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REMOTE SENSING AND IN-SITU-BASED ASSESSMENT OF GREENHOUSE GASES IN NIGERIA

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ABSTRACT

In data-sparse locations, the necessity for the integration of remote sensing and in-situ-based approaches in assessing greenhouse gases cannot be overstressed. Akin other countries in sub-Saharan Africa (SSA), Nigeria is yet to leverage on and fully maximize the potentialities offered by satellite remote sensing in monitoring and assessment of biophysical and ecological change indicators including greenhouse gases. This study was undertaken with the prime motivation of ascertaining the variations of greenhouse gases concentrations in Delta State, Nigeria as well as the correlation between in-situ measurement and satellite remote sensing observation. Datasets comprising carbon monoxide (CO), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) and were sourced from the archive of the European Space Agency and field sampling using Aeroqual S500 ambient air analyser. Descriptive statistics, independent Samples t-Test, analysis of variance (ANOVA), Tukey HSD test of multiple comparisons and simple linear regression (SLR) were the major inferential statistical frameworks used in the study. The results showed that greenhouse gases exhibited statistical significant spatial variability with the non-fictional variation of CO from *In-situ* measurement domiciled between Delta South Senatorial District (SD) and Delta North SD with Mean Difference of – 0.05 (p-value of $0.027 < 0.05$). Validity, extent of accuracy and reliability of remotely-sensed greenhouse gases with in-situ observations was also established with CO, SO_2 and NO_2 in Delta South SD being statistically significant at 95% confidence level. The paper recommends the adoption of space-borne satellite remote sensing resources and GIS in periodic monitoring, mapping and assessments of environmental change indicators.

Keywords: Satellite, Measurement, greenhouse gas, Delta, State, *In-situ*

INTRODUCTION

In data-sparse locations, the necessity for the integration of remote sensing and in-situ-based approaches in the assessment of greenhouse gases cannot be overstressed. Akin other countries in sub-Saharan Africa (SSA), Nigeria is yet to leverage on and fully maximize the potentialities offered by satellite remote sensing in monitoring and assessment of biophysical and ecological change indicators including greenhouse gases and their as emission sources. However, despite being signatory to the Paris Agreement, realizing the ambitious goal reducing Greenhouse gas emission come 2030 is likely to be a mirage. This is not unconnected to the absent of in-situ and remotely sensed greenhouse gas datasets and monitoring stations **(**Climate Transparency, 2021; Federal Ministry of Environment - FME, 2021).

Regrettably**,** extensive state-wide ground-based (in-situ) campaigns to measure, monitor and assess the concentration of greenhouse gas in the lower atmosphere are also lacking. Added to the aforementioned challenges is the fact that the current status of greenhouse gas emission in addition to the contribution from diverse anthropogenic sources is unknown. The only available record is the maiden national greenhouse gas catalog which covered 17 years starting from 2000 to 2017 and published in 2021 thus leaving a gap between 2018 till date. In the report, total emissions of greenhouse gas from all sources were estimated at about 10,386,957 Gg CO_2-eq with about carbon dioxide (CO_2) contributing up to 68%, methane (CH_4) 27% and nitrous oxide (N_2O) 5% **(**FME, 2021).

In as much as we see the FME (2021) as laudable baseline greenhouse gas emission and sequestration report of Nigeria, it is considered largely subjective with missing point-based and state-level assessment. Again, while the report is cautiously useful in country-wide tracking of greenhouse gas emissions**,** it may be incapable of supporting state-level policy initiatives. This is due to its coarseness**,** activity dataset discontinuities and excessive dependence on extrapolations from unverified quality global data catalogs and highly perforated archival datasets from allied national agencies. This therefore, calls for state-level assessment using a framework where location-based in-situ measurement is blended with remote sensing observations to derive a more reliable and integrated dataset to support state-level global warming and climate policies.

Application of Satellite Observation and Greenhouse Gases Monitoring

With the effect of greenhouse gas emissions on the environment becoming an issue of concern for policy makers, environmentalists and researchers in recent years (Anomohanran, 2012), it has fueled renewed interest which has led to a plethora of research activities aimed at measuring the quantity of emissions in a locality. The need to have a database to check the quantum of greenhouse gas emissions and measures trends overtime has become more imminent than ever. This is more so with the very limited information available with respect to the subject matter.

In recent years, there has been the development of greenhouse gases observing satellites which are a technology deployed to aid effective monitoring of greenhouse gas emissions (Lawal et al., 2023) This explains why utilizing satellite data to estimate a flux of greenhouse gas in the atmosphere has become a trending issue (Platonova & Klimova, 2021). Apart from the cost implications of this endeavour, it portends to be a reliable source of ascertaining the quantity of greenhouse gases emissions. Taking into cognizance the centrality of climate change to the entire globe and the long years of estimation, space agencies have called for the development of advanced technologies to map greenhouse gases and achieve precision (Broad, 2016).

Satellite observation carried out through remote sensing technology has a long history traceable to the post second world war era and the cold war (Onoda, 2008). Satellites have several uses to man. For instance, satellites have been used in pre, actual and post enumeration exercises (Guma et al., 2023) and to facilitate communication across geographical boundaries (Song et al., 2023). They have also been deployed in the monitoring of global environments especially with the rampaging and ravenous effects of climate change (Medina, 2010; Mirzakarimova et al., 2023). In recent years, several satellites have been built to provide observational platforms for monitoring ground-based Greenhouse gas concentrations in the space. For instance, GaoFen-5 satellite-II, an invention of the Chinese Space Agency have four sensor with enhanced capability and high precision of detecting the smallest fraction of O_2, CH_4, CO_2 at different wavelengths (Luo et al., 2023).

Similarly, IBUKI developed by the Japanese Space Authorities, equipped with multispectral sensors and commissioned in 2009 now measures the levels of CO_2 and CH_4 at very high temporal resolution the world over. This provides seamless access to high resolution satellite-generated datasets for real-time tracking of greenhouse gas and improvements in studies relating to changes in the earth’s climatic system (Imasu et al., 2023). Also, the Meteosat and Metop space-borne sensors carriers are satellite systems developed by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) have been monitoring greenhouse gas and other essential climatic variables (ECVs) since the 1970s till date. Presently, spatiotemporal studies of Greenhouse gas globally with the view to detecting past and present changes in addition to forecasting into the future can be carried out effortlessly (Agustí-Panareda et al., 2023; Zhang et al., 2023).

The United State’s National Aeronautics and Space Administration (NASA) with renewed commitment toward contributing to the scientific debates on global environmental change indicators and ECVs monitoring have also evolve several satellites systems, scanners and sensors with sophisticated capabilities. For instance, Aura Microwave Limb Sounder (AMLS) commissioned in 2004 track diurnal concentration of H_2O, O_3, HCl, CO, ClO and N_2O across the layers in the earth’s atmosphere. Now, long-termed climatic studies with particular reference to H_2O and N_2O in any location in the world can be executed using the high resolution AMLS-based datasets to support Greenhouse gas mitigation efforts (Livesey et al., 2021).

Also, reliable, accurate and real-time greenhouse gas datasets measured by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard NASA Aqua and Terra satellites can be retrieved for air quality and pollution studies. de Souza Maria et al (2023) recently utilised this satellite-based dataset in mapping the temporal and spatial pattern of CH_4 and CO_2 emitted during wildfire as well as impact on soil moisture and land surface temperature in Amazon region. The results showed average wet season CH_4 concentration of 1794ppb while it was 1789ppb in the dry season in the burnt areas investigated (de Souza Maria et al., 2023). Another study where satellite observation was used in greenhouse gas monitoring was in Southern Florida, USA and the results showed -4.9 ± 4.7 μmol CO_2 m^{-2} s^{-1} as well as 19.8 ± 41.1 nmol CH_4 m^{-2} s^{-1} in April 2022 with mangrove forest’s capability to sequester up to about 31.8 Tg CO_2-eq y^{-1} over a hundred years (Poulter et al., 2023).

While we allude to the efficacy of utilizing satellites in the monitoring of greenhouse gases emissions, it can be gleaned from extant literature that this practice is limited in developing climes especially our study area. The reason for this which is due to a plethora of factors calls for attention as this represents a significant pathway to address these accentuating emissions. This informs our embarking on this research with the hope of ascertaining the variations of greenhouse gases concentrations in delta state as well as the correlation between in-situ measurement and satellite remote sensing observation to support policy and scholarship.

