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# Analysis of Ground Level Ozone and Nitrogen Oxides in the City of Dar es Salaam and the Rural Area of Bagamoyo, Tanzania

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## Abstract

**From 2012 to 2015, we measured surface ozone, $NO_x$, $NO_2$, and NO levels at three urban sites (Mapipa, Ubungo, and Posta) and two suburban sites (Kunduchi and Vijibweni) in the city of Dar es Salaam and in the village of Mwetemo, a rural area of Bagamoyo, Tanzania. The average hourly $O_3$ concentrations at all sites were between 9 ppb and 30 ppb during our sampling periods. $O_3$ levels at suburban sites were generally higher than at urban sites. The average hourly concentrations in Dar es Salaam were 10 - 32 ppb, while in Bagamoyo they were 9 - 15 ppb. We observed a strong diurnal variation in Dar es Salaam while measurements from Bagamoyo showed little variation. At Dar es Salaam, the surface $O_3$ concentrations increased from their minimum level at sunrise (around 6:00 a.m.) to a maximum in the late afternoon (around 4:00 p.m.), and then decreased toward 11:00 p.m. Another secondary ozone peak appeared between midnight and ~4:00 a.m., after which the surface ozone concentrations decreased to a minimum around 7:00 a.m. $NO_2$ concentrations were higher at the urban sites of Ubungo and Posta, and their weekly average $NO_2$ concentrations were 246 ppb and 118 ppb, respectively. Weekly average $NO_x$ concentrations ranged from 39.4 ppb at the Kunduchi site (suburban) to 738 ppb at the Ubungo site (urban). To our knowledge, there were few continuous measurements of ozone and nitrogen oxides concentrations in Tanzania. Since high $NO_x$ concentrations were observed, continuous air quality monitoring and effective air pollution control measures are required in Dar es Salaam to prevent further deterioration of air quality and limit the possible negative impacts on humans and vegetation.**

## Keywords

**Ozone, $NO_x$, Daily Variation, Bagamoyo, Dar es Salaam**

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## 1. Introduction

Elevated tropospheric ozone ($O_3$) concentrations have received extensive attention around the world because of the damage caused to human health and ecosystems [1]-[6]. Ozone is a secondary pollutant formed through complex photochemical reactions involving $NO_x$ ($NO_2$ + NO) and Volatile Organic Compounds (VOCs) under favorable meteorological conditions such as high solar radiation and high temperatures [7]-[9].

In African cities, urban air pollution is emerging as a key threat to health, the environment, and the quality of life of millions of Africans as the levels of urbanization, motorization, and economic activity increase [10]. Low income levels have resulted in the import of older used vehicles and postponed vehicle maintenance. Anthropogenic air pollution caused by vehicular emissions, industrialization, and biomass burning has decreased air quality [11]-[13]. Two of the main traffic and fossil fuel combustion-derived pollutants are nitrogen oxides ($NO_x$) and VOCs, which are the primary precursors of ground level ozone.

Several researchers have also pointed out that biomass burning is a major contributor to regional pollution in Africa. One of the methods used to identify regional pollution is the vertical profiling of ozone using aircraft campaigns. Some of these studies in equatorial Africa include MOZAIC 1997-2003 [14] and the INDOEX experiment focused on pollution outflow from India over the Indian Ocean and towards eastern Africa during winter monsoon conditions [15]. In other tropical and southern African regions, several field campaigns have been conducted. These include TRACE-A 1992 [16], SAFARI 1992 [17], and SAFARI 2000 [18]. However, as Thompson *et al.* [19] argue, weekly observations of $O_3$ may not be robust enough for trend analysis in the tropics due to strong variability caused by deep convection.

Only a few studies have been conducted on ground level ozone and air quality in African cities. These include Khoder in Cairo [20], Acellet *et al.* in Cotonou [21] on the coast of the Gulf of Guinea and near Niamey in the Sahel region, and Adon *et al.* [22] in several cities in west and central Africa.

Air pollution, especially of ground level $O_3$, remains poorly understood and undocumented in Tanzania. The coastal city of Dar es Salaam has a population of approximately 4.4 million [23], and the city is one of the fastest growing in Africa. The traffic density growth rate is 6.3% annually [24]. However, the traffic growth rate greatly exceeds the development of a road network, which has resulted in severe traffic congestion [25]. To our knowledge, there is no continuous study on ozone and nitrogen oxide in Tanzania. In this study, we present and discuss ozone and nitrogen oxide concentrations in the city of Dar es Salaam and the Bagamoyo Pwani region of Tanzania, east Africa.

## 2. Materials and Methods

We performed ground level ozone concentration and nitrogen oxide measurements in Dar es Salaam and Bagamoyo, Tanzania. Dar es Salaam and Bagamoyo have two wet seasons (March-May and October-November) and two dry seasons (June-September and January-February). Sampling sites, sampling dates, and site descriptions are provided in **Figure 1** and **Table 1**.

**Table 1.** Sampling sites and their details for the measurement of the ground-level ozone, $NO_x$, $NO_2$ and NO concentrations.

| No | Sampling date | Monitoring sites | Description of the place |
|---|---|---|---|
| 1 | Feb. 2012 | Magomeni (Mapipa) | Junction of Kawawa and Morogoro roads, Urban area, many people, intensive traffic |
| 2 | Jun. 2013 | Posta, Askari Monument | Urban area, many people, intensive traffic |
| 3 | Jun. 2013 | Ubungo | Many people, intensive traffic, many vehicles (cars, big trucks, motorcycles and tricycles), power plants nearby, big bus station |
| 4 | Feb. 2012, Jun. 2013 | Kunduchi | Suburban area, housing, few vehicles, along the beach |
| 5 | Jun. (2014)-Jan. (2015) | Vijibweni | Suburban area, housing, few vehicles |
| 6 | Dec. 2013 to Dec. 2014 | Mwetemo village, Bagamoyo | Rural area, small scale farming, forest, very few vehicles |

