Altering rainfall patterns through aerosol dispersion

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Abstract. The possibility of recirculation mechanism on rainfall patterns is salient for sustenance of the human race through agricultural produce. The peculiarity of the lower atmosphere of south west region of Nigeria was explored using theoretical and experimental approach. In the theoretical approach, the reconstruction of 1D model as an extraction from the 3D aerosol dispersion model was used to examine the physics of the recirculation theory. The experimental approach which consists of obtaining dataset from ground instruments was used to provide on-site guide for developing the new recirculation theories. The data set was obtained from the Davis weather station, Nigeria Meteorological agency and Multi-angle Imaging Spectro-radiometer (MISR). We looked at the main drivers of recirculation and propounded that recirculation is a complex process which triggers a reordering of the mixing layer- a key factor for initiating the type of rainfall in this region.

1. Introduction
The role of aerosols in understanding the climatic system is enormous because it controls verse processes in the atmosphere like atmospheric circulation [1], rainfall pattern [2] cloud formation [3]. Its direct and indirect influence on the global climate can be very complicating when understudying the comparative role of aerosols to global energy balance [4]. Atmospheric aerosols have been reported to form heterogeneous or homogenous layers in the atmosphere [5]. Models are propounded to amplify the usefulness and exactness of the measuring instruments. Sadly, these model needs change in a few zones e.g. sufficient estimation of airborne scattering and statement, rates of new molecule arrangement and their reliance on controlling factors e.g. development and maturing. The aerosols dispersion and deposition technique requires a systemic evaluation of aerosols not only at ground level but also in the planetary boundary layer (PBL) to determine the aerosol transport mechanism-in relation to weather formation at the PBL [5, 6]. The planetary boundary layer contains a large variety of aerosols from anthropogenic and natural sources [1]. The planetary boundary layer (PBL) comprises of sub-layers e.g. mixed layer, surface layer, stable layer and residual layer. The surface layer is closest to the earth i.e. 10 percent of the height of the PBL. Turbulent stresses are relatively constant. The mixed layer or convective layer are directly above the surface layer and are characterized by convective motion and significant mixing of air. It makes up the entire layer of the PBL above the surface layer - during day and reduces drastically during the night. The stable layer is located above the mixed layer. It is the entry point where air from above the PBL entrains into the mixed layer. This stable layer restricts turbulence, prevents frictional influences from reaching above the PBL and prevents the continued upward motion of thermals. The residual layer is majorly residuals of the mixed layer and is not influenced by turbulent stresses. The PBL are influenced by environment forces like differential heating, energy budgets, moisture, diurnal variations, buoyancy, shear, and roughness length. The PBL takes out aerosol retention by means of regular components which works
either as wet deposition, dry deposition or chemical reactions. These procedures can happen exclusively or partially. Layering of the PBL is subject to its temperature. All the more for all intents and purposes, the review site that is featured in Emetere et al. [6] traverses the beach front area (in the south of Nigeria) to the sub-Sahel locale (in the north of Nigeria). Significantly, the wind transport instrument starts turbulent weight on the PBL. For instance, amid harmattan, the wind transports vast amounts of particulates from the Sahara Desert in the north toward the south. Likewise, aerosols due to bush burning, automobile activities in the south increase the aerosols content over the study site [6]. Amid the non-harmattan, the West African Sub area is washed by the sticky SW Monsoon winds from the Atlantic Ocean [7].

The recirculation theory helps us to understand the anomalies in both the aerosols dispersion and deposition points of the atmospheric field settings. The mysteries of the recirculation zones in the mixing layer of the lower atmosphere are yet to be explained i.e. comparing the pre-circulation and post circulation. The turbulent boundary layers formed during recirculation are somewhat complex when explaining the minute changes that triggers continuous recirculation [8, 9]. In this paper, we understudied a 3D dispersion model which was developed from the aerosols dispersion dynamics around a cement factory. We looked at the main drivers of recirculation and propounded that recirculation is a complex process which triggers a reordering of the mixing layer- a key factor for initiating the type of rainfall in this region.

2. Methodology

The Davis weather station used for this study was installed at Covenant University, Ota Nigeria. Ota is on 6.21°N and 3.21°E. The weather station was used to obtain the wind properties i.e. peculiar to the region. The Meteorological data for rainfall was obtained from the Nigerian Meteorological Agency for five States in the south-west i.e. Osogbo-Osun, Ilorin-Kwara, Ibadan-Oyo, Abeokuta-Ogun, Ondo-Ondo and Ikeja-Lagos. The main objective of the theoretical approach is to derive recirculation equations from micro scale. The theoretical approach to this studies can be obtained from the aerosol dispersion model [5, 6]. The mathematical representation of type 3 is given as

\[
\frac{\partial c}{\partial t} + V_x \frac{\partial c}{\partial x} - V_y \frac{\partial c}{\partial y} = \frac{\partial}{\partial z} \left( k \frac{\partial c}{\partial z} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_{yz} \frac{\partial c}{\partial z} \right) - B + D \tag{1}
\]

Here D represents the transport equations for recirculation; B is the pressure gradient force.

\[
D = \frac{\partial (V_x \varepsilon)}{\partial x} = \frac{\partial (V_x \varepsilon)}{\partial x} \left( \frac{\partial V_x}{\partial x} \right) - k \tag{2}
\]

\[
B = dP \cdot dA \tag{3}
\]

Here \(V_x\) is the mean velocity in x direction, P is the pressure, A is the surface area, \(V_t\) is the kinematic viscosity, \(\varepsilon\) is the turbulence kinetic energy, \(k\) is the dissipation rate, \(\sigma_\varepsilon\) turbulent diffusivity coefficient.

