A GIS-based assessment of the suitability of SCIAMACHY satellite sensor measurements for estimating reliable CO concentrations in a low-latitude climate

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Abstract

An assessment of the reliability of the SCIAMACHY satellite sensor measurements to interpolate tropospheric concentrations of carbon monoxide considering the low-latitude climate of the Niger Delta region in Nigeria was conducted. Monthly SCIAMACHY CO column measurements from January 2003 to December 2005 were interpolated using ordinary kriging technique. The spatio-temporal variations observed in the reliability were based on proximity to the Atlantic Ocean, seasonal variations in the intensities of rainfall and relative humidity, the presence of dust particles from the Sahara desert, industrialization in Southwest Nigeria and biomass burning during the dry season in Northern Nigeria. Spatial reliability of 74% and 42% are observed for the inland and coastal areas respectively. Temporally, average reliability of 61% and 55% occur during the dry and wet seasons respectively. Reliability in the inland and coastal areas was 72% and 38% during the wet season, and 75% and 46% during the dry season respectively. Based on the results, the WFM-DOAS SCIAMACHY CO data product used for this study is therefore relevant in the assessment of CO concentrations in developing countries within the low latitudes that could not afford monitoring infrastructure due to the required high costs. Although the SCIAMACHY sensor is no longer available, it provided cost-effective, reliable and accessible data that could support air quality assessment in developing countries.

Keywords: SCIAMACHY; carbon monoxide; low latitude; kriging; GIS; Niger Delta

1. Introduction

Optical satellite sensors continue to play significant roles in the local, regional and global assessment of concentrations of air pollutants and greenhouse gases (GHGs) within the lower troposphere (Buchwitz et al. 2006; Gupta et al. 2006; Lamsal et al. 2008; Li et al. 2011; Martin, 2008; Osterman et al. 2007; Shim et al. 2009). Although they are limited in their ability to directly estimate concentrations below cloud cover and in areas with high relative humidity (Levelt et al. 2006), mechanisms are currently available to estimate and correct for amounts of trace gas hidden below the clouds (Butchwitz et al. 2006; Dils et al. 2006; Frankenberg et al. 2005; Levelt et al. 2006; Ziemke et al. 2006). With a growing need for reliable spatially enhanced, timely and comparable data for air quality modeling (European Environmental Agency, EEA, 1999), and the availability and cost limitations of in-situ measurements in remote areas and developing countries (Gupta et al. 2006), satellite sensor measurements are increasingly relevant in providing continuous, reliable and comparable local and regional data for air quality purposes (Sifakis, 1999). Such data are being used in conjunction with in-situ measurements to provide ground-level concentrations of air pollutants (Lamsal et al. 2008). The use of satellite-based measurements for air quality assessment still requires ground-based measurement support. Methodologies that combine satellite-based measurements with ground based measurements and chemical transport models to predict ground-level concentrations of air pollutants have been developed (Di Nicolatino et al. 2009; Gupta et al. 2006; Hutchison, 2003; Lamsal et al. 2008). This paper presents an assessment of the suitability of the available total column measurements of carbon monoxide (CO) from the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) to generate reliable estimates over the Niger Delta region of Nigeria. This will be useful in determining the relevance of its measurements to support the assessment of the concentrations of air pollutants considering the atmospheric interferences over the representative low-latitude region. This assessment considers seasonal variations in the climatic conditions within this low-latitude region and proximity to the coast. The suitability assessment is based on a categorization of reliability of estimates generated from kriging interpolation of the SCIAMACHY sensor column measurements.

The Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) sensor was launched on-board the European Space Agency (ESA) Envisat in March 2002. The sensor measured atmospheric trace gases in the ultraviolet, visible and near-infrared wavelength region (240 – 2380 nm) at a moderate spectral resolution of 0.2 – 1.5 nm (Bovensmann et al. 1999). The trace gases measured by SCIAMACHY include carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nitrogen dioxide (NO_2), ozone (O_3) and sulphur dioxide (SO_2) in the atmosphere (Bovensmann et al. 1999; Buchwitz et al. 2006). The ground sampling distances (GSD) at nadir at which SCIAMACHY measured atmospheric trace gases vary. For instance, the ground sampling distance (GSD) for CO is 120 x 30 km, and for CO_2 and CH_4 is 60 x 30 km (Buchwitz et al. 2006). According to Bovensmann et al. (1999) and Gottwald et al. (2006), the objective of the SCIAMACHY mission was to improve the understanding of scientists on global atmospheric conditions and changes due to natural and anthropogenic activities.

Although SCIAMACHY is no longer available, the measurements taken by the sensor during its lifespan are very relevant in understanding the spatio-temporal distribution of trace gas concentrations globally, including carbon monoxide.