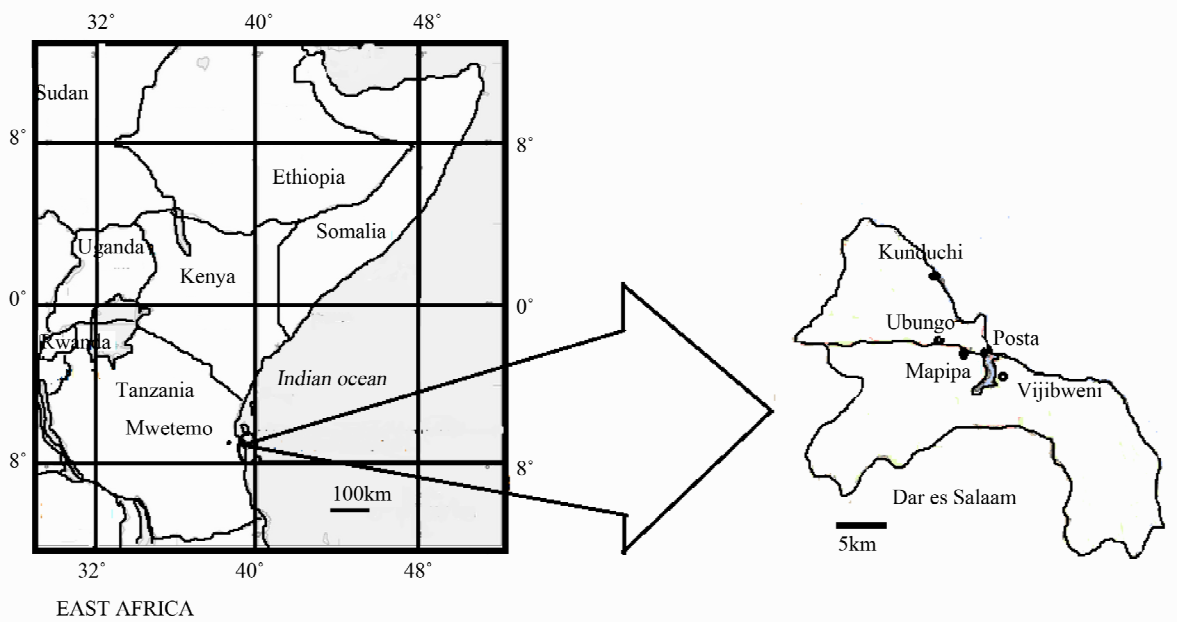



**Figure 1.** Dar es Salaam and Bagamoyo, Mwetemo village monitoring sites, Tanzania.

$NO_x$ and $NO_2$ were collected using Ogawa passive samplers with triethanolamine (TEA) as an absorbent [26]-[29]. Each sampler collected $NO_x$ and $NO_2$ over a 24-h period. Absorbed $NO_x$ and $NO_2$ were examined colorimetrically (Axiom Spectrophotometer, Germany), per the manufacturer's protocol (Ogawa & Company, USA, Inc. 2006). Standard solutions were prepared daily and samples were analyzed within 24 h of collection.

Ground level ozone was measured continuously (at 1-min intervals) using an ozone ambient air quality monitoring system (S500 V5.1, Aeroqual), which has been used successfully in other studies [30] [31]. Aeroqual monitors were fitted with sensor heads (Aeroqual Outdoor Ambient Air Quality Monitor; Auckland, New Zealand) based on Gas Sensitive Semiconductor (GSS) technology. The operating principal is a combination of smart measurement techniques and mixed metal oxide semiconductor sensors that exhibit an electrical resistance change in the presence of a target gas. This resistance change is caused by a loss or a gain of surface electrons as a result of adsorbed oxygen reacting with the target gas. Quantitative responses from the sensor are possible as the magnitude of change in electrical resistance is a direct measure of the concentration of the target gas present. The operating parameters were: detection range of 0 - 150 ppb, resolution of 1 ppb, temperature of −5˚C - 50˚C, and relative humidity of 5% - 95%. Data were recorded as 1-min averages, which in turn were compiled to yield hourly, daily, weekly, and monthly means, grouped into seasons.

Other physical parameters such as temperature, humidity, and UV radiation were measured using an illuminance UV recorder (TR-74Ui, T&D Corporation) with multiple sensors for temperature, humidity, and UV radiation.

Air mass-backward trajectories were calculated using the National Oceanic and Atmospheric Administration (NOAA) internet-based model of a Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT 4, NOAA, http://www.noaa.gov/). Each calculation was made for 3 days (72 h), fixed at heights of 500 m and 1000 m.

## 3. Results and Discussion

### 3.1. Ozone Concentration

#### 3.1.1. Daily Variation of Surface Ozone Concentrations in Dar es Salaam

In Dar es Salaam, surface ozone concentrations showed strong diurnal variation at all sites. The diurnal variations in $O_3$ concentrations showed four main stages. The $O_3$ concentration peaked from around 12:00 p.m. to 4:00 p.m., which aligns with maximum solar radiation. Ozone concentrations decrease from 5:00 pm until 11:00 p.m. which coincides with decreases in solar radiation. $O_3$ concentrations started to decrease in the early morn-

ing around 4:00 a.m. and reached their lowest levels by 6:00 a.m. From 8:00 a.m. onwards, $O_3$ concentrations increased; this may be a result of the photochemical reactions of nitrogen oxides.

Mean weekly and monthly $O_3$ concentrations in Dar es Salaam and Bagamoyo are shown in **Figure 2** and **Figure 3**, and **Table 2**. Ozone concentrations were measured weekly in Feb 2012 at Kunduchi and Mapipa and