\[
\frac{\partial c}{\partial t} + V_x \frac{\partial c}{\partial x} = V_x \frac{\partial c}{\partial x} + \frac{\partial}{\partial x} \left( \frac{\partial V_x \varepsilon}{\partial x} \right) - k \tag{4}
\]

Equation 7 has important implications for precipitation formation via the recirculation region. The recirculation region initiates the nucleation scavenging which grows the precipitation size. The ability of aerosol particles to act as a cloud condensation nuclei (CCN) depends on its size [10]. The solution of equation (4) is given as

\[
\varepsilon = \frac{\sigma_\varepsilon}{V_t} (-V_x(kt + C - x) - PAx) \tag{5}
\]

The solution i.e. equation (5) shows that the updraft term \(xV_x \frac{\sigma_\varepsilon}{V_t}\) was able to initiate the nucleation scavenging. Hence, large scale recirculation may influence precipitation over an area provided that
other terms in equation (5) are quite low. This assumption was verified by the rainfall and aerosol optical depth over the research site.

3. Results and Discussion
In this section we tried verifying how intense is the relationship between the aerosol content of an area and the rainfall pattern. The data duration is thirteen years. First we examine the wind speed data (Figures 1(a) and 1(b)) from the Davis weather station to determine the various expected possibilities in the recirculation zones.

The wind data set for January, 2013 was used to estimate the recirculation zone in 1D where \( x=z \). More specifically, the recirculation zone occurs more frequently along the SE, S, ESE, ENE, E, SSW and SSE as shown in Figure 1(b). If we assume that all the negative terms in equation 8 are minute, then the turbulence kinetic energy which defines the sustenance of the recirculation zone can be written as

\[
\varepsilon \approx xV^2_x \frac{\sigma_x}{V_x}
\]

where

\[
V_x(\theta) = \begin{cases} 
V \sin \theta & \text{if } 0 < x < 480, \quad 0 < \theta < \pi/16 \\
V \cos \theta & \text{if } 480 \leq x < 960, \quad \pi/16 < \theta < \pi/8 \\
V (\sin \theta + \cos \theta) & \text{if } 960 \leq x < 1440, \quad \pi/8 < \theta < \pi/4 \\
V \sin^2 \theta & \text{if } 1440 \leq x < 1920, \quad \pi/4 < \theta < \pi/2 \\
V \cos^2 \theta & \text{if } 1920 \leq x < 2400, \quad \pi/2 < \theta < \pi \\
\end{cases}
\]

\( \sigma_x/V_x = 0.01 \), and \( V =7.8 \) m/s i.e. the highest speed with an equivalently high frequency. Let \( x \) be the altitude of the lower atmosphere where altitude 1440 m to 2400 m represents the free troposphere. The recirculation activity was theoretically represented in Figure 2.

![Figure 1. (a) Magnitude of wind speed within different directions and (b) Frequency of wind directions](image)

The 3D representation of the recirculation parameters illustrated in equation (9) where the maximum turbulence kinetic energy over the research area-which is about 261 J/Kg and occurs between 1000 m to 1500 m altitude (see Fig. 3). The divergence of recirculation features as seen by the red dotted lines is evidence that the recirculation zones are unpredictably dynamic. Hence, it possesses a verse ability to influence rainfall over an area. We understudy the rainfall pattern between the years 2000 to 2012 over the research area. A comparative analysis between the rainfall pattern and the aerosol optical depth was carried to further explain the dynamic nature of the recirculation zones. This study provides the hint into understanding the tropospheric anomaly noticed by Lee et al. [11]. Lee et al. [11] proposed that via statistical analysis that biomass burning aerosol (BBA) affects liquid clouds- leading to an increase in cloud droplet number concentrations and a decrease of droplet...
effective radii. In the long run, this process leads to geographical rearrangements of rainfall patterns. The theory of recirculation as explained in this paper sheds more light on the possibility of rainfall suppression and promotion [12, 13]. The recirculation activity can influence the normal deceleration (in form of normalization, accelerating or decreasing) of auto-conversion processes in the lower atmosphere [14].
The images display line graphs comparing rainfall data from various locations in Nigeria over different years. Each graph plots rainfall (mm) against months of the year. The cities included are Ilorin, Ikeja, Ibadan, Oshogbo, Ondo, and Abeokuta. The graphs show variations in rainfall patterns across the months, highlighting the differences in rainfall amounts and peak rainfall months for each location.
4. Conclusion
The recirculation zone is comprised the negative recirculation which supports the downdraft activities and positive recirculation which supports the updraft activities within the lower atmospheric setting. The negative recirculation has no influence on the rainfall pattern of an area-as seen in Osogbo-Osun. The positive recirculation has significant influence on the rainfall pattern of an area-as seen in Ikeja-Lagos. The maximum turbulence kinetic energy over the research area is about 261 J/kg and occurs between 1000 m to 1500m altitude. This altitude shows the role of recirculation in cloud formation and rainfall. Hence, the meteorological data set for the six locations shows that Ondo and Ikeja-Lagos has the highest value of turbulence kinetic energy. Also, we discover that the turbulence kinetic energy of negative recirculation is low i.e. compared with the turbulence kinetic energy of positive influence. The rainfall pattern of 2001 seems to be uniquely uniform with a clear evidence of uniform recirculation activity throughout the six locations. It was shown that recirculation activity influences the nature of clouds. The glaring results are the increase in cloud droplet number concentrations and a
decrease of droplet effective radii. This result is possible because nucleation scavenging triggers rainfall both at the long or short term as shown in the results.

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