Carbon monoxide is a criteria air pollutant with serious health impacts on humans and animals. The pollutant is released from anthropogenic activities which include transport, industrial production, power generation, energy use, gas flaring and burning of fossil fuels and biomass (Barker et al. 2007; Forster et al. 2007; Huston and Marland, 2003; Kampas and Castanas, 2008; UNEP, 2005, USEPA, 2006). A number of algorithms developed for the retrieval of CO total column measurements from SCIAMACHY are based on the principle of the differential optical absorption spectroscopy (DOAS) (Buchwitz et al. 2006; Dils et al, 2006; Frankenberg et al. 2005; Gloudemans et al. 2005). The DOAS technique has the capability to differentiate highly-reactive trace gases in a well-mixed atmosphere based on variations in their absorption wavelengths, usually in the near ultraviolet and visible wavelengths of the electromagnetic spectrum (Honninger et al. 2004; Platt and Strutz, 2008; Richter, 2006; Strutz and Platt, 1996).

Buchwitz et al. (2007) retrieved vertical columns of CO, CO_2 and CH_4 using the Weighting Function Modified Differential Optical Absorption Spectroscopy (WFM-DOAS) algorithm. The algorithm is a least squares method based on scaling pre-selected vertical profiles, which produce vertical columns of trace gases (Buchwitz et al. 2007). The spectral fitting window for the retrieval of CO is 2324.4-2335.0 nm (Channel 8) (Buchwitz et al. 2009). The SCIAMACHY CO data product retrieved from the WFM-DOAS algorithm is available from January 2003 to December 2005. The 2003 data was retrieved using the WFM-DOAS version 0.5 (Buchwitz et al. 2006), while the 2004 to 2005 data were retrieved using the WFM-DOAS version 0.6 (Buchwitz et al. 2009).

Dils et al. (2006) validated the SCIAMACHY data products retrieved from WFM-DOAS (version 0.5 for CO) from January to December 2003 using a quasi-global network of eleven Fourier-transform infrared (FTIR) spectrometers operated at the Network for Detection of Stratospheric Change (NDSC) stations at different locations around the globe. The FTIR data were obtained under clear-sky conditions. Therefore, the data used for the comparison do not represent daily coverage. Consequently, the FTIR data were interpolated to third-order polynomial to generate daily representations, which were used for the comparison (Dils et al. 2006). The comparison showed that CO measurements produced average bias estimated at +9.2% for the 2003 data and +0.5% for the 2004 data. The standard deviation of the difference for 2003 and 2005 were +/- 20.5% and +/- 21.0% respectively (Buchwitz et al. 2009; Dils et al. 2006). In addition to the FTIR validation, the retrieved CO data was compared with Measurement of Pollution in the Troposphere (MOPITT) data products during the same period, and were found to be within an acceptable 20% error limit (Buchwitz et al. 2007). The measurements were generally more reliable under cloud-free conditions. The low-level reliability of SCIAMACHY measurements under cloudy conditions necessitate the importance of further studies on its relevance to monitoring concentrations of CO in a developing region within a tropical environment such as the Niger Delta.

The Niger Delta region is located in the southern part of Nigeria in West Africa, within the low latitudes of 4° 15'N and 9° 21'N and longitude 4° 21'E and 9° 29'E. For this study, the Niger Delta has been defined using the administrative boundary of the nine States out of the thirty-six States of the Nigerian Federation where oil and gas activities take place (UNDP, 2006). Included in this area is the geographical delta area formed by the Niger River (ERML, 1997). The Niger Delta has a tropical monsoon climate along the coast, with rainfall peaks in June and September / October. As a result, the region experiences partial or full cloud coverage almost all year round. According to Leroux (2001) mean rainfall range in the Niger Delta region is at a minimum in December / January (estimated at 20 mm – 75 mm) and at its maximum in June (estimated at 300 mm – 700 mm). The annual mean total rainfall is between 1,500 mm and 3,000 mm; although coastal towns receive more rainfall (e.g. average annual rainfall in Bonny town is estimated at 4,520 mm). Mean monthly temperatures in the Niger Delta are lowest in August during the rainy season (24 °C – 25 °C), and highest around March / April (27 °C - 29 °C) in the period between the end of the dry season and the commencement of the rainy season. The annual mean temperature is 26 °C. The maximum daily temperatures are recorded between January and March (33 °C), while the minimum daily temperatures are recorded in July and December (21 °C) (Leroux, 2001).

2. Materials and methods

2.1. Datasets

2.1.1. SCIAMACHY CO data

SCIAMACHY WFM-DOAS Level 2B CO data product consists of files containing monthly total column classified as "*good*". The Level 2B data have been extracted from the raw Level 2A datasets consisting files of each orbit of the satellite sensor (Buchwitz, 2009). Each file consists of detailed header information and a table of data. The header information gives a detailed description of each column in the table of data. The location of a column measurement in the data product is defined by the central x- and y-coordinates of a specific area defined by a set of four x- and y- coordinates

2.1.2. Meteorological data

Meteorological data from eight stations within the Niger Delta region were acquired and processed from January 2001 to December 2005 in order to understand the climatic variations in the region during the period of study. Four of the stations are located in the coastal part of the region and the remaining four are located in the inland part of the region (Table 1). The meteorological parameters that affect optical satellite measurements and atmospheric concentrations of pollutants were given particular priority over others. These parameters are cloud, relative humidity, rainfall and wind direction.