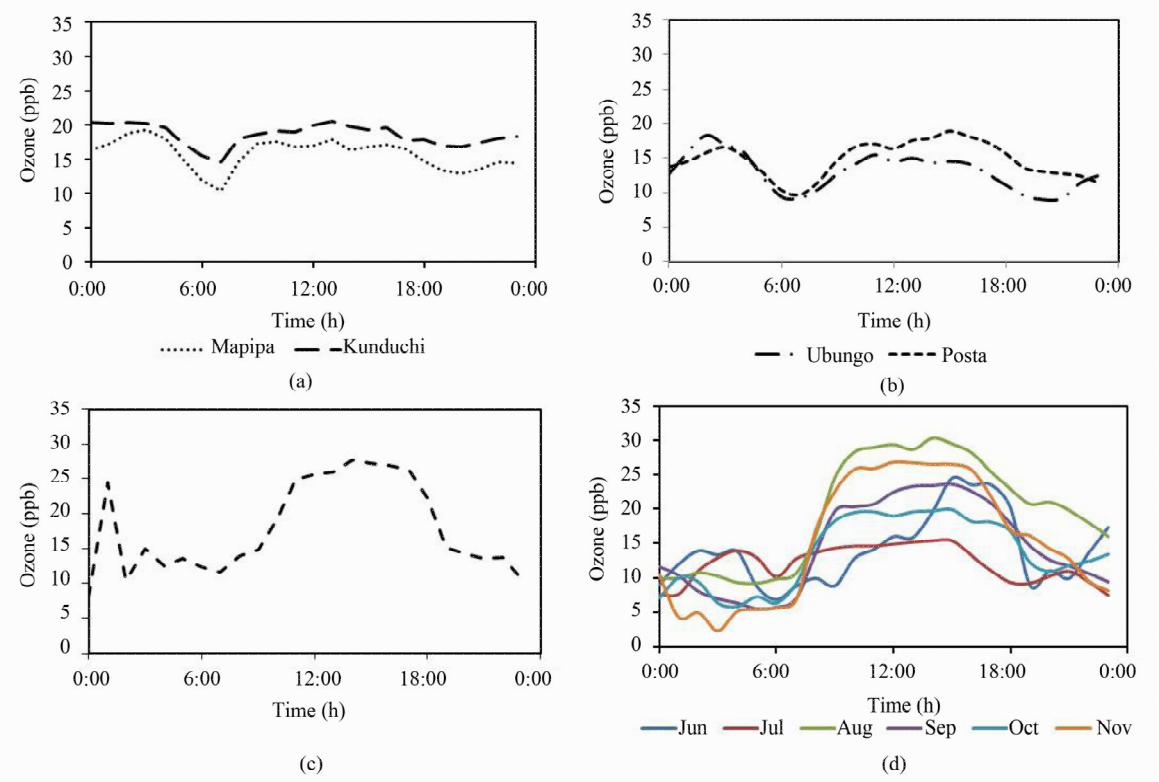



**Figure 2.** Daily variation of $O_3$ concentrations in Dar es Salaam: (a) Kunduchi and Mapipa sites (February 2012); (b) Posta and Ubungo sites (June 2013); (c) Kunduchi site (June 2013); and (d) Vijibweni site (June-November 2014).

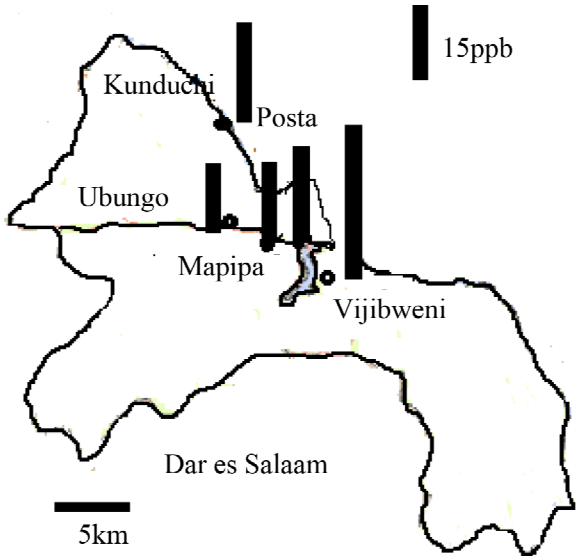



**Figure 3.** Monthly and weekly mean concentrations of ozone in Dar es Salaam.

**Table 2.** Mean ozone concentration with maximum reading and standard deviation in Dar es Salaam and Bagamoyo.

| Sampling Location | Date | Maximum reading (ppb) | Mean ± S.D (ppb) |
|---|---|---|---|
| Mapipa, Dar es Salaam | Feb. (1-7) 2012 | 31 | 15 ± 2.3 |
| Kunduchi, Dar es Salaam | Feb. (1-7) 2012 | 32 | 19 ± 2.3 |
| Kunduchi, Dar es Salaam | Jun. (1-7) 2013 | 44 | 17 ± 6.6 |
| Ubungo, Dar es Salaam | Jun. (17-23) 2013 | 25 | 13 ± 2.7 |
| Post, Dar es Salaam | Jun. (17-23) 2013 | 33 | 16 ± 2.6 |
| Vijibweni, Dar es Salaam | Jun.-14 | 29 | 14 ± 5.2 |
| | Jul.-14 | 18 | 11.6 ± 2.6 |
| | Aug.-14 | 41 | 18.3 ± 8 |
| | Sep.-14 | 32 | 15 ± 6.5 |
| | Oct.-14 | 33 | 14 ± 5.1 |
| | Nov.-14 | 33 | 15 ± 8.9 |
| | Dec.-14 | 34 | 20.5 ± 1.7 |
| | Jan.-15 | 49 | 28.6 ± 1.4 |
| Mwetemo, Bagamoyo | Dec.-13 | 23 | 17.4 ± 3.0 |
| | Jan.-14 | 24 | 14.5 ± 0.7 |
| | Feb.-14 | 36 | 14 ± 1.1 |
| | Mar.-14 | 28 | 9.6 ± 0.5 |
| | Apr.-14 | 26 | 8.9 ± 1.0 |
| | May-14 | 24 | 9.6 ± 0.5 |
| | Jun.-14 | 27 | 10.6 ± 1.9 |
| | Jul.-14 | 27 | 12.2 ± 1.1 |
| | Aug.-14 | 33 | 11.8 ± 2.5 |
| | Sep.-14 | 30 | 13.4 ± 1.5 |
| | Oct.-14 | 25 | 10.4 ± 2.0 |

were 10 - 20.5 ppb. They were measured at Posta and Ubungo in Jun 2013 and were 9 - 19 ppb. $O_3$ levels at Kunduchi (the suburban site) were generally higher than at Mapipa (the urban site). Also, $O_3$ levels at the Posta site were slightly higher than those at the Ubungo site.