MATERIALS AND METHODS

Geography of the Study Area

The study was conducted in Delta State, Nigeria with Bayelsa State and Atlantic Ocean (south), Ondo State (west), Edo State (north) as well as Anambra and Rivers States (east) as neighbouring spatial entities as seen in Figure 1. The latitudinal extent of Delta State is from 4^{O} 59' 13.211" – 6^{O} 27' 33.308" North of the Equator while the longitudinal coverage is from 4^{O} 27' 57.288" – 6^{O} 16' 28.085" East of the Greenwich. There are 25 Local Government Areas (LGAs) in Delta State grouped into three senatorial districts (SDs) namely, Delta North, Delta Central and Delta South. The 2006 population census showed that at 4,112,445 (2,069,309 males and 2,043,136 female) resided in Delta State with population density of 238 persons per square kilometer in a total land area of 17, 239.24km^2 (National Population Commission [NPopC], 2010).

Delta State is distinguished by an assortment of vegetation classes and resources among whom are lowland rainforest, water swamp forest as well as mangrove swamp forest with notable conservatories in Okpe-Urhobo, Ogwashi-Uku, Gilii-Gilli and Olague (Eguavoen, 2007). The lowland rainforest can be seen in Illah, Agbor and Ogwashu-Uku among other notable settlements in the state with diverse variety of trees including the Benin ebony (*Diospyros crassiflora),* White cedar (*Pycnathus angolensis*), charcoal-tree (*Trema orientalis)*, Star apple (*Chrysophyllum edule),* Lagos silk rubber *(Futumia elastica),* Oil palm (*Elais guineensis),* Raphia palm (*Berlinia auriculata) and host of* shrubs along with climbers (Okomu National Park, 2021).

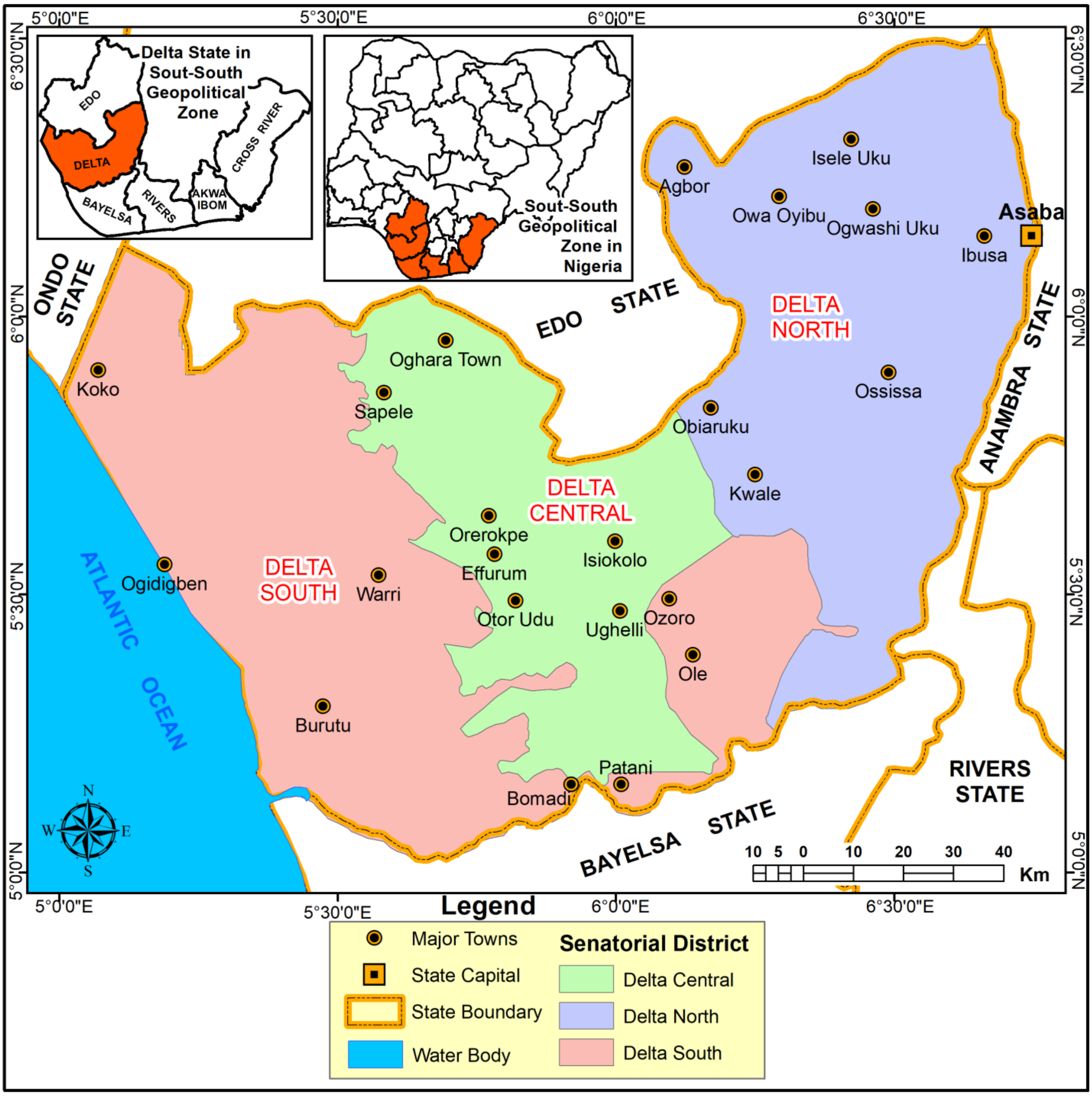

Figure 1: Delta State Showing Senatorial Districts and Major Towns
Source: Authors' Compilation (2023)

The fresh water swamp forests can still be spotted in Uzer, Oghar and Koko areas to name a few with notable trees, shrubs, grasses and climbers including *Christmas bush or dovewood* (*Alchornea cordifolia*), lipstick tree (*Bixa Orellana*), *stool or pattern woods* (*Alstonia boonei*), *cabbage plant (Anthocleista vogelii),* bamboo (*Bambusa vulgaris*) as well as *five-fingered morning glory* (*Ipomoea carica*) among others (Ugwuzor et al., 2022). Similarly, at the littoral fringe of Delta State, there is also mangrove swamp forest commonly with notable spots in Otor-Udu, Okerenkoko and Patani settlements. Some of the ominant plant diversities found in this vegetation zone includes: true/*red mangroves* (*Rhizophora racemosa*), nipah/mangrove palms (*Nypa fructicans*), *blackish mangroves* (*Avicennia germinans*) in addition to *leather/mangrove ferns* (*Acrostichum aureum*) and many others (Asuk et al., 2018).

An appraisal of key remotely-sensed essential climatic variables (ECVs) dataset released by the United State of America National Aeronautics and Space Administration (NASA) from January 1981 to December 2021 (Rienecker et al., 2011; Bosilovich et al., 2016; Zhang et al., 2021; Stackhouse et al., 2022) showed distinctive vagaries of climatic conditions across different ecological zones in Delta State. For instance, the mean annual relative humidity (RH) in lowland rain forest near Okwashi-Uku community is 85%, 86% in fresh water swamp ecological zone near Uzere and 88% in mangrove swamp area near Okerenkoko. The lowest RH of 74%, 76% and 80% are normally recorded in lowland rain forest (LRF), fresh water swamp forest (FWSF) and mangrove swamp forest (MSF) respectively the month of January. In contrast, the peak RH of 91%, 90% and 91% are normally recorded in LRF, FWSF and MSF respectively the month of September and October.

The three eco-vegetative zones (EVZs) in Delta State receive rainfall throughout the year occasioned by characteristic bi-modal pattern with the first peak in June while the second peak is in September. Mean annual rainfall is 1937mm in LRF, 2137mm in FWSF and 2001mm in MSF. The mean annual maximum temperature stands at 34^{O}C in LRF, 35^{O}C in FWSF and 34^{O}C in MSF. The hottest month in the year in LRF and MSF is February whereas in FWSF it is February and March. On the contrary, July and August remain months with lowest maximum temperature. Similarly, mean annual minimum temperature stand at 15^{O}C in LRF and in FWSF and 16^{O}C in MSF with January being the coldest month in the year across Delta State.