Table 1: The eight meteorological stations located within the Niger Delta region

Station	Location	Longitude (Decimal degrees)	Latitude (Decimal degrees)	Height Above Sea Level (Metres)
Akure	Inland	5.18	7.17	375.0
Ondo	Inland	4.50	7.06	287.3
Owerri	Inland	7.00	5.29	91.0
Uyo	Inland	7.55	5.30	38.0
Benin	Coastal	5.06	6.19	77.8
Calabar	Coastal	8.21	4.58	61.9
Port Harcourt	Coastal	7.01	4.51	19.0
Warri	Coastal	5.44	5.41	6.1

2.2. Data processing

2.2.1. Demarcation of the Niger Delta region

In order to verify the extent of the suitability of SCIAMACHY satellite sensor measurements to estimate concentrations of CO over the Niger Delta region, considering climatic seasons, the region is demarcated into four segments - northwest, northeast, southwest and southeast. The bases for the demarcation are the hydrology and proximity to the Atlantic Ocean. Based on these, the region is categorized into coastal (or southern) and inland (or northern) sections (Fig. 1). The hydrological consideration focused on the major tributaries of and the delta formed by the Niger River, the majority of which are within the southern sections.

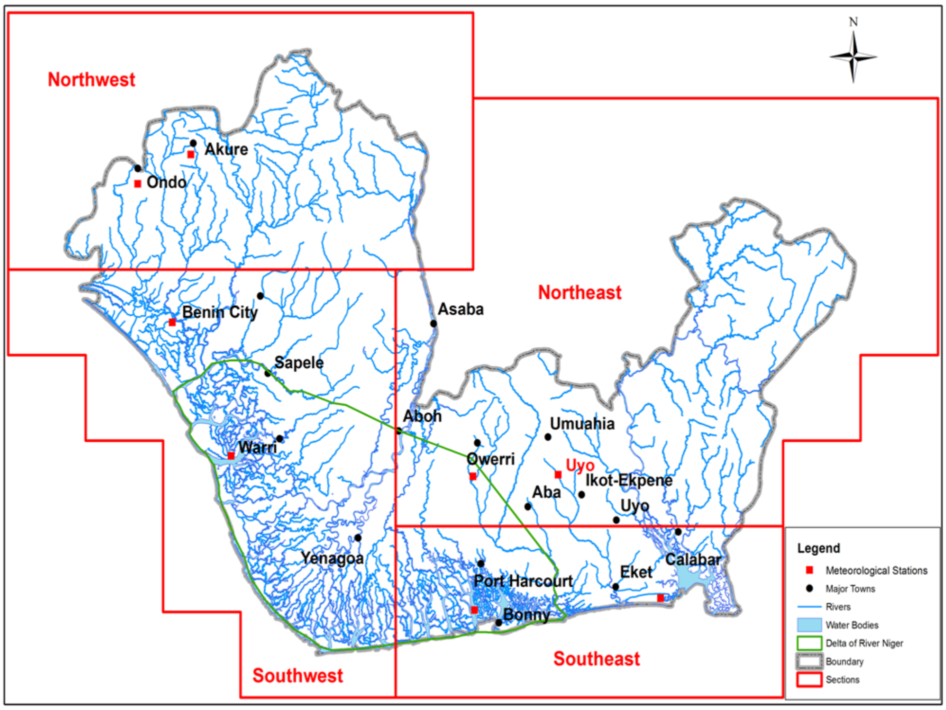


Fig. 1 Map of the study area showing the inland and coastal sections (in red boxes) and the delta of the Niger River (in green)

2.2.2. SCIAMACHY CO data processing

The relevance of kriging interpolation as a geo-statistical interpolation technique for air pollution assessment has been demonstrated based on its ability to generate prediction surfaces, uncertainty surfaces, probability maps and quantile maps (Attorre et al. 2007; Johnston et al. 2001; Kanaroglou et al. 2002; Kassteele, 2006; Kumar et al. 2007; Zimmerman et al. 1999).

The interpolation of SCIAMACHY CO considered the column measurements that fell within the boundary of the Niger Delta sections, which were extracted from global coverage data. The plotted points were used to generate interpolations (or prediction) surface representations of column concentrations using the ordinary kriging method in ArcGIS Geostatistical Analyst extension. A graph of the seasonal variation in mean CO concentrations was generated using the monthly mean concentration obtained from satellite and interpolation.

2.2.3. Definition and categorization of reliability and resolution of interpolated estimates

The term '*reliability*' has been defined as the level of acceptability of the prediction interpolated column concentration estimates of CO from the available column measurements from the SCIAMACHY satellite sensor within each of the defined sections of the Niger Delta region. The reliability of the interpolated CO column concentration estimates is based on the calculated mean of the Euclidean distances between the column measurements. The mean of the Euclidean distance, which represents the mean sampling distance between the column measurements in each of the sections of the Niger Delta, and. defined as a straight line between two points based on their coordinates (Lyon et al. 2008), is one of the measures of fit that can be used to determine the level of conformity or representation of an interpolated surface to the observed point data (Azpurua and Ramos, 2010). The value of the mean of the Euclidean distance also defines the *resolution of SCIAMACHY satellite measurements* within the sections of the Niger Delta. The assessment of the reliability of the interpolated estimate is supported by the prediction standard error maps generated for each interpolation, which provides an indication of where predictions are not reliable (Kruvoruchko and Gribov, 2004). The term '*resolution*' of the prediction interpolated column estimates of CO over the Niger Delta is the mean of the Euclidean distance between the column measurements over the entire Niger Delta region. The shorter the mean of the Euclidean distance, the greater the level of representation of the interpolation surface to the observed points and the higher its reliability and resolution.