Ozone concentrations in Vijibweni were measured continuously from June 2014 to January 2015. The diurnal cycle of mean ozone concentrations during each month in Vijibweni, Dar es Salaam, from June to November 2014 is shown in **Figure 2(d)**. Mean monthly concentrations ranged from 5 ppb at around 6:00 a.m. to 30 ppb at peak time around 12:00 p.m. to 4:00 p.m. The mean monthly ozone concentrations in August were the highest, and the maximum reading recorded was 41 ppb, followed by levels in Nov and Sep with strong diurnal variation. Previous studies have also found low ozone concentration in East Africa. Sauvage *et al.* [14] analyzed the vertical profile of ozone between April 1997 and March 2003 in equatorial Africa and found that east Africa had lower concentrations, never exceeding 20 - 40 ppb on average in the lower troposphere. Henne *et al.* [32] conducted a continuous $O_3$ measurement study at Mt. Kenya, and the concentrations were between 15 ppb and 40 ppb during 2002 and 2006.

### 3.1.2. Temporal Variation of Ozone at the Rural Sites

The $O_3$ concentration levels at a rural site (Mwetemo village, Bagamoyo) were analyzed based on several different scales, such as hour, month, and season, from December 2013 to October 2014. **Figure 4** shows monthly

mean $O_3$ concentrations with error bars showing standard deviation. The monthly mean $O_3$ concentrations ranged from 9 ppb to 17 ppb, with the lowest levels in April and the highest levels in December. There was a small fluctuation of ozone concentrations in the months of March through May (MAM), compared to the other months. Also, the mean monthly ozone concentration was the lowest in MAM. This may be the result of a period of heavy rain, when air is much cleaner.

The diurnal cycle of $O_3$ concentrations in Bagamoyo in different seasons is shown in **Figure 5**. In Tanzania, we have a dry season in December through February (DJF), a wet season in MAM, followed by another dry season in June through August (JJA), and a period of light rain in September and October (SO). The diurnal cycle of ozone in Mwetemo village was lowest during the daytime between noon and 4 p.m. and highest at night. A study by Henne *et al*. [32] at Mt. Kenya found a similar diurnal cycle. This was explained by the photochemical destruction of ozone in the free troposphere under low $NO_x$ conditions, which are likely far cleaner in east African areas, but this may also be due to dry surface deposition [32]-[33]. Mwetemo, a small village with small scale farming, surrounded by forest about 45 km from the coastal town of Bagamoyo, had low $NO_x$ concentrations (below 12 ppb; see **Table 3**).

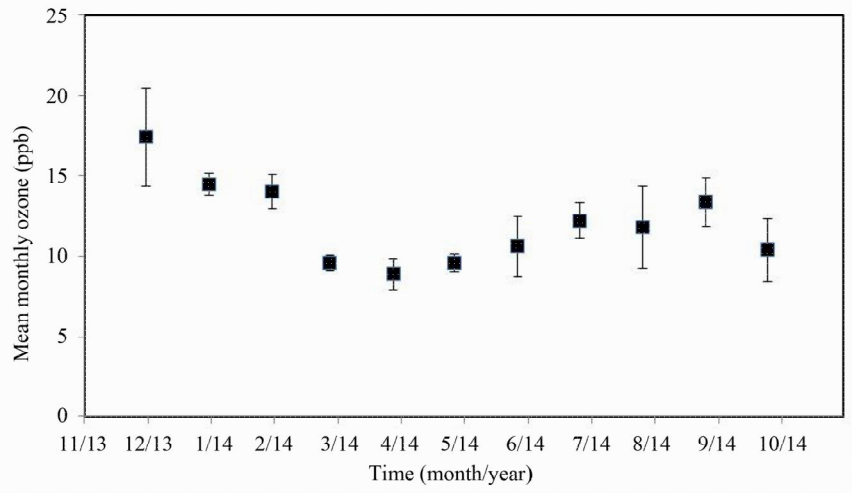



**Figure 4.** Monthly mean $O_3$ concentrations with standard deviations, in the Mwetemo, Bagamoyo, rural site in Tanzania from December 2013 to October 2014.

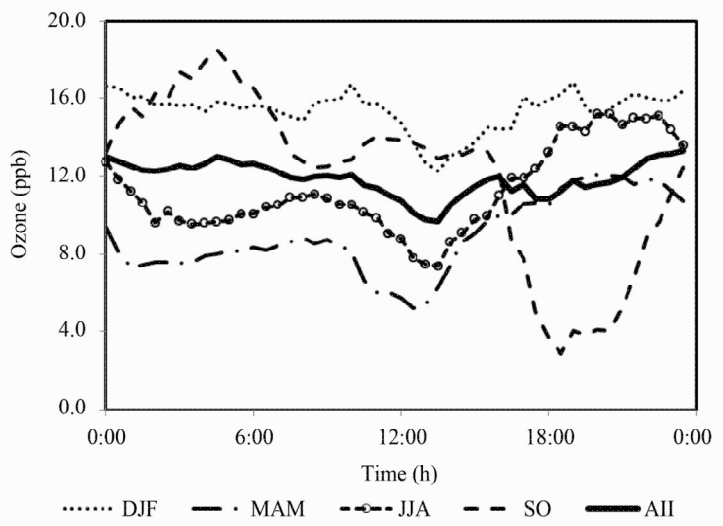



**Figure 5.** Hourly mean $O_3$ concentrations over different seasons in Mwetemo village, Bagamoyo, a rural site in Tanzania.