The temperature of the soil at root level in Delta State is generally described as isohyperthermic (Egbuchua, 2014) with average yearly values equals to or greater than 22^{O}C with marked seasonal variation below 5^{O}C (Cornell University, 2020). In terms of moisture, soils in Delta State are generally wet all through the year because of the abundant and even spread of rainfall (Egbuchua, 2014). Satellite-based dataset also show that the wind velocity at 10 meters from the ground across Delta State varies from light to gentle and moderate breeze ranging from 7.4m/s in LRF, 5.4m/s in FWSF and 3.7m/s in MSF. Sometimes, LRF may experience the wind velocity as low as 3.8m/s and as high as 7.4m/s in January.

In terms of livelihood, majority of the population are farmers although Delta state is known for illegal refineries which though boost the socio-economic status of its participants constitutes a significant degree of threat to their health and the environment. Trading is also a major activity embarked upon in Delta State especially by women who trade food commodities and other goods as a means of sustaining their families and augmenting the income of their spouse. Due to the rate of economic exploration in the state which has exposed the environment to a great deal of degradation, some of the livelihood activities of residents such as fishing have been adversely affected. This state of affairs has necessitated the indigenes to diversify their income streams by engaging in trading activities with some committing themselves to engage in illegal practices such as unauthorized refining of petroleum products among others.

The main staple food crops grown in the area include cassava (*Manihot esculenta*), white guinea yam (*Dioscorea rotundata*) water yam (*Dioscorea alata*), plantains/bananas (*Musa* spp.) cocoyam (*Colocasia esculenta*) and groundnuts (*Arachis hypogaea*). Other important cash crops produced in the area are the tree crops rubber and oil palm, both of which are tolerant of the acidic sandy soils (Osayande et al., 2016). The farmers also grow tree crops, especially rubber (*Hevea brasiliensis*) purely in order to generate income. Another cash crop which Delta State was among the leading producer is cocoa (*Theobroma cacao*) but inability of cocoa farmers to access stress-tolerant, more productive, diseases/pest resistant and best-output seedlings relegated commercial cocoa production and its associated value chains to the background (Ibirogba, 2021).

Fishing is another key livelihood engagement in Delta State and is carried out in the Atlantic Ocean, main streams, rivers, lakes and ponds with widespread deployment of nets, hooks, traps and other fishing gears. The catch consists mainly of tilapia (*Tilapia* spp.) and catfish (*Clarias* spp.). As a result of pollution of streams and rivers by crude oil during oil spills, mainly resulting from lapses by oil producing companies, the fishery resources of many rivers have been decimated (Olawuyi & Eludoyin, 2022). This has rendered farmers, fishermen jobless and they have to migrate to cities such as Warri and Sapele in search of jobs, thereby worsening social problems in the towns (Aweto, 2002).

The mineral resources are crude oil and natural gas, although there are deposits of clay locally utilized for pottery production. There are numerous oil fields in the area (e.g. Kokori and Kwale, Ebedei, etc) which make a significant contribution to Nigeria's crude oil output. Crude oil exploration has impacted negatively on the people and economy of oil bearing communities (Biukeme et al., 2022). Periodic spills have resulted in destruction of farmland, rubber plantations and aquatic biota, thereby undermining the rural economy and leaving the people unemployed and pauperized (Daku & Okechukwu, 2023).

Anthropogenic-induced ecological problems in Delta State includes: frequent crude oil spillage, gas flaring and solid waste pollution among others which are key culprits in greenhouse gases emission and subsequent global warming. The pollution of air and water resources have exposed the area to air and water borne diseases like cancer, malaria, diarrhea, typhoid and cholera have been reported in several parts of the state at various occasions (Osewezina, 2017). The commitment and proactive policies and strategies of mitigating these myriad untoward ecological externalities are what will engender sustainable development in the petroleum-affluent Niger Delta state.

Dataset and Sampling Procedures

The principal greenhouse gasses datasets used for the study include CO, NO_2 and SO_2 and were sourced from the archive of the European Space Agency (ESA, 2015) and field survey after reconnaissance trips to some of the sites in the study area. These datasets were to establish the correlation between in-situ measurement and satellite remote sensing observation in south-south of Nigeria. However, based on resource and time constraints, it was practically impossible to study the whole south-south of Nigeria which comprise of Akwa Ibom, Bayelsa, Cross Rivers, Delta, Edo and Rivers States hence, the necessity for sampling.

Thus, based on the existence of several major upstream and downstream crude oil and natural gas activities in the area, Delta State was purposively chosen for the study. This was followed by sub-division of Delta State into Senatorial Districts (SDs) namely, Delta South, Delta Central and Delta North with four communities each having oil and gas facilities as well as flow stations. This gave a total of 12 communities which also served as the locations for in-situ greenhouse gas measurement for ground trouthing the remotely-sensed satellite datasets. The geographic coordinates of the *in-situ* greenhouse gases data collection locations which were around oil and gas facilities in Delta State, Nigeria is presented in Table 1.

Table 1: Greenhouse Gases Ground Sampling Locations

Senatorial District	LGA	Communities	Latitude	Longitude	Elevation (Meters)
Delta North	Ukwuani	Ebedei	5.824552	6.255102	29
	Ndokwa West	Kwale	5.712138	6.423352	21
	Ndokwa West	Okpai	5.683835	6.591858	14
	Ndokwa West	Beneku	5.716763	6.484513	18
Delta	Ethiope East	Kokori	5.628901	6.031773	13

Central	Ethiope East	Orogun	5.683318	6.213720	18
	Ethiope East	Erhioke	5.896998	5.582431	9
	Ughelli North	Evwreni	5.394538	6.057511	12
Delta South	Isoko South-West	Uzere	5.327112	6.244326	15
	Isoko South	Olomoro-Oleh	5.413123	6.137883	14
	Isoko North	Ozoro	5.550826	6.231578	15
	Isoko North	Oweh	5.454311	6.202963	16

Methods of Data Collection

Two methods were used in the collection of data used for the study. The first method was the downloading of the remotely sensed based satellite concentration of CO, NO_2 and SO_2 from the online archive of the European Space Agency (ESA, 2015). The second method involved the use of Aeroqual S500 ambient air analyser used for greenhouse gases field sampling, measurement/mapping. During field survey, each of the parameters (CO, NO_2 and SO_2) were collected and analyzed on-site using the Aeroqual S500 ambient air analyser embedded with dedicated sensors and calibrated prior to use in line with ASTM D3249. The ambient greenhouse gases measurements were carried out upwind and down wind and at east, west, south and north position with respect to the prevailing wind direction to generate the quadruplicate reading at each locations.

Data Analysis

A blend of descriptive and inferential statistical frameworks was deployed in data analysis and presentation of results. Four measures of central tendencies and dispersion namely: mean, minimum, maximum and standard deviation were the descriptive statistics approaches deployed to investigate the variations of greenhouse gases concentrations in Delta State. Similarly, Independent Samples t-Test, analysis of variance (ANOVA), Tukey HSD test of multiple comparisons and simple linear regression (SLR) were the major inferential statistical frameworks used in the study.

The independent samples t-Test is an analytical approach for the comparison of averages from two different samples devoid of normality hypothesis although it assumes equality in standard deviations of the samples (Ross & Willson, 2017). The rationale for deploying the test was to establish whether the greenhouse gases concentration from *In-situ* measurement were similar to that retrieved from Satellite observation. Similarly, ANOVA is a parametric analytical tool for the evaluation of the variants in two or more sample distributions using the average in each cluster taking cognizance of a predictor and dependent variables, cluster normality, sample autonomy as well as identical difference (Delacre et al., 2019).

The basis for using ANOVA test was to further explore the existence or non-existence of spatial variation of greenhouse gases concentration across the three SDs in Delta State. Also, the justification for the utilisation of SLR was to probe the correlation of greenhouse gas with in-situ and satellite-based measurement. Also, SLR is a statistical approach deployed in modeling the correlation of distinct autonomous determinant factor with another solo subservient indicator (Kumari & Yadav, 2018). The rationalization for using SLR was to facilitate in examining the correlation of greenhouse gas from in-situ and satellite-based measurement. All the analyses were carried out with 95% confidence level two-tailed test using the International Business Machine (IBM) Statistical Packages for Social Sciences (SPSS) Version 22.

