop during the dry season (Prihodko Lara, 2012).

Numerical modeling of transport, deposit dispersion and chemical transformation of aerosols from biomass fires has contributed significantly to improving knowledge of their global properties (Malavelle, 2001). Several models have been developed for this purpose, including HYBRID Single Particle Lagrangian Integrated Trajectory, which is one of the most widely used models for the study and observation of atmospheric aerosol dispersion (Stein *et al*., 2015). One of the most common HYSPLIT model applications is backward trajectory analysis to determine the origin of particle-laden air masses in order to establish source-particle receptor relationships (Draxler, 1998). In this work, for the first time, this application of the HYSPLIT model is used to locate the biomass fires in the Baoulé loop in Mali by calculating and analysing the backward trajectories maps and the $PM_{2.5}$ particles deposits on the Néguèla site.The analysis of the retrotrajectoires makes it possible to know the source of origin of the particles whose deposits are measured by the instruments deployed on the site (Prihodko Lara, 2012). The results of model deposits will be compared to in situ measurements.

MATERIALS AND METHODS

Study area: The Baoulé Loop is a Sudano-Guinean climate and vegetation zone where a classified forest has been erected and where the locality of Néguéla (12.86 ° North, 8.45 ° West) is located 50 km north-east. west of Bamako. LOSSA measuring equipment is installed on the site of this locality. Figure 1 gives a map of the extraction domains of the meteorological data files constituting the input of the HYSPLIT model including the study area. The Global Data Assimilation System (GDAS) data files extract on a first domain D1 between -20° and 20° longitude and 5° to 35° latitude and a second D2 between -20° to 5° longitude and 5° to 28° of latitude to better simulate the evolution of particles. The Boule loop is a classified forest area where the town of Neguela is located. GDAS files consist of U and V wind speed fields, T temperature and precipitation rate.

HYSPLIT contains scripts that allow from these basic fields to calculate the other meteorological quantities along the trajectories such as the relative and specific humidity, the pressure, the height of the relief relative to the level of the sea and the solar radiation (Draxler, 1997). The Meteorological data files covering the study area shown in Figure1 can be downloaded from the website www.arl.noaa.gov/HYSPLIT.php and reformatted in GRidded Information in Binary (GRIB) format (Draxler, 2018). The data used in this work is from the NCEP GDAS archive database of 1° resolution from 2006 to the last seven days of the current year. The data downloaded for the simulations are from February 2011 to January 2012 according to the measurement period. Most biomass fires in the study area are of anthropogenic origin, such as bush fires accidentally caused by peasants or as part of transportation, among others. There are other anthropogenic activities such as coal production and domestic combustion that are likely to increase the concentrations of $PM_{2.5}$ particles in the atmosphere (Figure 2).

HYSPLIT model description: HYBRID Single Particle Lagrangian Integrated Trajectory (HYSPLIT) is a complete system for calculating simple air mass trajectories as well as complex simulations of transport, dispersion, chemical transformation and deposition of gaseous or particulate pollutants. HYSPLIT continues to be one of the most widely used atmospheric transport and dispersion models in the atmospheric science community (Stein *et al*., 2015). The model calculation method is an hybrid between the Eulerian approaches (the concentrations are calculated for each cell of the grid using the integration of pollutant flows at each cell interface of the grid due to advection and diffusion) and Lagrangian (concentrations are calculated by adding the contribution of each pollutant "puff" that undergoes advection through the cell of the grid represented by its trajectory). The advection and diffusion calculations are performed in a Lagrangian setting while the concentrations are calculated on a fixed grid. HYSPLIT has evolved for more than 30 years, from the estimation of simplified simple trajectories based on radiosonde observations to a system that takes into account the multiple interacting pollutants transported, dispersed and deposited on local to global scales (Draxler, 1998).