**Table 3.** $NO_x$, $NO_2$ and NO concentrations in the four sampling sites in Dar es Salaam city (Feb. 2012 and Jun. 2013), Mwetemo, Bagamoyo (Dec. 2013-2014).

| Sampling Location | Date | $NO_x$ (ppb) | $NO_2$ (ppb) | NO (ppb) |
|---|---|---|---|---|
| Mapipa, Dar es Salaam | Feb (1-7) 2012 | 86.3 | 21.7 | 64.5 |
| Kunduchi, Dar es Salaam | Feb (1-7) 2012 | 40.5 | 33.2 | 7.3 |
| Kunduchi, Dar es Salaam | June (1-7) 2013 | 39.5 | 17.6 | 21.9 |
| Ubungo, Dar es Salaam | June (17-23) 2013 | 1476.4 | 246.1 | 1216.8 |
| Posta, Dar es Salaam | June (17-23) 2013 | 217.1 | 117.9 | 99.2 |
| Mwetemo, Bagamoyo | Dec 13-Dec 14 | 5.1 - 12.1 | 3.5 - 11.4 | bbl - 3 |

### 3.1.3. Comparison of Ozone Concentrations in Urban Sites and Rural Sites

Ozone concentrations in the urban Dar es Salaam sites were generally higher than concentrations in Bagamoyo, a rural site. **Figure 6** shows the mean hourly concentrations in Bagamoyo (Mwetemo village) and Dar es Salaam (Vijibweni). The mean hourly concentrations in Dar es Salaam were 10 - 30 ppb, while in Bagamoyo they were 9 - 15 ppb. We observed strong diurnal variation in Dar es Salaam, while Bagamoyo showed little variation. This may be because Dar es Salaam is more polluted with higher levels of $NO_x$ than Bagamoyo (see **Table 3**). Bagamoyo is more remote and $NO_x$ concentrations were very low. Ozone might also be photochemically destroyed in the free troposphere under low $NO_x$ conditions [33]. Being 45 km from the sea, clean air from the Indian Ocean travels to the Mwetemo village. These results agree with those observed by others [32] [34].

### 3.1.4. Ozone Episode in January 2015, Vijibweni

In January 2015, $O_3$ concentrations at the Vijibweni site were rather distinctive with little daily variation. The mean hourly concentrations were rather high compared to other seasons, with a concentration range of 27.5 - 32 ppb (**Figure 7(b)**). **Figure 7(a)** shows 24-h ozone concentrations on Jan 19, 2015, where the maximum $O_3$ reading reached 49 ppb. To understand the situation better, we performed air mass backward trajectory analysis using NOAA's model on Jan 19, one day before, and one day after, for 72 h (**Figures 8(a)-(d)**). The air mass trajectory indicated that Dar es Salaam received air from parts of Chad, the Congo, and from the Gulf of Arabia. January is a period of north-easterly monsoon wind. Lelieveld *et al.* [15] found high pollution level outflows from India over the Indian Ocean towards eastern Africa between January and March. Hao *et al.* [35] indicated that DJF is a biomass burning season in central Africa. Sauvage *et al.* [14] found that the $O_3$ concentration in Brazzaville, Congo was 55 - 65 ppb. It is highly likely that Dar es Salaam in January through March could be affected by regional pollution rather than in situ photochemical production from local pollution.

## 3.2. $NO_x$, $NO_2$, and NO Concentrations

We determined $NO_x$, $NO_2$, and NO concentrations along with $O_3$ levels at four sites in Dar es Salaam (February 2012 and June 2013), and in Bagamoyo (December 2013 to December 2014). **Table 3** and **Figure 9** summarize the nitrogen oxide concentrations at all studied sites. In Dar es Salaam, weekly mean $NO_x$ concentrations ranged from 39.3 ppb at the Kunduchi site to 738 ppb at the Ubungo site, while $NO_2$ concentrations ranged from 17.5 ppb in Kunduchi to 123 ppb in Ubungo. NO concentrations were high at the Ubungo site, with a weekly mean of 609 ppb. The Ubungo site, besides having high traffic levels, is close to a major power plant and power station. Fossil fuel combustion and power plants emit high concentrations of $NO_x$. Sillman [36] indicated that power plant emissions of NO could account for 90% of the total $NO_x$ in the air. The $NO/NO_2$ ratio at the Ubungo site was 4.9, higher than at other sites, suggesting that the power plant contributed significantly to $NO_x$ concentrations (**Table 3**).

As shown in **Table 2**, ozone concentrations were lowest at the Ubungo site in Dar es Salaam, which may be due to the higher concentrations of $NO_x$. There can be significant loss of $O_3$ through $NO_x$ titration in the reaction of $NO + O_3 \rightarrow NO_2 + O_2$. Sillman [36] suggested that in the vicinity of large NO emission sources, a net conversion of $O_3$ to $NO_2$ could occur. This is most common in the vicinity of large NO point sources, whereby ozone is depressed immediately downwind and becomes elevated as the plume moves further downwind [36]-[38]. This

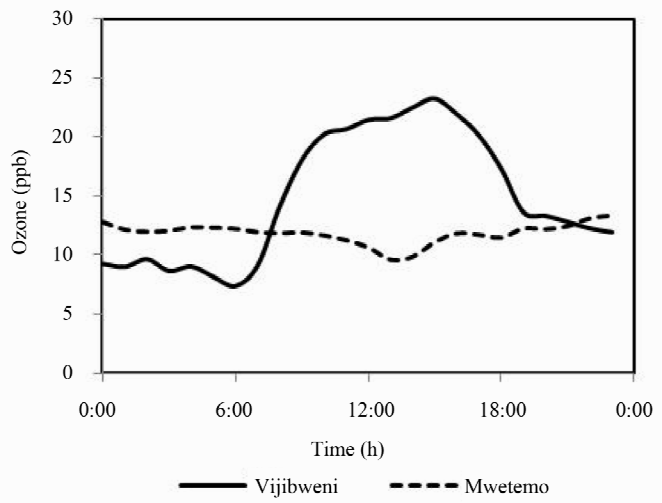



**Figure 6.** Mean hourly ozone concentrations from June 2014 to January 2015 in Vijibweni, Dar es Salaam (solid line) and in Mwetemo, Bagamoyo from December 2013 to October 2014 (dotted line).