The classification of the reliability and resolution of the interpolation estimates was based on the resolution of interpolated climate surfaces for global land areas (Hijmans et al. 2005) and over the USA and Alaska continental area (Joyce et al. 2011), from which it is postulated that high-resolution interpolation surface could have a resolution of up to 20 km. Consequently, the estimated mean of the Euclidean distances observed for each of the sections of the Niger Delta region and over the entire region are categorized into levels of reliability and resolutions as high, medium, low and unreliable as contained in Table 2. Areas with unreliable estimates are areas with mean Euclidean distances of 0 km and greater than 100 km. Areas with mean Euclidean distances of 0 km are sections with no, or just one, column measurement.

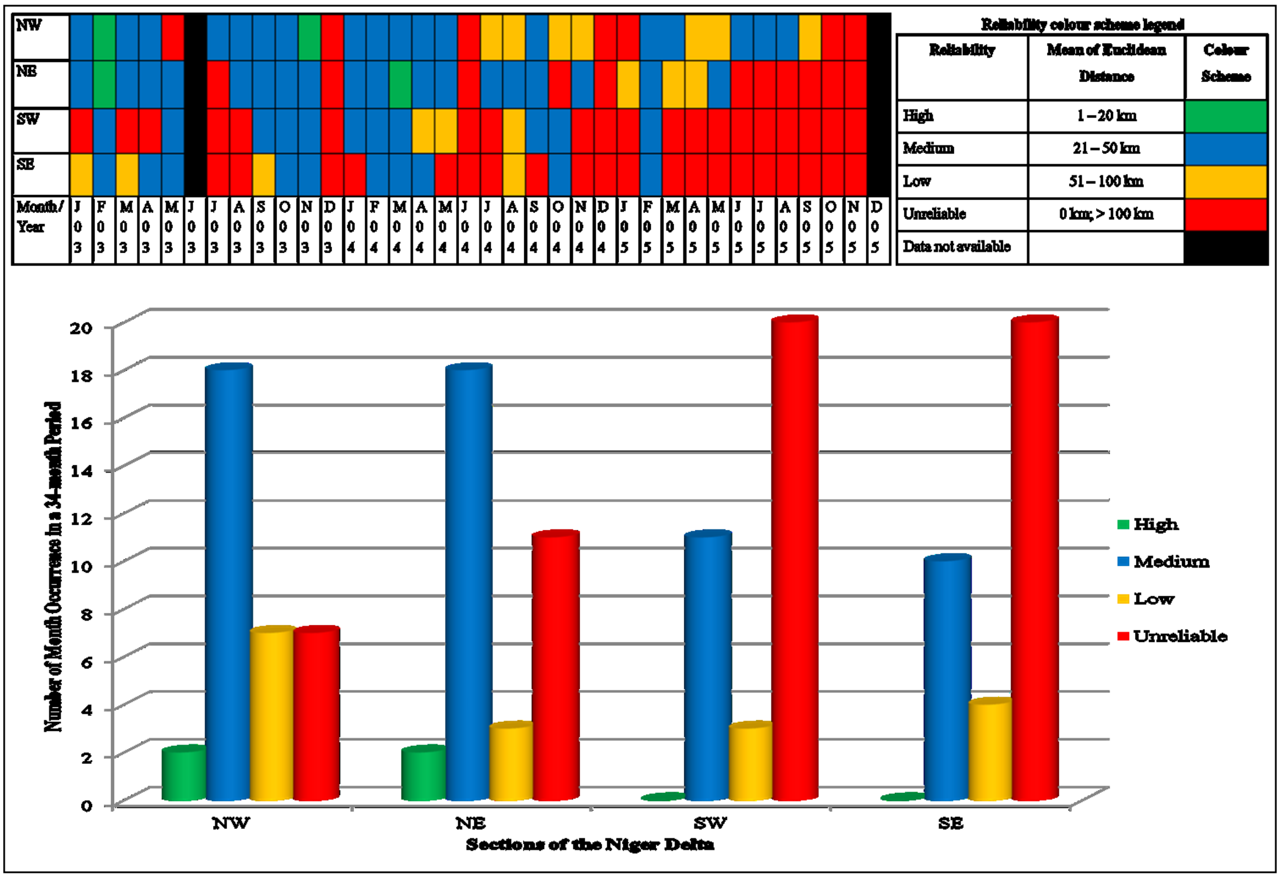
Table 2: Categorisation of the reliability and resolution of the interpolation estimates generated from column measurements over the Niger Delta based on the estimated mean of Euclidean distances.

Reliability / Resolution category	**Range of mean Euclidean distance**
High	1 km – 20 km
Medium	21 km – 50 km
Low	51 km – 100 km
Unreliable	0 km; above 100 km

3. Results

3.1 Reliability of CO concentration estimates

The assessment of the reliability of prediction interpolated estimates over the Niger Delta, as defined in Section 2.2.3, produced the reliability chart shown in Fig. 2.