The model uses meteorological data on one of three conforming map projections (Polar, Lambert and Mercator) (Ghebrehiwot *et al*., 2011). The dispersion model requires meteorological data fields that can be obtained from outputs of the archive or forecast models, and the data must be formatted for HYSPLIT model input (Stein *et al*., 2015). In addition, the internal structure of the model has an internal coordinate interpolation system that gives it the ability to use different sources of meteorological data and adapt them to its internal grid. Using the BlueSky module incorporated in the HYSPLIT model, multiple $PM_{2.5}$ species concentrations for biomass fires can be calculated A more detailed description of the HYSPLIT model can be found in Draxler and Hess1997, 1998 and Stein *et al*., 2015 (Draxler, 1997). The current version of the HYSPLIT model (version 4.9) is a computer application with a graphical user interface (GUI) pre-installable on the chosen system, (Draxler, 2018). The software is accompanied by scripts often in C code for the pre-processing of meteorological data and the post processing of the output results. These are the accompanying software for the proper operation of the model, others are optional that can be installed if necessary. The model is available in PC version under Windows, Linux or

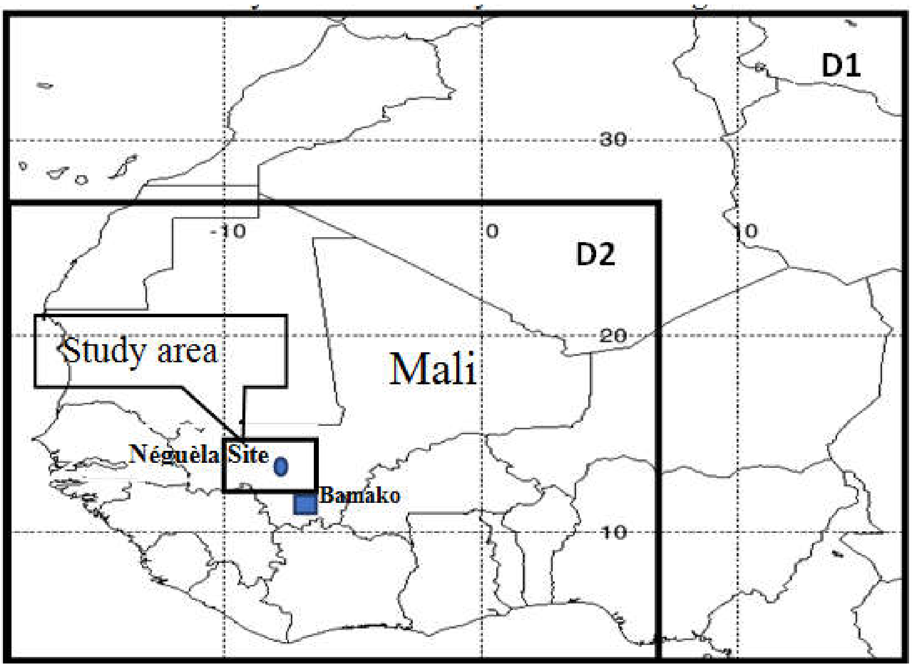

Figure 1. Study area and GDAS data extraction domains on the sitewww.noaa.gov/READY

Figure 2. Photos from left to right: a case of a forest fire, a burn of fields, a coal production site and a case of domestic combustion in the study area