RESULTS AND DISCUSSION

Variations of Greenhouse Gases Concentrations in Delta State

The descriptive statistics of greenhouse gases concentrations from *In-situ* measurement and satellite observation across the three SDs in Delta State is presented in Table 2. As it could be seen, negligible minimum concentration were observed in all the sampled *In-situ* greenhouse gas measurements in Delta Central and Delta North SDs except CO which had 0.1ppm in Delta South SD. In contrast, minimum concentration of CO from satellite observation was 0.04853ppm in Delta North SD, 0.04930ppm in Delta Central SD and 0.04737ppm in Delta North SD. All the sampled *In-situ* greenhouse gas measurements in the three SDs recorded the same maximum concentrations of 0.02ppm while it varied from 0.00001ppm for SO_2 in Delta South and Delta North SDs to 0.05037ppm for CO in Delta Central.

Similarly, the mean concentration and standard deviation (SD) of CO from *In-situ* measurement was 0.137500pp with 0.05ppm respectively in Delta South SD while it was 0.049169ppm (mean) and 0.0005003ppm (SD) from Satellite observation. In Delta Central SD, CO recorded a mean value of 0.0075ppm and SD of 0.00683 from *In-situ* measurement even as it was 0.04988ppm (mean) and 0.0003946ppm (SD) from Satellite observation. In Delta North SD, CO also recorded a mean value of 0.0875ppm and SD of 0.050 from *In-situ* measurement whereas it was 0.048764ppm (mean) and 0.0008511ppm (SD) from Satellite observation.

Table 2: Descriptive Statistics of Greenhouse Gases Concentrations in Delta State

Senatorial District	Greenhouse Gas	*In-situ Measurement*				*Satellite Observation*			
		Minimum	Maximum	Mean	Standard Deviation	Minimum	Maximum	Mean	Standard Deviation
South	CO	0.10000	0.20000	0.137500	0.0500000	0.04853	0.04977	0.049169	0.0005003
	NO_2	0.00000	0.02000	0.006875	0.0070415	0.00005	0.00006	0.000056	0.0000034
	SO_2	0.00000	0.02000	0.010000	0.0081649	-0.00002	0.00001	-0.000005	0.0000103
Central	CO	0.00000	0.20000	0.106250	0.0573731	0.04930	0.05037	0.049880	0.0003946
	NO_2	0.00000	0.02000	0.007500	0.0068313	0.00006	0.00007	0.000061	0.0000030

	SO_2	0.00000	0.02000	0.008125	0.0075000	0.00000	0.00519	0.001452	0.0024584
North	CO	0.00000	0.20000	0.087500	0.0500000	0.04737	0.05003	0.048764	0.0008511
	NO_2	0.00000	0.02000	0.005000	0.0063246	0.00005	0.00007	0.000061	0.0000042
	SO_2	0.00000	0.02000	0.003750	0.0061914	0.00000	0.00001	0.0000028	0.0000048

Likewise, the mean concentration and SD of NO_2 from *In-situ* measurement was 0.006875pp with 0.0070415ppm respectively in Delta South SD while it was 0.000056ppm (mean) and 0.0000034ppm (SD) from Satellite observation. Concerning Delta Central SD, NO_2 recorded a mean value of 0.0075ppm and SD of 0.006831ppm from *In-situ* measurement just as it was 0.000061ppm (mean) and 0.000003ppm (SD) from Satellite observation. Pertaining to Delta North SD, NO_2 also recorded a mean value of 0.005ppm and SD of 0.0063246ppm from *In-situ* measurement whereas it was 0.000061ppm (mean) and 0.0000042ppm (SD) from Satellite observation.

Correspondingly, the mean concentration and SD of SO_2 from *In-situ* measurement was 0.01pp and 0.0081649ppm in that order in Delta South SD whereas it was -0.000005ppm (mean) and 0.0000103ppm (SD) from Satellite observation. Regarding Delta Central SD, SO_2 recorded a mean value of 0.008125ppm and SD of 0.0075ppm from *In-situ* measurement at the same time as it was 0.001452ppm (mean) and 0.0024584ppm (SD) from Satellite observation. With respect to Delta North SD, SO_2 also recorded a mean value of 0.00375ppm and SD of 0.0061914ppm from *In-situ* measurement despite the fact that it was 0.0000028ppm (mean) and 0.0000048ppm (SD) from Satellite observation. Interestingly, the mean values of CO, NO_2 and SO_2 were comparatively lower the outcome of the research carried out by Ahmad et al (2018) from 1999 to 2011 in the state of Terengganu in Malaysia.

The results of independent samples t-Test of similarity and/or difference in greenhouse gases concentration from *In-situ* measurement and Satellite observation is presented in Table 3. As it could be seen, despite the fact that there were marked variations in the t-values from 4.24 for SO_2 to 5.27 for CO, the Mean Difference between *In-situ* measurement and satellite observation of greenhouse gases in Delta State were statistically significant at 95% confidence level. Besides, ANOVA outcome measuring the spatial variation of greenhouse gases concentration across the three SDs in Delta State is shown in Table 4. It is obvious of the occurrence of statistical significant difference in the concentration of CO (p-value of $0.033<0.05$) from In-situ measurement across the SDs in Delta State. While NO_2 and SO_2 from In-situ measurement and SO_2 from Satellite observation showed no marked spatial variations, CO (p-value of $0.010 < 0.05$) and NO_2 (p-value of $0.028<0.05$) from Satellite observation demonstrated statistical significant spatial variation across the SDs in Delta State.

Nevertheless, to ascertain empirically, where the actual spatial variability occurred, we computed the Tukey HSD test of multiple comparisons of mean concentration of greenhouse gases from *In-situ* measurement and satellite observation across the three SDs in Delta State. The results as seen in Table 5 showed that the actual significant spatial variation of CO from *In-situ* measurement existed between Delta South SD and Delta North SD with Mean Difference (I-J) of – 0.05 (p-value of $0.027 < 0.05$). Also, the real significant spatial variation of CO from satellite observation existed between Delta Central SD and Delta North SD with Mean Difference (I-J) of 0.001116 (p-value of $0.007 < 0.05$). Besides, the actual significant spatial variation of NO_2 from satellite observation existed between Delta North SD and Delta South SD with Mean Difference (I-J) of 0.00000504 (p-value of $0.038 < 0.05$).

Table 3: Test of Difference between *In-situ* Measurement and Satellite Observation of Greenhouse Gases in Delta State

		Levene's Test for Equality of Variances		**t-test for Equality of Means**						
		F	**Sig.**	**t**	**df**	**Sig. (2-tailed)**	**Mean Difference**	**Standard Error Difference**	**95% Confidence Interval of the Difference**	
									Lower	**Upper**
CO	Equal variances assumed	18.55	0.00	5.27	69	0.00	0.0612	0.01162	0.03803	0.0844
	Equal variances not assumed			7.64	47.040	0.00	0.0612	0.00801	0.04509	0.0773
NO_2	Equal variances assumed	90.38	0.00	4.58	69	0.00	0.0064	0.00140	0.00361	0.0092
	Equal variances not assumed			6.64	47.000	0.00	0.0064	0.00096	0.00446	0.0083
SO_2	Equal variances assumed	58.45	0.00	4.24	69	0.00	0.0069	0.00161	0.00363	0.0101

	Equal variances not assumed	5.99	53.711	0.00	0.0069	0.00114	0.00455	0.0091

Table 4: ANOVA Test of Spatial Variation in Mean Concentration of Greenhouse Gases from *In-situ* Measurement and Satellite Observation in Delta State

Test variables		Sum of Squares	df	Mean Square	F	Sig.
CO (In-situ)	Between Groups	0.02	2	0.01	3.693	0.033*
	Within Groups	0.124	45	0.003		
	Total	0.145	47			
NO_2 (In-situ)	Between Groups	0	2	0	0.596	0.555
	Within Groups	0.002	45	0		
	Total	0.002	47			
SO_2 (In-situ)	Between Groups	0	2	0	3.062	0.057
	Within Groups	0.002	45	0		
	Total	0.003	47			
CO (Satellite)	Between Groups	.000	2	.000	5.907	.010*
	Within Groups	.000	20	.000		
	Total	.000	22			
NO_2 (Satellite)	Between Groups	.000	2	.000	4.288	.028*
	Within Groups	.000	20	.000		
	Total	.000	22			
SO_2 (Satellite)	Between Groups	.000	2	.000	2.833	.083
	Within Groups	.000	20	.000		
	Total	.000	22			

* The mean difference is significant at the 0.05 level.