NW	🟦	🟩	🟦	🟦	🟥	⬛	🟦	🟦	🟦	🟦	🟩	🟥	🟦	🟦	🟦	🟦	🟦	🟥	🟨	🟨	🟦	🟨	🟨	🟥	🟥	🟦	🟦	🟨	🟨	🟦	🟦	🟦	🟨	🟥	🟥	⬛
NE	🟦	🟩	🟦	🟦	🟦	⬛	🟥	🟦	🟦	🟦	🟦	🟥	🟦	🟦	🟩	🟦	🟦	🟥	🟦	🟦	🟦	🟥	🟦	🟥	🟨	🟦	🟨	🟨	🟦	🟥	🟥	🟥	🟥	🟥	🟥	⬛
SW	🟥	🟦	🟥	🟥	🟦	⬛	🟥	🟥	🟦	🟦	🟦	🟥	🟦	🟦	🟦	🟨	🟨	🟥	🟥	🟨	🟦	🟦	🟥	🟥	🟥	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛
SE	🟨	🟦	🟨	🟦	🟦	⬛	🟥	🟥	🟨	🟦	🟦	🟥	🟥	🟦	🟦	🟦	🟥	🟥	🟥	🟨	🟥	🟦	🟥	🟥	🟥	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛
Month/ Year	J 03	F 03	M 03	A 03	M 03	J 03	J 03	A 03	S 03	O 03	N 03	D 03	J 04	F 04	M 04	A 04	M 04	J 04	J 04	A 04	S 04	O 04	N 04	D 04	J 05	F 05	M 05	A 05	M 05	J 05	J 05	A 05	S 05	O 05	N 05	D 05

Reliability colour scheme legend

Reliability	Mean of Euclidean Distance	Colour Scheme
High	1 – 20 km	🟩
Medium	21 – 50 km	🟦
Low	51 – 100 km	🟨
Unreliable	0 km; > 100 km	🟥
Data not available		⬛

Fig. 2 Reliability chart for interpolated CO column concentrations over the Niger Delta from January 2003 to December 2005

Out of the 36 month-period of study from January 2003 to December 2005, only nine months have reliable estimates generated over the entire region (Fig. 3 a - i). A total of eight months (January 2003, March 2003, April 2003, May 2003, January 2004, May 2004, September 2004 and October 2004) produced reliable estimates over three out of four sections of the Niger Delta. Reliable estimates were generated over two sections (the northern sections) of the region in August 2003, July 2004, November 2004, March 2005, April 2005 and May 2005. A period of six months (July 2003, January 2005, June 2005, July 2005, August 2005 and September 2005) produced reliable estimates in only one section of the region. There were no satellite measurements for June 2003 and December 2005. For the remaining five months, unreliable estimates were produced over the entire region. The resolutions of the prediction interpolation estimates for the months with reliable estimates over the four sections of the Niger Delta, as presented in Fig. 3, are presented in Table 3.