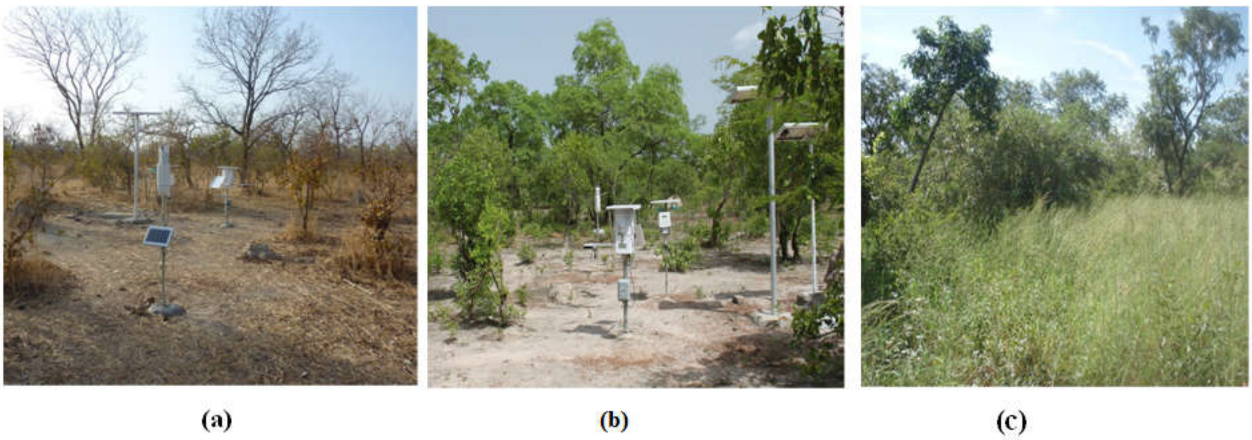

Figure 3. Photos of the Neguèla site in Mali with the instruments deployed: dry season (a) February, and wet season (b) June and August (c)

MAC and web version. The Web version has been configured with some limitations to avoid the computational saturation of the ARL web server (Stein *et al*., 2015). The PC version with registration is complete without calculation restriction, except that users must obtain their own meteorological data files. The version obtained without registration is identical to the registered version, except that the plume concentrations cannot be calculated with the forecast meteorological data files.

The trajectory model only has no restrictions and the prediction or archival trajectories can be calculated with either version (Draxler, 1997). The web version and the Windows PC version were used in this study.

Equations of the trajectory and deposition model: To calculate the average trajectory of the particles, we follow a single particle (Draxler, 1998).

The advection of this particle from time t to time t + Δt (in hours) is calculated from the average of the three-dimensional velocity vectors from the initial position P (t) to the final position P (t + Δt) passing through a first position P '(t + Δt). Mean velocity vectors (V) are interpolated linearly in space and time. The first approximation position is:

$$P'(t + \Delta t) = P(t) + V(P, t)\Delta t, \tag{1}$$

and the integrated end position as follows:

$$P(t + \Delta t) = P(t) + 0.5[V(P, t) + V(P', t + \Delta t)]\Delta t, \tag{2}$$

The time step of the integration (Δt) can vary during the simulation. It is calculated from the requirement that the advection distance per time step should be less than the grid spacing. The speed of maximum particle transport is determined from the maximum transport speed U_{max} during the previous hour(24). The time steps can vary from 1 minute to 1 hour and are calculated from the relation,

$$U_{max}\,(\text{grid unit}.\,min^{-1})\Delta t(min) < 0.75\ (\text{grid unit}). \tag{3}$$

Following the horizontal direction of the grid, the integration of the position vector is done in grid units, while in its vertical direction a standardized sigma coordinate system is used for integration (Draxler *et al*., 1998). The equation of this sigma coordinate system is:

$$\sigma = \frac{Z_{top} - Z_{msl}}{Z_{top} - Zt_{gl}}, \tag{4}$$

where $Z_{ms}l$ is the height from the mean sea level to convert to sigma, Z_{gl} is the height from ground level and Z_{top} defines the height of scale of the top of the model, the height at which the internal sigma surfaces flattens out from the ground (25). The internal scaling height is set to 25 km. This value is used with the default model setting of 10 km for most Planetary Boundary Layer Height (PBLH) applications in the model configuration file called CONTROL that defines the vertical boundary of the internal weather grid. The other configuration file of the model is called SETUP which makes it possible to draw a trajectory by time interval (Stein *et al*., 2015). The deposition of the particles is calculated by considering the two cases of atmospheric aerosol deposition. In the case of dry deposition, the particles are removed from the atmosphere by falling under their own weight. To conFigure the simulation of particle deposition, it is necessary to define their characteristics. The dry deposition rate of the particle is calculated by assuming that it has a spherical shape of diameter (d_p) and density (ρ_g) by the relation:

$$V_g = d_p^2 g(\rho_g - \rho)(18\ \mu)^{-1} \tag{5}$$

where (ρ) is the density of the air and (μ) the dynamic viscosity of the air. The wet deposition of particles is divided into two processes in which the particles become nuclei of condensation of the cloud from a boundary layer and in the one where the falling rain intercepts and drives the layer of particles (Stein *et al*., 2015). The leaching equations of the atmospheric particles have been simplified with the new versions of HYSPLIT. The wet deposition rate is defined as a scanning coefficient expressed as a constant (β) modifiable by the precipitation rate P (in mm / h) and which is given by the relation (Draxler, 1998):

$$\beta_{....} = 8.10^{-5}(P)^{0.79} \tag{6}$$

The in-situ measurements: In situ measurements were made by Prihodko *et al*., 2012 in previous studies at the Néguéla site. Site facilities consist of a weather station and $PM_{2.5}$ particle sensors for measuring wet and dry deposition (Prihodko Lara, 2012). Figure 3 shows the photos of equipment in the dry season (Figure 3-a) and wet season (Figure 3-b and 3-c). The data from the meteorological station make it possible to determine the climatic situation of the study area and the conditions of use of this zone. The measurements extend from February 28, 2011 to January 31, 2012 have identified the two seasons of the zone. The season has been subdivided into three stages and the rainy season defines four seasons represented by dates from which HYSPLIT is configured to compute and display trajectory and dispersal maps (Victor Ongoma1, 2014). Thus, the beginning of the dry season (BDS) was defined in early November, the end of the dry season (EDS) corresponding to mid-April and the mid-dry season starting from January (MDS). Therainy seasonorwintering (RSW) settles from mid-May is defined second. These periods make it possible to define four representative dates of different seasons.

Configuration of the HYSPLIT model: After the installation of the software, the representative dates of the seasons are defined according to the climatology of the study area (Draxler, 2018). Four dates are defined for this purpose for different seasons and according to the peak concentrations found in the in-situ measurements. These peaks are due to the climatology and weather conditions of the area. These four dates are: the end of the dry season or the beginning of wintering (EDS), the rainy or wintering season (RWS), the mid-dry season (MDS) and the beginning of the dry season (BDS). The geographical coordinates of the Néguéla site and the height of the atmospheric column are configured in sequence through its model graphical user interface (GUI). The configuration ends with the selection of the meteorological data corresponding to each season (Table 1).

RESULTS AND DISCUSSION

Backward trajectories: Figure 4 shows backward trajectories for the four seasonal periods defined above configured using the first case of variation in height. The trajectories of the end of the dry season show several source zones (Figure 4-a). The particles located between 1000 and 1500m above the Neguela site come from north-eastern Mali via northern Burkina Faso and the Ivory Coast. As for the particles of height between 0 and 500 m, they have rather a provenance close to Néguéla and going up to the cotes of Guinea and Sierra Leone while crossing the forest. According to the shape of these backward trajectories, at the approach of the rainy season, $PM_{2.5}$ particles simulated by the model come from Guinea, northern Ivory Coast, southern Sahelian central Mali and around the site of Neguela. It is a period of biomass burning as evoked in Lara *et al*, 2012 because the concentration of levoglucosan and other tracer gases are peaks (18). This is the period of burning brush, an activity conducted by the population for agricultural purposes.