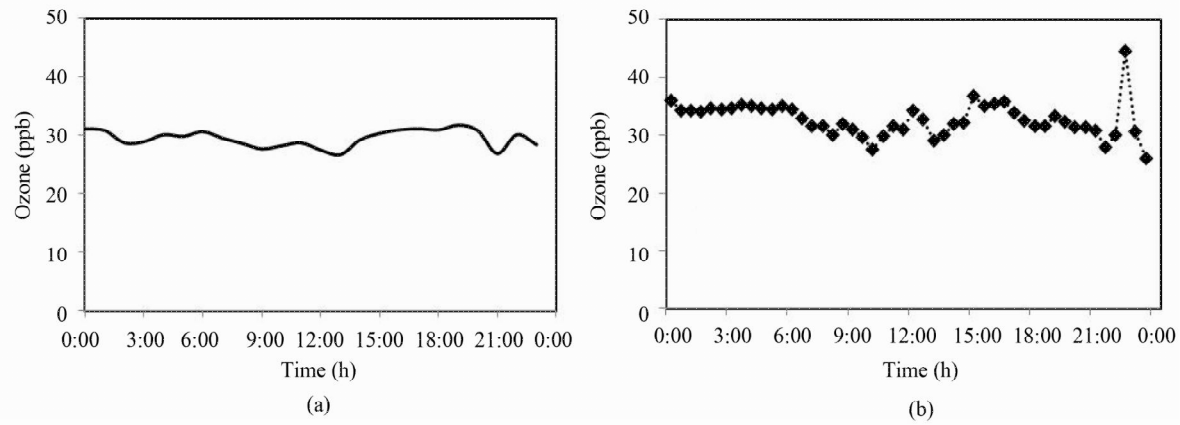



**Figure 7.** (a) Mean hourly ozone concentrations in January; (b) mean hourly ozone concentrations on January 19, 2014 in Vijibweni, Dar es Salaam.

also suggests that high concentrations of ozone at the rural sites of Kunduchi and Vijibweni could be caused by movement of the pollution plume from the city center to suburban areas and by the conversion of $NO_2$ to $O_3$ through photochemical reactions.

At the Mapipa site, $NO_2$ concentrations were in the range of 17.6 - 26.0 ppb, which was lower than at the other urban sites. Othman [39] reported comparable results, which suggests that the site is an open-air location with strong winds. Thus, air pollutants are continuously transported away from the site. This differs from the Posta site, which has narrower streets surrounded by tall buildings that hinder free air movement, allowing air pollutants to linger.

Othman [39] reported daily mean concentrations of 532 ppb for $NO_2$ and 488 ppb for NO at the Posta site, which is higher than our data from the same site (118 ppb for $NO_2$ and 222 ppb for NO). Mbuliwe and Kasenga [40] reported that $NO_x$ in Dar es Salaam was lower than 2000 ppb and $NO_2$ concentrations were below 500 ppb.

Mwetemo village, Bagamoyo, is a remote site with small-scale farming activity surrounded by forest. The concentrations of $NO_x$ were very low, from below the detection limit (bdl) to 10.5 ppb, which is very different from the city of Dar es Salaam. The concentrations of $NO_2$ in Bagamoyo ranged from bdl to 10 ppb, while the concentrations of NO were from bdl to 2.7 ppb. Since Mwetemo village is a remote site, the reason for the low concentrations of $NO_x$ could be due to fewer pollution sources.