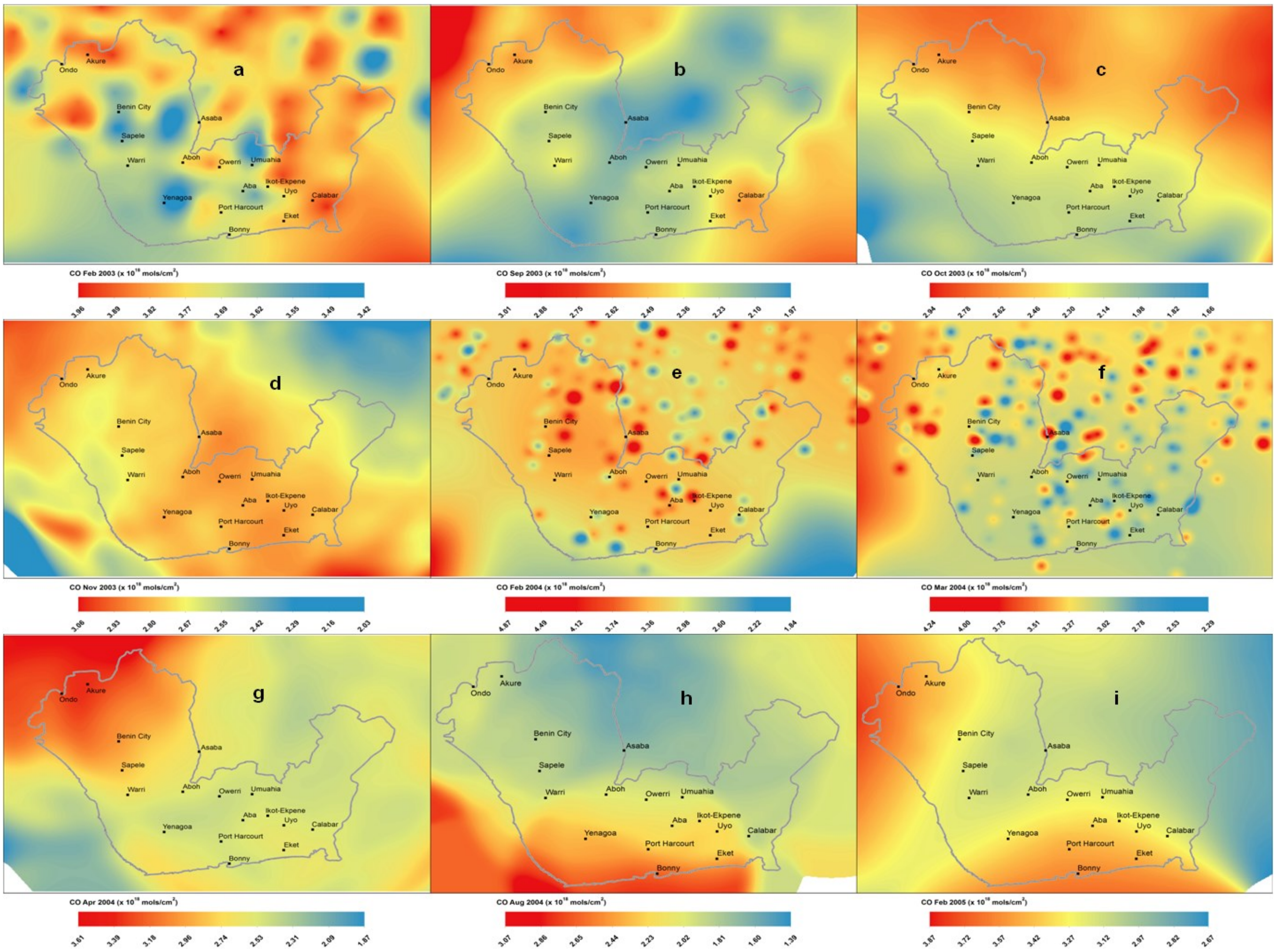


Fig. 3 Map showing months with reliable CO prediction interpolated concentration estimates generated over the entire Niger Delta region over a three-year period (a) February 2003, (b) September 2003, (c) October 2003, (d) November 2003, (e) February 2004, (f) March 2004, (g) April 2004, (h) August 2004, (i) February 2005

Table 3: Resolution of satellite measurements over the sections of the Niger Delta and resolution of prediction interpolated estimates for the months with reliable estimates

Month / Year	**Satellite Measurement Resolution / Reliability**								**Interpolation Resolution Niger Delta**
	NW Section		**NE Section**		**SW Section**		**SE Section**		
	MED (Km)	**Reliability**	**MED (Km)**	**Reliability**	**MED (Km)**	**Reliability**	**MED (Km)**	**Reliability**	**MED (Km) / Resolution**
February 2003	18.0	High	9.1	High	20.5	Medium	34.9	Medium	20.6 / Medium
September 2003	23.5	Medium	29.1	Medium	35.7	Medium	55.2	Low	35.9 / Medium
October 2003	20.8	Medium	24.7	Medium	33.6	Medium	23.1	Medium	25.6 / Medium
November 2003	16.2	High	27.0	Medium	31.5	Medium	35.0	Medium	27.4 / Medium
February 2004	20.3	Medium	24.4	Medium	29.7	Medium	48.8	Medium	30.8 / Medium
March 2004	20.7	Medium	16.0	High	21.2	Medium	22.0	Medium	20.0 / High
April 2004	37.2	Medium	32.7	Medium	69.1	Low	38.8	Medium	44.5 / Medium
August 2004	89.5	Low	41.8	Medium	52.5	Low	72.0	Low	64.0 / Low
February 2005	24.4	Medium	21.4	Medium	27.7	Medium	33.5	Medium	26.8 / Medium

3.2. Seasonal variations of mean CO concentrations

Seasonal variations are observed in the monthly mean total column concentrations of CO as measured from satellite (Mean Measured) and observed from interpolated estimates (Mean Predicted) (Fig. 4). The trends observed in both measurements are similar. The seasonal trend showed that peak concentrations occurred during the dry season months over the three-year period of study. It is observed that there was a consistent decrease in concentrations from the onset of the rainy season in March to the peak of rainy season in July / August / September. This is then followed by an increase in concentrations from the cessation of the wet season in October into the dry season. The highest concentration estimated at 4.63 x 10^{18} molecules/cm^2 was observed in March 2003, and the lowest concentration of 1.79 x 10^{18} molecules/cm^2 was observed in October 2004. The observed seasonal spatial distributions of CO total column concentrations over the region show that climatic elements play roles in the concentrations, irrespective of areas with significant anthropogenic sources of CO in the area.