Table 1. Dates and meteorological data files configured in the Hysplit model to simulate the transport and dispersion of $PM_{2.5}$ at the Neguela site

Saisons	EDS	RWS	BDS	MDS
Dates simulées	15 au 17 /04/2011	15 au 17 Aout 2011	06 au 08 Novembre2011	26 au 28 Janvier 2012
Données météo	extract_gdas_24288w3.bin	extract_24347w3.bin	extract_gdas_24372.bin	extract_gdas_24368w4.bin

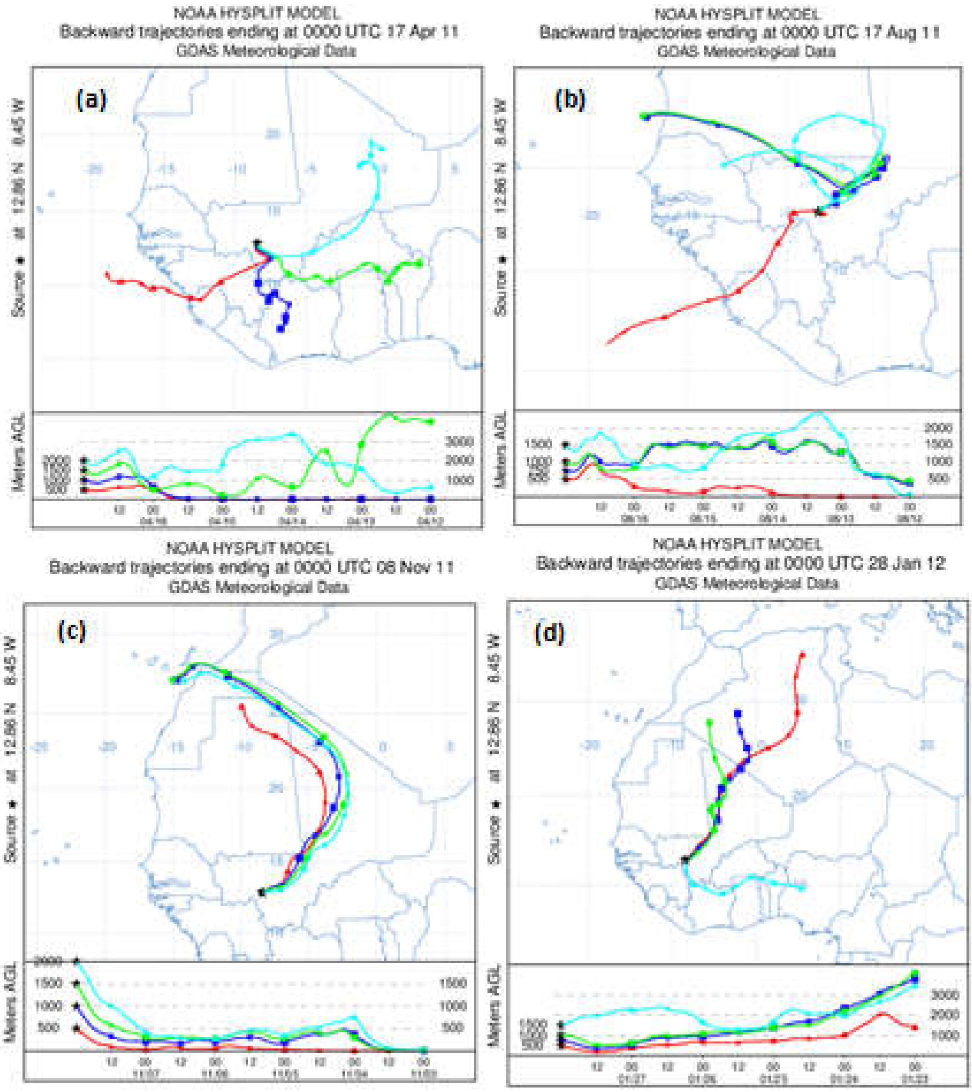

Figure 4.Three days HYSPLIT backward trajectories in Néguéla endpoint heights, (a) April 17, 2011 at 00H, (b) August 17, 2011, (c) November 08, 2011 and (d) January 28, 2012