Table 5: Tukey HSD Test of Multiple Comparisons of Mean Concentration of Greenhouse Gases from *In-situ* Measurement and Satellite Observation Across Senatorial Districts in Delta State

Dependent Variable			Mean Difference (I-J)	Standard Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
CO (In-situ)	Delta South	Delta Central	0.031250	.01858726	.223	-.0137983	.0762983
		Delta North	.0500000*	.01858726	.027	.0049517	.0950483
	Delta Central	Delta South	-0.0312500	.01858726	.223	-.0762983	.0137983
		Delta North	0.0187500	.01858726	.575	-.0262983	.0637983
	Delta North	Delta South	-0.050000*	.01858726	.027	-.0950483	-.0049517
		Delta Central	-0.0187500	.01858726	.575	-.0637983	.0262983
CO (Satellite)	Delta South	Delta Central	-0.0007112	.00036702	.154	-.0016398	.0002174
		Delta North	0.0004048	.00034067	.474	-.0004571	.0012667
	Delta Central	Delta South	0.0007112	.00036702	.154	-.0002174	.0016398
		Delta North	0.001116*	.00032510	.007	.0002935	.0019385
	Delta North	Delta South	-0.0004048	.00034067	.474	-.0012667	.0004571
		Delta Central	-0.001116*	.00032510	.007	-.0019385	-.0002935
NO_2 (Satellite)	Delta South	Delta Central	-0.0000052	.00000203	.050	-.0000103	.0000000
		Delta North	-0.00000504*	.00000189	.038	-.0000098	-.0000003
	Delta Central	Delta South	.00000515	.00000203	.050	.0000000	.0000103
		Delta North	0.00000010	.00000180	.998	-.0000045	.0000047
	Delta North	Delta South	.00000504*	.00000189	.038	.0000003	.0000098
		Delta Central	-0.00000010	.00000180	.998	-.0000047	.0000045

*. The mean difference is significant at the 0.05 level.

Correlation of Greenhouse Gases from In-situ and Satellite-based Measurement

The need to establish the associational relationship between greenhouse gas datasets obtained from ground measurement and that retrieved from satellite observation cannot be over-emphasized. This is to establish to degree of validity in addition to the extent of accuracy and reliability of remotely-sensed earth's observational resources in global environmental change indicators monitoring and assessments. A parametric-based simple linear regression (SLR) framework facilitated the establishment of the association and the result is presented in Table 6

Table 6: Regression Results of In-situ and Satellite of Greenhouse Gases Dataset

Greenhouse Gas	Summary Statistics	Senatorial District		
		Delta South	**Delta Central**	**Delta North**
Carbon(ii) oxide (CO) (ppm)	R	0.806*	0.302	0.294
	R^2	0.649	0.091	0.086
	Adjusted R^2	0.532	-0.363	-0.370
	Standard Error of the Estimate	0.007375	0.00826301	0.00789235
	Sig. (T-test of R)	0.006	0.123	0.364
Sulphur(iv) oxide (SO_2) (ppm)	R	0.692*	0.272	0.324
	R^2	0.479	0.074	0.105
	Adjusted R^2	0.306	-0.389	-0.342
	Standard Error of the Estimate	0.00002169	0.02726830	0.00415674
	Sig. (T-test of R)	0.012	0.588	0.837
Nitrogen(iv) oxide (NO_2) (ppm)	R	0.448*	0.471	0.250*
	R^2	0.201	0.222	0.062
	Adjusted R^2	-0.066	-0.167	-0.406
	Standard Error of the Estimate	0.00000768	0.00000697	0.00000280
	Sig. (T-test of R)	0.001	0.215	0.003

* Regression coefficient significant at 0.05 (2-tailled test)

As it could be seen, there is a marked variation in the degrees of association between the investigated greenhouse gases (CO, SO_2 and NO_2) across the three senatorial districts (SD) in Delta State. In Delta South SD, the regression between CO dataset obtained from ground measurement and that retrieved from satellite observation returned a regression coefficient (R) of 0.806, in Delta Central SD (R = 0.302) while it was 0.294 in Delta North SD. Similarly, R of in-situ and satellite-retrieved SO_2 were 0.692 in Delta South SD, 0.272 in Delta Central SD and 0.324 in Delta North SD. Again, R of in-situ and satellite-retrieved NO_2 were 0.448 in Delta South SD, 0.471 in Delta Central SD and 0.250 in Delta North SD.

Interestingly, when the R of CO, SO_2 and NO_2 across the three SD in Delta State were subjected to tests of significance, it was found that all the investigated greenhouse gases in Delta South SD were statistically significant while it was not statistically significant in the other SDs at 95% confidence level. In contrast, R of CO, SO_2 and NO_2 were not statistically significant in Delta Central SD. Besides, in Delta North SD, R of CO and SO_2 were also not statistically significant while NO_2 was statistically significant in Delta North SD.

The linear relationship between ground-based and satellite-derived greenhouse gases in Delta State is also presented in Figures 2 – 10. As it could be seen in Figure 2, the coefficient of multiple determination (R^2) of the relationship between ground-based CO and satellite-based CO is 0.641. This value however translates to the fact that up to about 64% of the variation in ground concentration of CO in Delta South SD can be explained by satellite-based measurement. In Figure 3, the R^2 of 0.091 is a pointer that only about 9% of the variation in ground-based CO level in Delta Central SD can be statistically explained by satellite-based measurement. Taking a look at Figure 4, the R^2 of 0.086 indicates that about 8.6% of the deviation in ground-based CO level in Delta North SD can be statistically clarified by satellite-based measurement.