**Table 4** summarizes previously reported surface ozone and $NO_2$ concentrations in Africa along with results

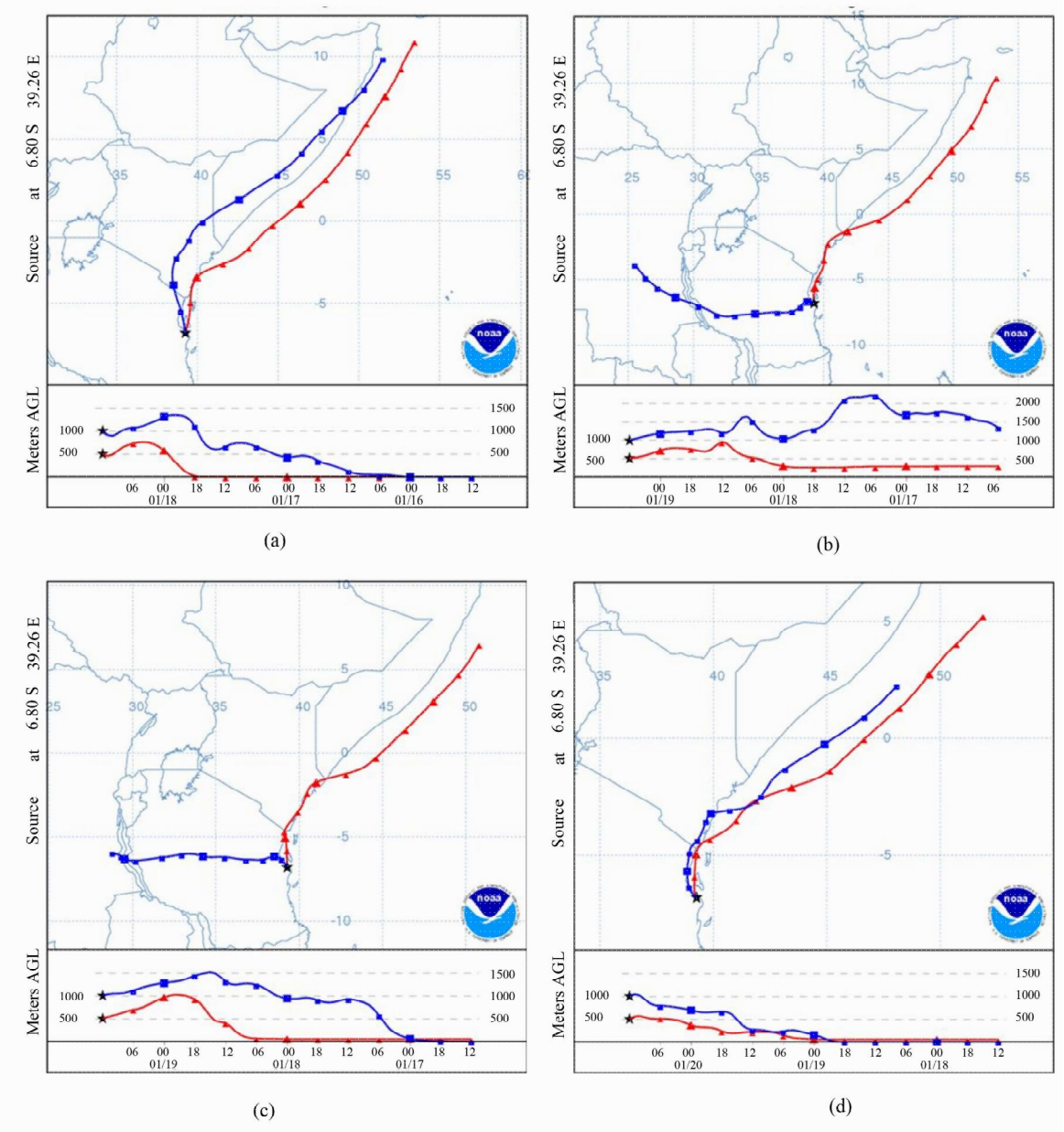



**Figure 8.** Backward trajectory of air mass from January 18 (a), 19 (b) (c) and 20 (d), 2015.

from this study. Our $O_3$ results for Dar es Salam are similar to those of Lacaux *et al.* [41] Jonnalagadda *et al.* [42] and Augustine [43] in Zimbabwe, Central Africa, and Port Harcourt, Nigeria, respectively. Among the limited $NO_x$ data, Odhiambo *et al.* [44] reported high $NO_2$ concentrations of 976 ppb in Nairobi. The increased nitrogen oxide concentrations could increase $O_3$ concentrations through photochemical reactions in remote areas; thus, air quality studies are required within the city and in remote areas where most agricultural crops are produced.

### 3.3. Variations in Ozone and Meteorological Parameters

Meteorological conditions can affect ozone production and dispersion at local and regional scales. Solar radiation, temperature, relative humidity, and wind are important meteorological parameters. Ozone levels tend to increase under hot and sunny conditions favorable for photochemical $O_3$ production. However, rainfall and high

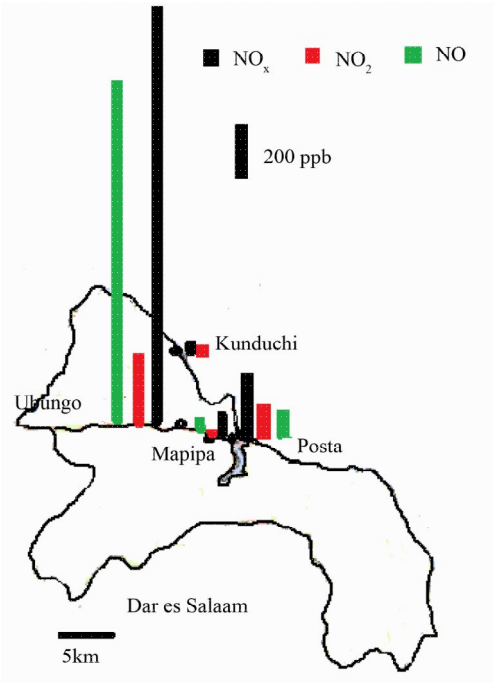



**Figure 9.** Concentrations of $NO_x$, $NO_2$, and NO at different sites in Dar es Salaam.

**Table 4.** Surface ozone levels and $NO_2$ studies in Africa.

| Location | Ozone level (ppb) | $NO_2$ levels (ppb) | Region | Suggested pollution source | Reference |
|---|---|---|---|---|---|
| Nairobi, Kenya | 0 - 125.8 | 11- 976 | urban | traffic related | [44] |
| Cairo, Egypt | 29.69 - 64.0 | 50 - 140 | urban | city emission | [20] |
| South Africa Zambia Zimbabwe | 19.7 - 61.9 | - | rural | - | [45] |
| Mpumalanga Highveld, South Africa and Botswana | 20 - 90 | - | rural/industrial area | industrial/biogenic | [46] |
| Zimbabwe | 33 - 48 | - | rural | biomass burning | [42] |
| Central Africa | 30 - 40 | - | | biomass burning | [41] |
| Port Harcourt, Nigeria | 30 - 40 | - | urban | city emission | [43] |
| Dar es Salaam, Tanzania | 0 - 44 | 17 - 123 | urban, sub-urban | city emission | This study |

relative humidity are associated with low $O_3$ levels due to wet $O_3$ deposition. Here we analyzed the influence of temperature, relative humidity, illuminance, and UV light on ozone to increase our understanding of ozone pollution in Dar es Salaam. A time series of daily average ozone concentrations, illuminance, UV light, temperature, and relative humidity over a 1-week period at the Kunduchi site is shown in **Figure 10**.

Temperature can enhance the propagation of radical chain reactions, and has an opposite effect on the termination rate of these chains [47] [48]. Therefore, high temperatures facilitate ozone production. Relative humidity may play a role in the overall reactivity of chain termination reactions and the production of wet aerosols, which in turn affects ultraviolet actinic flux [49] [50].

$O_3$ production did not correspond perfectly with UV light at the Kunduchi site in June 2013 (**Figure 11**). For example, over Jun 1-3, a sharp peak in ozone was measured at night. Jun 3 was a cloudy day with weaker UV levels, but there was a sharp increase in ozone, levels that reached much higher concentrations than on other days with stronger UV levels. This suggests that the Kunduchi site received polluted air with increased $O_3$ levels.