The backward trajectories of the wet season show that the air masses from 0 to 800m high above ground level and all have the same transport route that is to say a source area located to the southwest of Néguèla (Figure 4-b). There is no biomass burn at this time, although ground-collected samples from the site analysed by Prihodko *et al*., 2012 show an increase in levoglucosan concentration in soil samples. The rainy season is a period of wet deposition of aerosol particles and leaching of the atmosphere. With the presence of the monsoon, particles are transported from the ocean to the land masses, in most cases marine aerosols (Ambre Demoisson, 2014). The trajectories of the beginning of the dry season (Figure 4-c) show source areas located northeast of Neguela. Deposition measurements in the samples collected at the site show a peak in the concentration of levoglucosan and other carbohydrates, indicating a biomass burning, as well as a peak in calcium and phosphorus concentrations, indicating a source of dust. The dry mid-season trajectories (Figure 4-d) show a transport path farther north. The measurements of the deposition samples indicate a biomass combustion. This period is the season of north-easterly winds (harmattan) that blow almost constantly and carrying a large amount of dust mixed with fires from the Sahel.

Depositions: Particle deposition is either wet deposition in winter and dry deposition in dry seasons. The calculation of the deposits requires an additional calibration of the model for it to take into account in the calculation of the concentrations. The deposit is the most important at the approach of the rainy season, we note all around the Neguela area a deposit greater than 30µg/m^2 (Figure 5-a). This is due to biomass fires. On the other hand, in the rainy season, the deposition is lower by the quasi absence of particle (Figure 5-b). The deposit is a little more than 1µg/m^2 in this period.