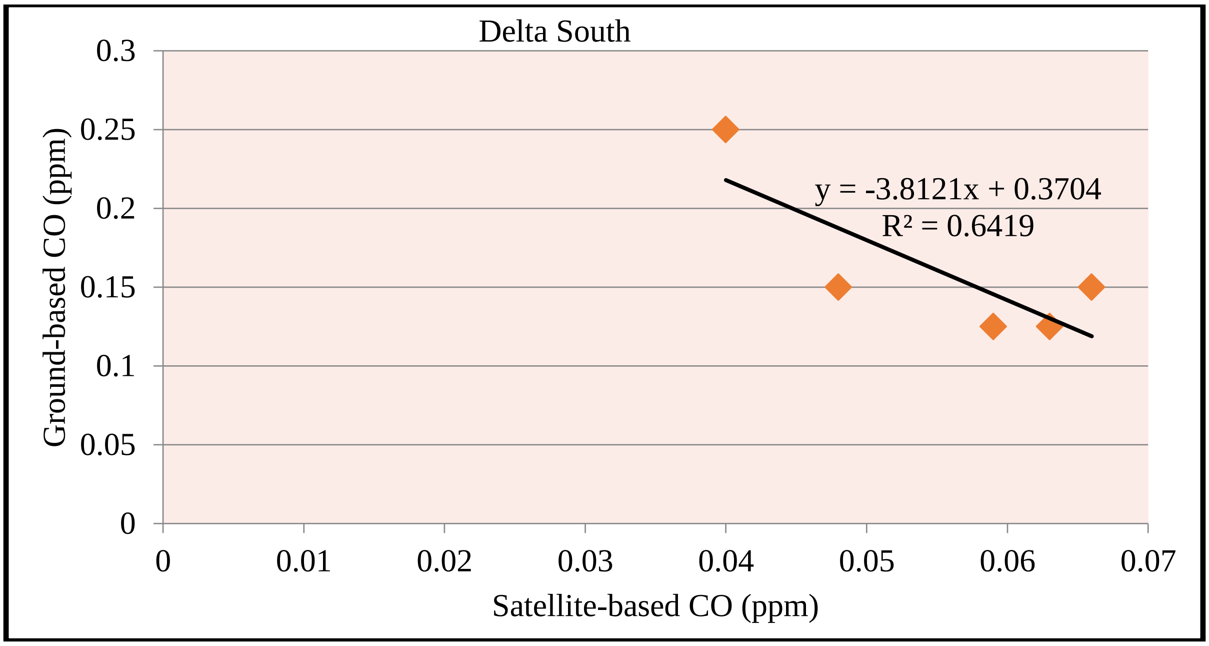

Figure 2: Linear Relationship between Ground and Satellite CO in Delta South SD

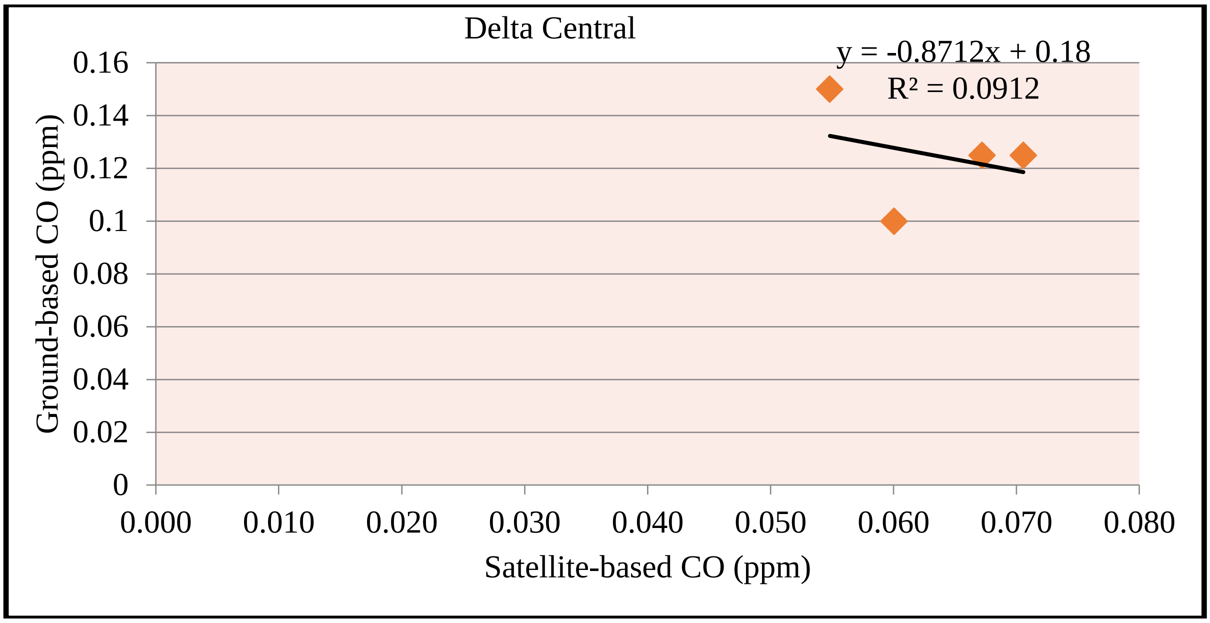

Figure 3: Linear Relationship between Ground and Satellite CO in Delta Central SD

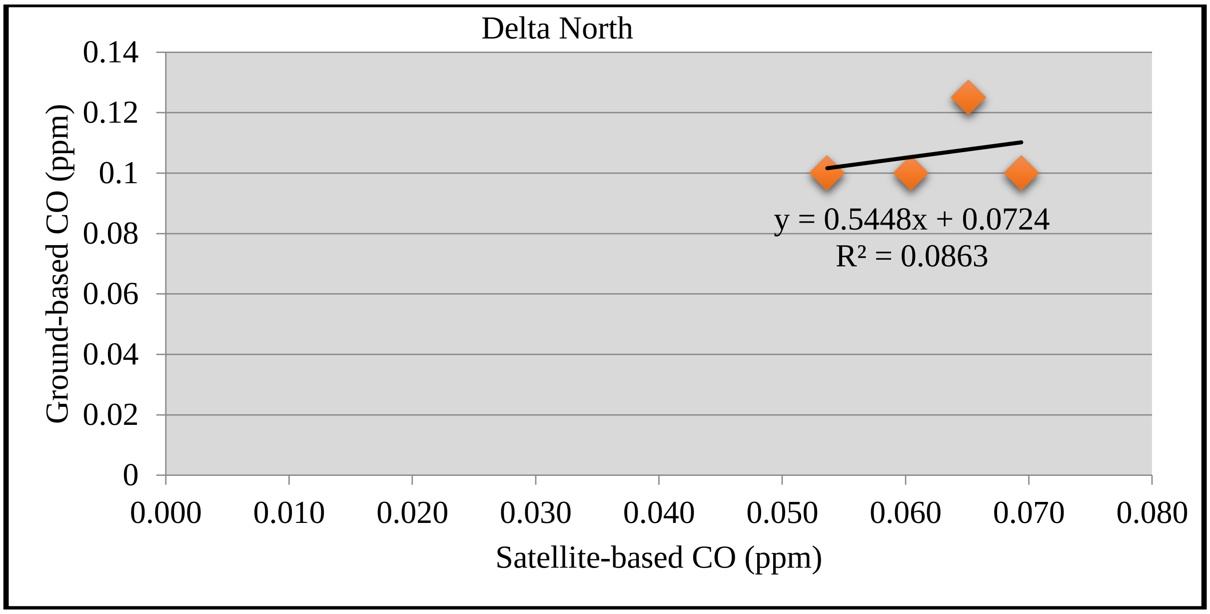

Figure 4: Linear Relationship between Ground and Satellite CO in Delta North SD

Again, the linearity in the association between ground-based and satellite-derived SO_2 in Delta State is also presented in Figures 5 – 7. As it could be seen in Figure 5, R^2 of the relationship between ground-based SO_2 and satellite-based SO_2 is 0.480. This figure nevertheless portrays to the fact that close to about 48% of the variability in ground concentration of SO_2 in Delta South SD can be justified by satellite-based measurement. In Figure 6, the R^2 of 0.073 signifies that only about 7.3% of the variation in ground-based SO_2 level in Delta Central SD can be statistically explained by satellite-based measurement. Regarding Figure 7, the R^2 of 0.105 indicates that about 11% of the deviation in ground-based SO_2 level in Delta North SD can be statistically clarified by satellite-based measurement.

Similarly, the linear relationship between ground-based and satellite-derived NO_2 in Delta State is also presented in Figures 8 – 10. As it could be seen in Figure 8, R^2 of the relationship between ground-based NO_2 and satellite-based NO_2 is 0.219. This value nevertheless portrays to the fact that approximately 22% of the variability in ground concentration of SO_2 in Delta South SD can be accounted by satellite-based measurement. In Figure 9, the R^2 of 0.240 signifies that only about 24% of the variation in ground-based NO_2 level in Delta Central SD can be statistically explained by satellite-based measurement. With respect to Figure 10, the R^2 of 0.022 indicates that only about 2.2% of the difference in ground-based NO_2 level in Delta North SD can be statistically clarified by satellite-based measurement.

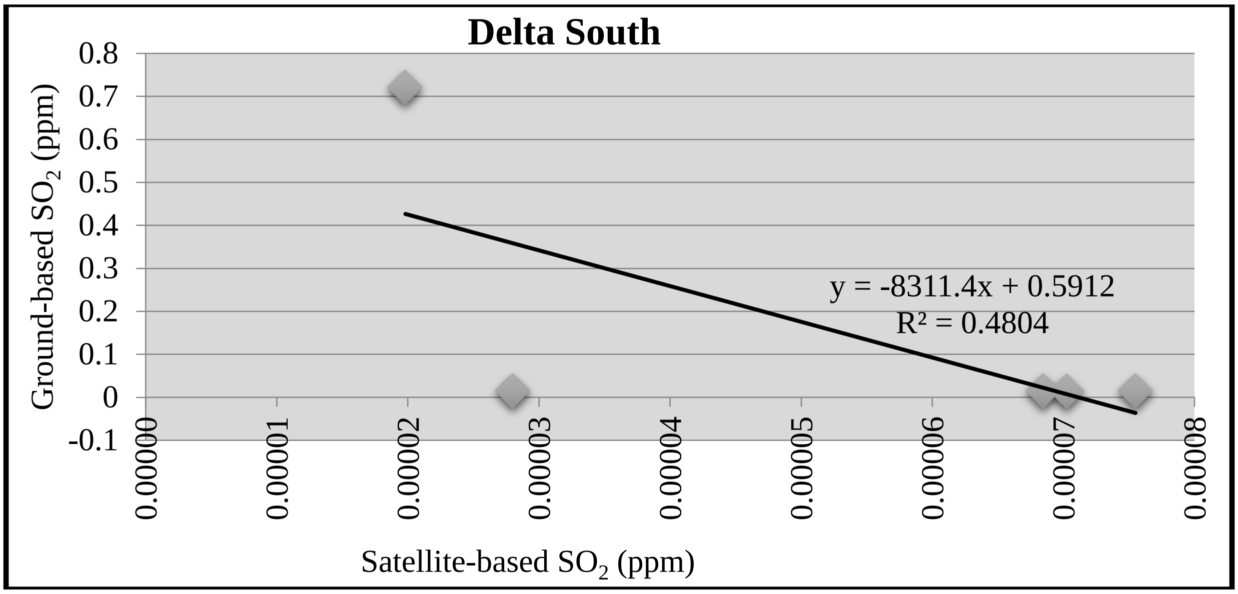

Figure 5: Linear Relationship between Ground and Satellite SO_2 in Delta South SD