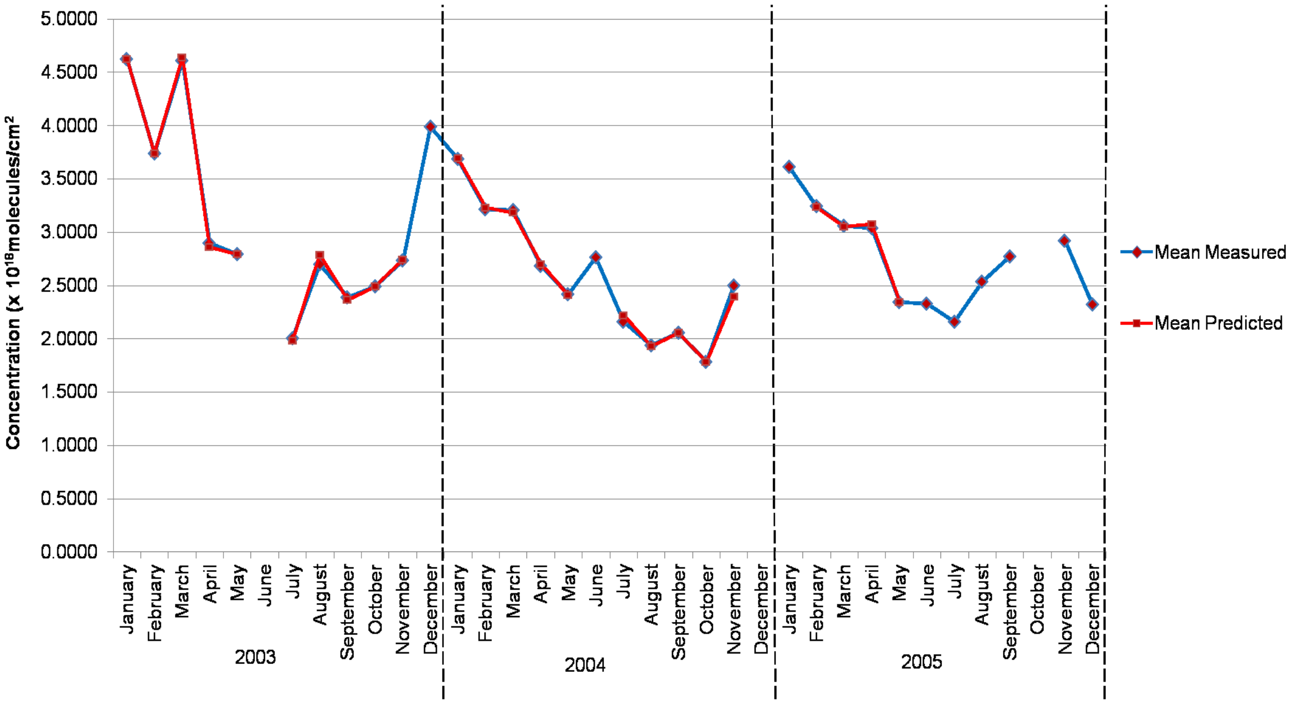


Fig. 4 Seasonal variations in the mean measured and mean predicted CO total column concentrations over the Niger Delta

3.3. *Interpolation error assessment*

For a kriging interpolation to produce prediction estimates close to the measured, the root mean square standardized error (RMSS) must be close to 1 (Johnston et al. 2001). This is in line with Caruso and Quarta (1998) who state that the expected variance (R^2) gives the degree of the prediction of the interpolation process. If the RMSS error is greater than 1, it indicates an underestimation of the variability in the predictions. If the RMSS error is less than 1, there is overestimation of the prediction variability (Johnston *et al.* 2001). The RMSS errors generated from the interpolation process ranged from 0.98 to 1.29. The percentage error generated ranged from -4% to 3% (Table 4)

Table 4: Kriging interpolation error assessment

Year	Month	Measured / Column (x 10^{18} mol/cm^2)			Predicted / Surface (x 10^{18} mol/cm^2)			RMS	ASE (x 10^{17} mol/cm^2)	RMSS	Error %
		Min	**Max**	**Mean**	**Min**	**Max**	**Mean**				
2003	January	2.44	6.64	4.62	3.63	5.22	4.62	9.36	9.02	1.04	0.001
	February	1.30	6.28	3.74	3.42	3.96	3.74	9.84	9.73	1.01	0.01
	March	2.44	6.64	4.61	3.75	5.26	4.64	9.50	9.03	1.05	0.53
	April	1.18	5.80	2.90	1.91	4.17	2.86	7.96	8.10	0.99	-1.45
	May	0.92	5.28	2.79	1.18	4.79	2.80	7.87	8.34	1.07	0.10
	June	Data not available									
	July	0.77	3.90	2.01	0.98	2.72	1.98	9.34	9.31	1.02	-1.11
	August	1.13	4.68	2.70	1.14	3.26	2.79	9.26	8.80	1.04	3.10
	September	0.78	4.23	2.39	1.97	3.01	2.36	8.51	8.65	0.98	-1.13
	October	1.01	5.08	2.49	1.66	2.94	2.49	8.24	7.81	1.05	0.01
	November	1.04	4.91	2.74	2.03	3.06	2.74	9.64	9.73	0.99	0.22
	December	1.26	6.20	3.99	There are not enough column measurements to generate a surface.						
2004	January	1.95	6.09	3.69	2.93	5.24	3.70	10.06	9.85	1.03	0.12
	February	1.01	5.93	3.21	1.47	4.01	3.19	10.25	9.98	1.03	-0.69
	March	1.11	5.86	3.21	2.16	4.14	3.18	9.89	9.42	1.05	-0.72
	April	1.15	5.84	2.68	1.87	3.61	2.70	10.15	10.27	0.99	0.49
	May	1.05	4.37	2.42	1.75	2.94	2.41	9.00	8.76	1.03	-0.32
	June	2.14	3.88	2.77	There are not enough column measurements to generate a surface.						
	July	0.98	3.31	2.16	1.66	3.31	2.22	7.31	7.16	1.01	2.61
	August	0.94	3.64	1.94	1.39	3.07	1.93	6.94	6.94	1.00	-0.35
	September	1.19	3.57	2.06	1.61	2.52	2.05	7.56	6.63	1.13	-0.23
	October	1.02	3.16	1.79	1.11	2.03	1.79	7.20	6.71	1.08	-0.06
	November	1.78	3.70	2.50	1.78	3.29	2.40	9.06	6.36	1.29	-3.98
	December	Data not available									
2005	January	1.44	5.12	3.61	There are not enough column measurements to generate a surface.						
	February	1.99	4.93	3.25	2.67	3.87	3.24	7.18	6.93	1.04	-0.284
	March	1.93	3.97	3.06	1.94	3.96	3.05	6.62	5.46	1.13	-0.356
	April	1.99	4.79	3.04	2.38	3.99	3.08	8.82	8.99	1.00	1.355
	May	1.25	3.80	2.34	1.56	3.07	2.35	7.77	7.60	1.03	0.253
	June	1.49	3.02	2.33	There are not enough column measurements to generate a surface.						
	July	1.43	2.94	2.16	There are not enough column measurements to generate a surface.						
	August	1.25	3.73	2.54	There are not enough column measurements to generate a surface.						
	September	1.96	3.94	2.77	There are not enough column measurements to generate a surface.						
	October	Data not available									
	November	2.07	3.77	2.92	There are not enough column measurements to generate a surface.						