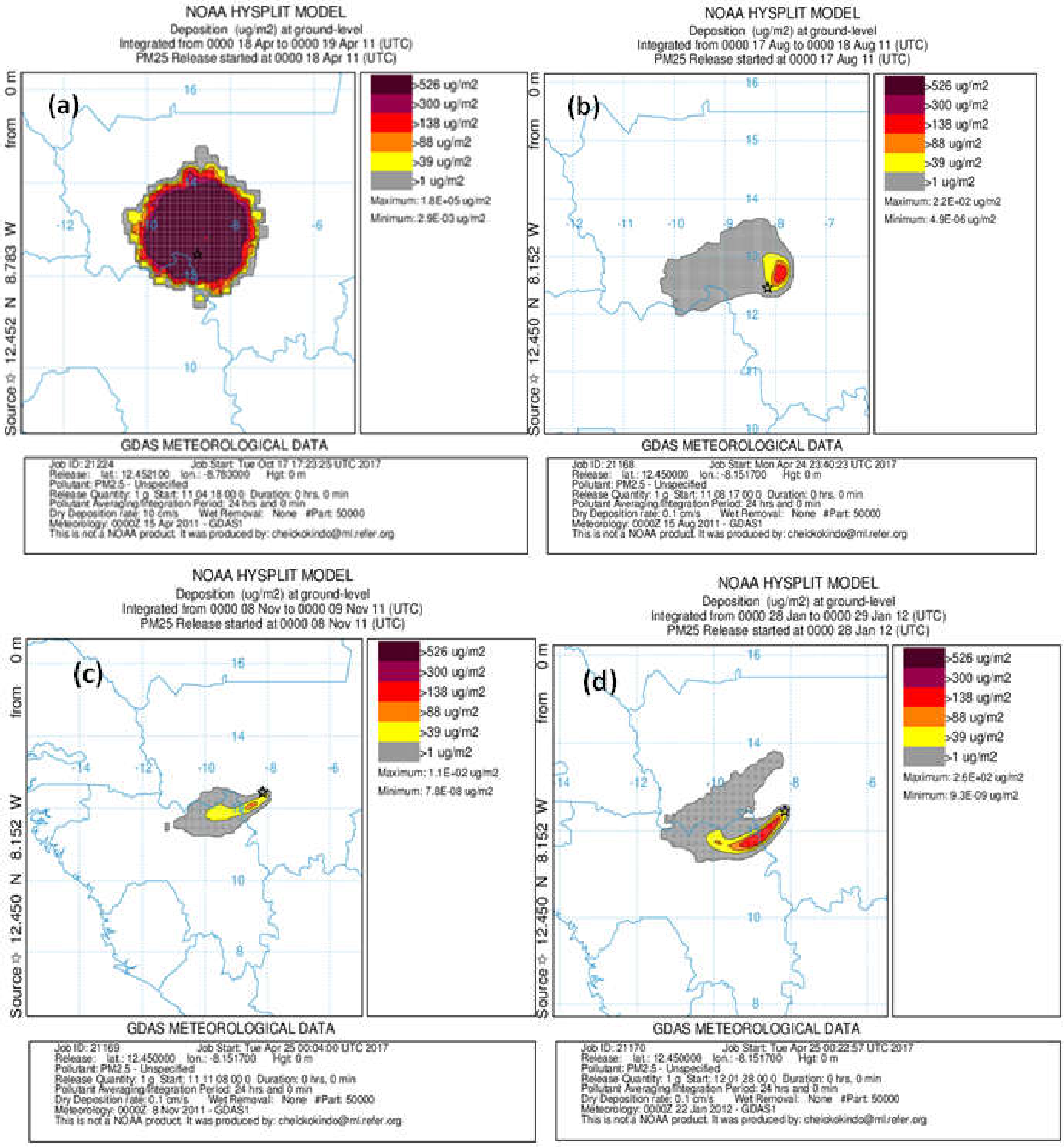

Figure 4. Simulated $PM_{2.5}$ particle deposition over 24 hours (a) from 18 to 19 April 2011 (b) from 17 to 18 August 2011 (c) from 08 to 09 November 2011 and (d) from 28 to 29 January 2012

Tableau 2. Seasonal deposition $PM_{2.5}$ to Néguèla calculated by HYSPLIT (µg / m²)

Saisons	Nutriments	Minimums	Moyennes	Maximums
FSS	1,67	3,90	13,90	180
HVG	0,54	1,01	3,70	10,2
DSS	1,58	3,91	30,00	160
MSS	3,48	4,32	15,20	120
Annual average	1.87	3,28	15,70	153,3

In the dry season, deposits are gradual, from 3.9 µg/m² in November to 8.9 µg/m² in December (Figures 5-c and 5-d). This period is characterized by the dry deposition of atmospheric aerosols.

Seasonal variation of the deposition: Table 3 gives a summary of the deposits on the Neguela site. According to the results of the model, the PM2.5 particle load on the Baoulé loop came from four zones, sources namely: the Sahara and the Sahel for mineral dust, the Guinean forest for biomass fires smoke and the sea of the Gulf of Guinea and the surroundings of Neguela for fires due to biomass burn.

Concentrations are estimated as mean values for nutrients, levoglucosan and carbohydrates, in mean and maximum values for the $PM_{2.5}$ aerosol particle set. The histograms of $PM_{2.5}$ particulate deposition show that the values decrease considerably during wintering (Figure 8).

At the end of the dry season, the maximum reaches 180 µg/m², which shows that bushfires are frequent during this period since at the same time the levoglucosan level is high. After the harvests, people burn the fields to get rid of the remains of the plants. This explain the increase in concentrations in this period.