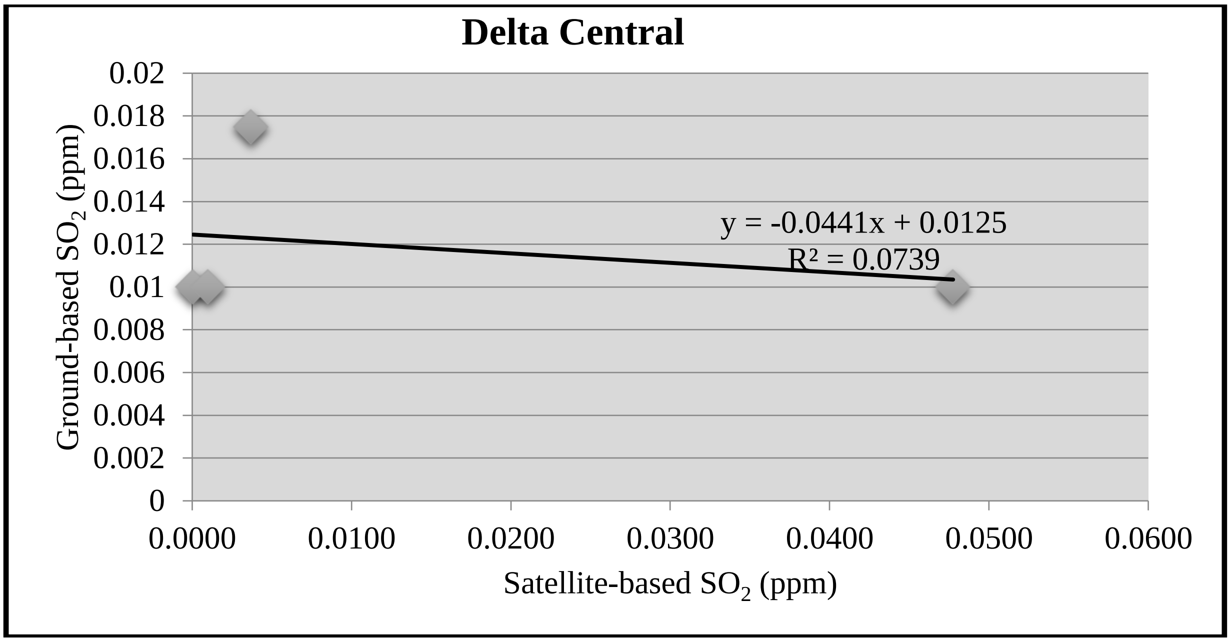

Figure 6: Linear Relationship between Ground and Satellite SO_2 in Delta Central SD

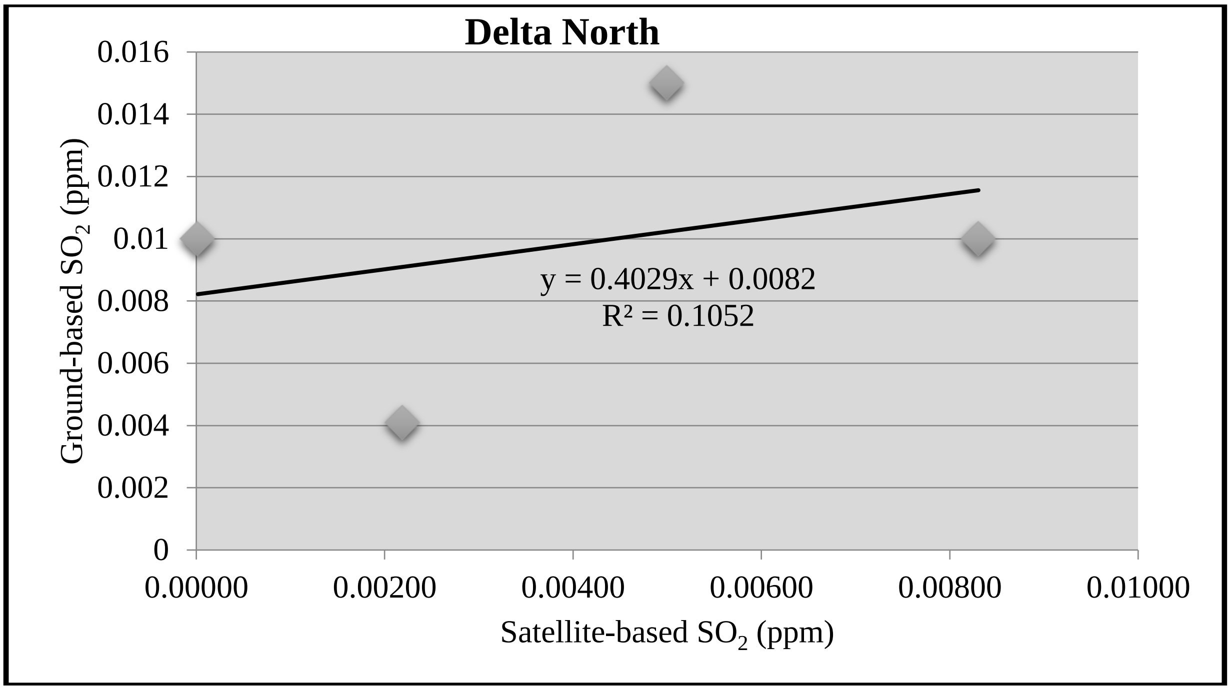

Figure 7: Linear Relationship between Ground and Satellite SO_2 in Delta North SD

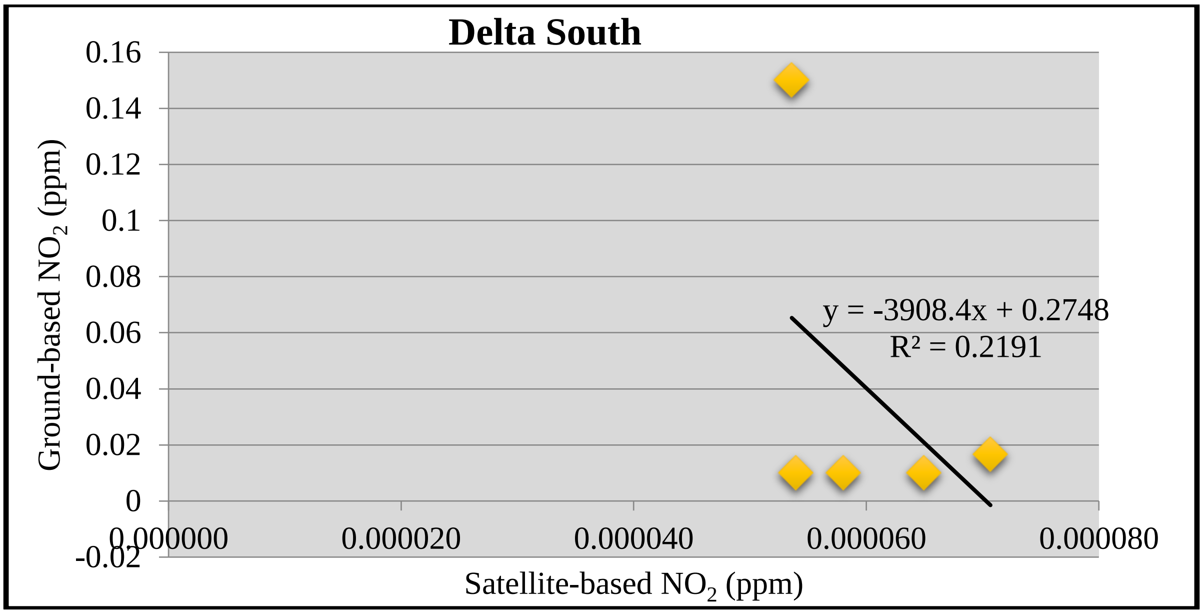

Figure 8: Linear Relationship between Ground and Satellite NO_2 in Delta South SD