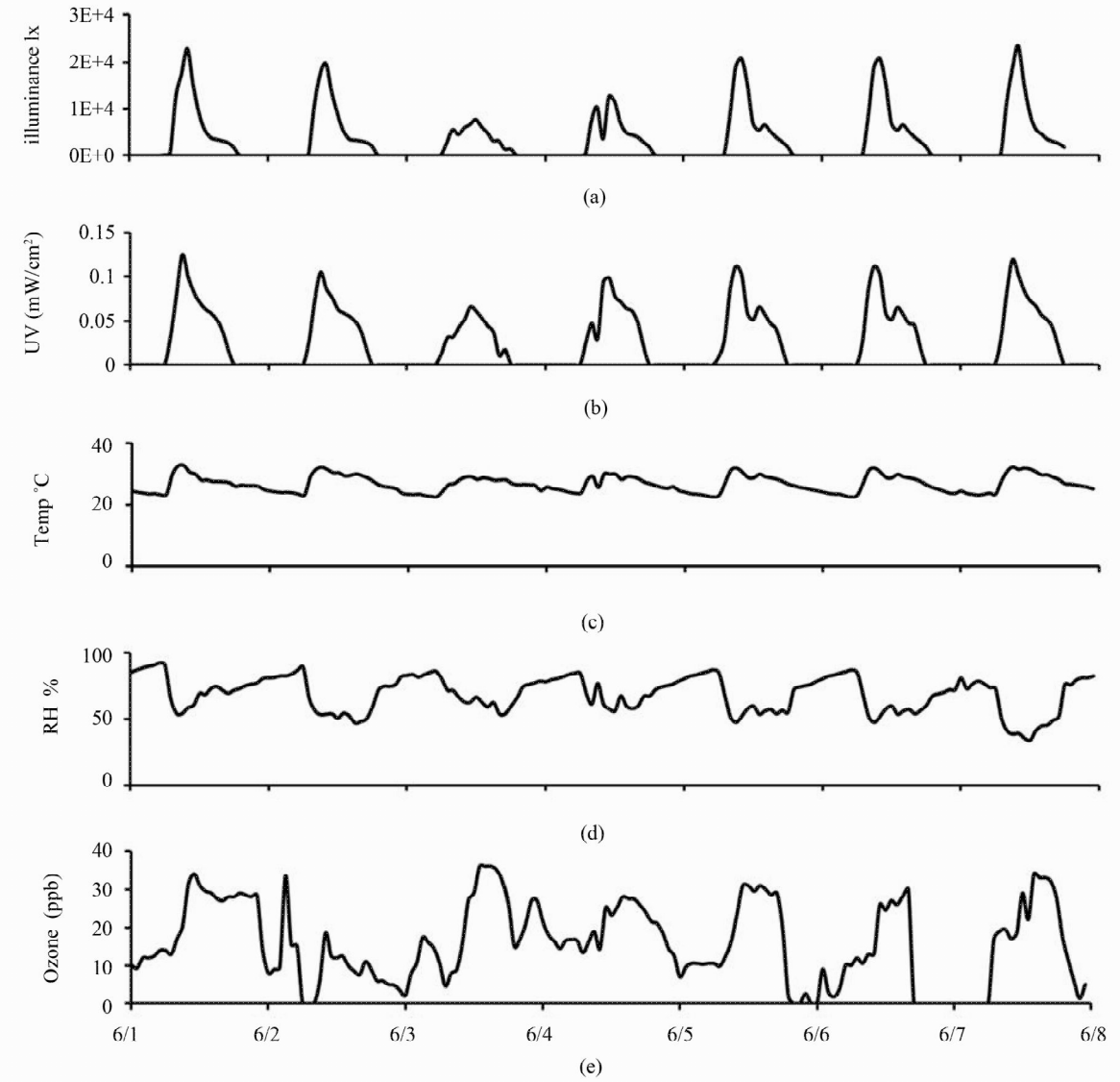



**Figure 10.** Time series data of daily mean ozone concentrations and meteorological parameters in Kunduchi in June 2013. Figures 10(a)-(e) show daily average illuminance, UV light, temperature, relative humidity, and ozone, respectively.

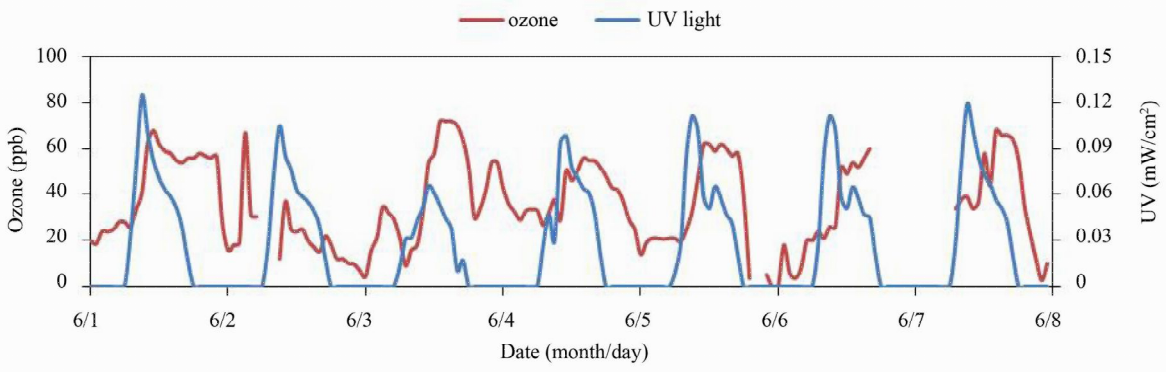



**Figure 11.** Ozone variation with UV light in Kunduchi in June 2013.

Similar trends of high ozone concentrations in suburban areas compared to urban areas have been also reported [51]-[53].

## 4. Summary

Our study showed that surface ozone levels at three urban sites in Dar es Salaam (Mapipa, Ubungo, and the Askari Monument) and two suburban sites (Kunduchi and Vijibweni) were between 10 and 32 ppb. Surface ozone levels at the suburban sites of Kunduchi and Vijibweni were generally higher than at the urban sites. There was strong diurnal variation in the city of Dar es Salaam, while the rural area of Bagamoyo showed little variation. In Dar es Salaam, diurnal variation in surface $O_3$ concentrations was clear, increasing from a minimum near sunrise around 6:00 a.m. to a maximum in the late afternoon around 4:00 p.m., and then decreasing toward 11:00 p.m., indicating in situ photochemical production of $O_3$.

Nitrogen dioxide concentrations were highest at the urban sites of Ubungo and Posta. The Ubungo site showed a higher $NO/NO_2$ ratio, suggesting that the nearby power plant could be a significant contributor of $NO_x$. The low surface ozone concentrations at the studied sites could be caused by titration of $O_3$ by NO. Continuous air quality monitoring and effective air pollution control measures (e.g., reduction of $NO_x$ emissions) are required in Dar es Salaam and many other cities in Africa to prevent further deterioration of air quality and to control threats against agricultural crop production via photochemical conversion of $NO_x$ to $O_3$.

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