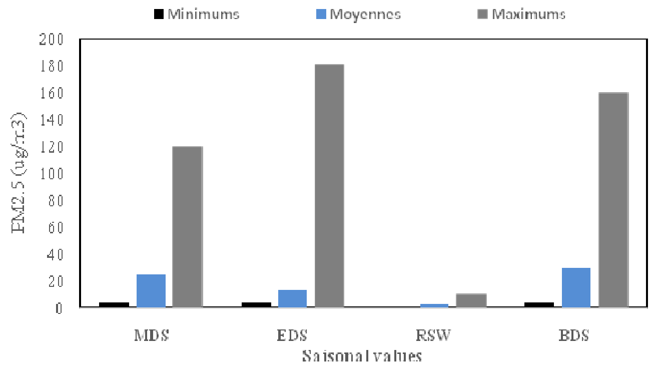

Figure 5. Histogram of seasonal depositions

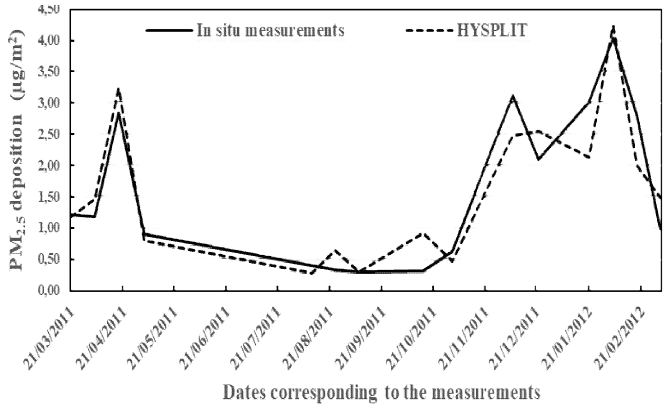

Figure 6. Overlay of measured and measured $PM_{2.5}$ concentration variations

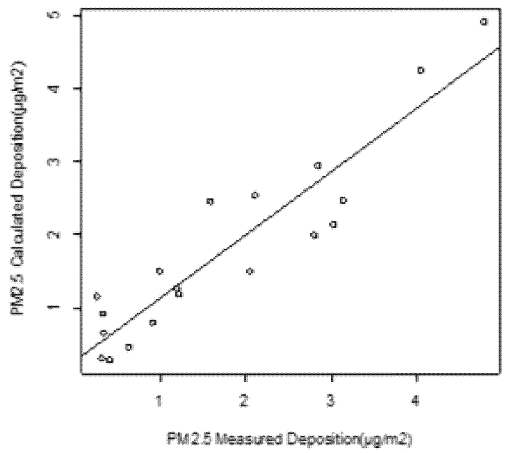

Figure 7. Cloud points and Correlation between calculated and measured $PM_{2.5}$ particle deposition

Seasonal variation of the depositions: To validate the model results, the concentrations calculated by the model were superimposed on the observed concentrations for comparison (Figure 6). For concentrations, estimates from in situ measurements indicate values between 1.2 and 5µg / m3. Figure 9 gives a comparative daily evolution of the concentrations measured and calculated by the model from 2011 to 2012 (Prihodko Lara, 2012). The curves of the concentration curves are almost identical. This shows that the model's predictions are in good agreement with the measures.

Statistical analysis of HYSPLIT model forecasts: To verify the performance of the HYSPLIT model, statistical computation was performed to verify the level of correlation with in situ measurements (Figure 7). The regression line gives a coefficient of determination of 0.84. The regression line model results are well correlated with in situ measurements. The HYSPLIT model is a highly predictive model.

CONCLUSION AND PERSPECTIVES

This work is focused on the use of the HYSPLIT model to calculate the backward trajectories and the deposition of $PM_{2.5}$ aerosol particles emitted during biomass fires in the Néguèla area, in the Baoulé loop in Mali over the period from February 2011 to January 2012 and compare the results with in-situ measurements made by Prihodko *et al.*, 2012 to validate the model. Back trajectory analysis with the HYSPLIT model suggests that the deposition during these events is originating north of the research site. In contrast, during the wet season we do not see evidence of biomass burning. However, we do see elevated gaseous nitrogen deposition as well as elevated nitrogen in wet deposition at the beginning of the wet season that is likely related to releases from the soil (gaseous) as well as remaining biomass-burning emissions in the atmosphere (wet). In addition, we see an elevation in carbohydrates, glucose in particular, that might be attributable to ecosystem activity. Back trajectory analysis during this time period indicates transport from the south. In perspective, thanks to its dust module, we plan to apply the HYSPLIT model to simulate dust storms in Mali, which is a Sahelian country bordering the Sahara. With the integrated trajectory and dispersion model, HYSPLIT also applies to simulate the transport and dispersion of pollutants in Mali's major cities such as Bamako. In addition, the trajectory model can simulate the transport of precipitating air masses and their climatology over Mali. This would provide important explanations for the drought episodes that have occurred in the last sixty years.

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