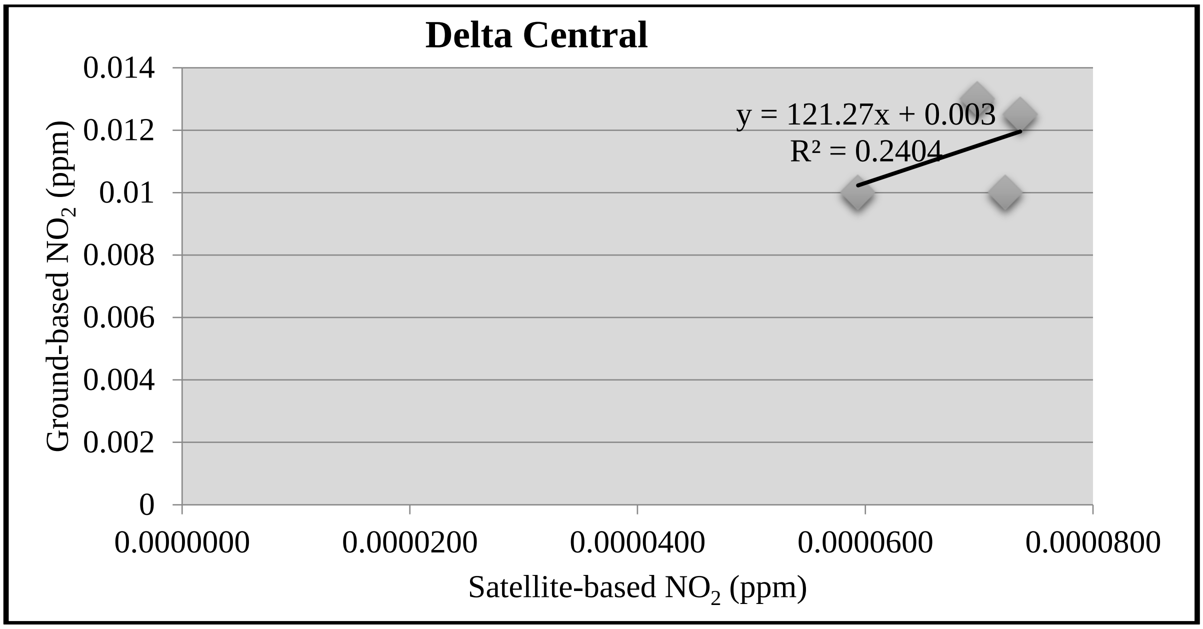

Figure 9: Linear Relationship between Ground and Satellite NO_2 in Delta Central SD

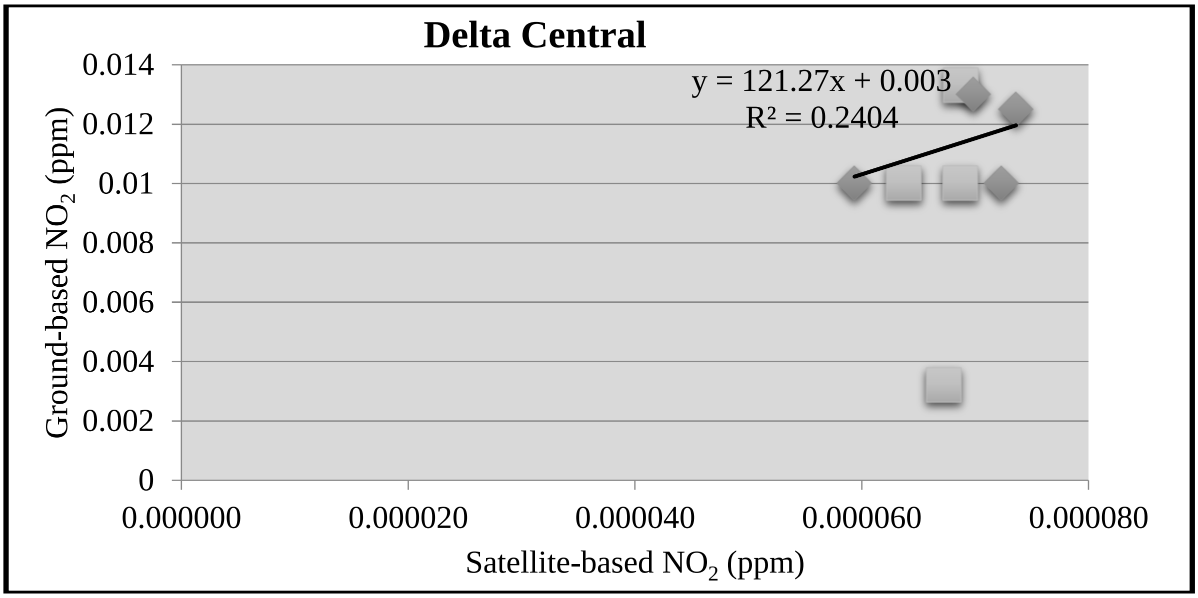

Figure 10: Linear Relationship between Ground and Satellite NO_2 in Delta North SD

The implication of these finding is that in locations where the level of association is 0.5 or greater, remotely-sensed satellite-based measurement can be deployed in the assessment of Greenhouse gas. On the contrary, in-situ measurements of Greenhouse gas work better in locations with low ground-to-satellite correlations. This finding is consistent with earlier and recent studies of Hasan et al (2014), Choudhary et al (2022) and Hashim et al (2023) among others. For instance, less than 50% R^2 have been reported by Hasan et al (2014) while probing the correlation of Greenhouse gas from in-situ measurements and remotely-sensed satellite-based observations. In the Iraqi city of Kirkuk, the authors uncovered R^2 of 0.48 and 0.52 between the thermal bands 10 and 11 respectively of Landsat-8 generated and in-situ SO_2 data thus proving the utilitarian value of remotely-sensed data in monitoring environmental change indicators.

Similarly, in a study epoch spanning 2012 to 2017 in the Indian metropolitan city of New Delhi, Choudhary et al (2022) uncovered R^2 of 0.383 with root mean square error (RMSE) of 17.672 between NO_2 dataset derived from space-borne EO sensors and in-situ data. In contrast, R^2 of 0.68 was observed between in-situ CO and remotely-sensed unmanned aerial vehicle (UAV) measurement, 0.71 for CO_2, 0.63 for NO_2 and 0.42 for CH_4 across various land use in Malaysian industrialized areas (Hashim et al., 2023). Cusworth et al (2023) assessment of the correlation of satellite-based data and ground observation of CO_2 emitted by 34 fossilized electricity generating stations in 2021 to 2022 across USA, Germany, Kuwait, India, Indonesia, South Korea, Japan, China and South Africa also resulted in R^2 of 0.43 with improved value of $R^2 = 0.51$ using Gaussian CO_2 column framework.

CONCLUSION

The study is able to unravel distinct statistical disparity between *In-situ* measurement and satellite observation of greenhouse gases in Delta State with actual variation of *In-situ*-based CO domiciled between Delta South SD and Delta

North SD (p-value of $0.027 < 0.05$). Besides, the real significant spatial variation of satellite-based CO also existed between Delta Central SD and Delta North SD (p-value of $0.007 < 0.05$). Similarly, the actual spatial variability of satellite-based NO_2 existed between Delta North SD and Delta South SD with (p-value of $0.038 < 0.05$). Validity, extent of accuracy and reliability of remotely-sensed greenhouse gases when correlated with in-situ observations in Delta State was established at 95% confidence level. Specifically, CO, SO_2 and NO_2 in Delta South SD were statistically significant while it was not significant in the other SDs. In contrast, R of CO and SO_2 were not statistically significant in Delta Central and Delta North SDs while NO_2 was significant in Delta North SD but not significant in Delta Central SD. The paper recommends the exploration and adoption of the comparative advantage as well as the utilitarian worth offered by space-borne satellite remote sensing resources and GIS in periodic monitoring, mapping and assessments of environmental change indicators.

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AUTHOR'S CONTRIBUTIONS:

Nicholas Omougbo UWADIA, Chukwudi Nnaemeka EMERIBE, Peter Adamson NDEM, Obot Akpan IBANGA and Emmanuel Temiotan OGBOMIDA, conceived research, designed the study protocol, developed the study methodology, analyzed the data and wrote the manuscript. Edidiong Samuel AKPABIO handled literature review embedded in the introductory section of the manuscript, grammatical editing of the entire paper, formatting of in-text citation and referencing in line with the journal guidelines. Nelson Onaivi OSEH, Akinjagunla AKINMOLADUN and Thompson Aiyevbekpen EHIGIEGBA were responsible for data entry and administrative support. All authors have read, reviewed and approved the final manuscript before submission.

CONFLICT OF INTEREST

The authors declare the non-existence of any conflict of interest in the paper.

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