Year	**Month**	**Measured / Column (x 10^{18} mol/cm^2)**			**Predicted / Surface (x 10^{18} mol/cm^2)**			**RMS**	**ASE (x 10^{17} mol/cm^2)**	**RMSS**	**Error %**
		Min	**Max**	**Mean**	**Min**	**Max**	**Mean**				
	December	2.16	2.49	2.32	There are not enough column measurements to generate a surface.						

3.4. Meteorological assessment of the Niger Delta

The Niger Delta experiences two climatic seasons. The rainy season is from April to October, and the dry season is from November to March. Using the World Meteorological Organization (WMO) cloud cover classifications (WMO, 1995), the average cloud cover observed from the meteorological stations in the Niger Delta range from 6 oktas in some parts of the inland areas to 7 oktas in the coastal areas for all the months of the year. Water vapor content in the region was high throughout the year. Over the period from January 2001 to December 2005, the lowest relative humidity of 36% was observed in the inland part of the region in January and the maximum relative humidity of 86% was observed along the coast in August. The majority of the region has relative humidity greater than 40% all through the year. The average monthly rainfall observed in the Niger Delta is lowest (4 mm) in the inland area in December and highest (542 mm) in the coastal area in July. Mean annual rainfall for January 2001 to December 2005 over the stations range from 1,409 mm to 2,794 mm. Results show that the tropical maritime (south-westerly) air mass prevailed over the region almost all year round, with little seasonal change in wind direction. This verifies the observations of Olaniran (1986). During the dry season, the dry continental air mass (or the north-easterly winds) is predominant over inland stations in Ondo and Akure only in December and January. Cloud cover, relative humidity and rainfall are high over the region due to the prevalence of the moisture-laden south westerly winds.

4. Discussions

4.1. Reliability of interpolated estimates

According to the chart showing the monthly reliability of the estimates generated over the Niger Delta from available column measurements (Fig. 2), the estimates generated over the inland areas have higher reliability than those generated over the coastal areas. The percentage of months with varying levels of reliability over the northern and southern sections during the dry and wet seasons, over the entire period of study, is calculated and shown in Table 5.

Table 5: Percentage of months with reliable and unreliable CO estimates over the northern and southern sections of the Niger Delta during the seasons and the entire period of study.

Pollutant	**Section**	**Dry season (14 months)**		**Wet season (20 months)**		**Total (34 months)**	
		Reliable (%)	**Unreliable (%)**	**Reliable (%)**	**Unreliable (%)**	**Reliable (%)**	**Unreliable (%)**
CO	Inland	71	29	65	35	68	32
	Coastal	50	50	27	73	35	65
	Niger Delta	60.5	39.5	46	54	51.5	48.5

Based on the percentage distribution of reliability during the period of study, the northern (inland) sections have more periods of reliable estimates than the southern (coastal) sections. Out of the 34-month period of this study for which data is available, 74% of the entire period produced reliable results over the northern sections. In the southern sections, only 42% of the period of study produced reliable estimates. In addition, over both sections, more reliable estimates are generated during the dry season than during the wet season. In the dry season, the minimum occurrence of reliable results estimated at 46% was generated over the coastal areas. Only 38% of the entire months of the wet season produced varying degree of reliable results. This clearly indicates that over the inland part of the Niger Delta, data from SCIAMACHY produced reliable estimates of CO for the Niger Delta region during both seasons. However, over the coastal areas, SCIAMACHY measurements can only produce reliable regional-scale estimates during the dry season.

4.2. Climatic limitations to SCIAMACHY CO measurements over the Niger Delta

The reliability of interpolated CO concentration estimates is dependent on the influence of climatic conditions on the available imaging windows and the ability of the retrieval algorithm to correct for atmospheric interferences. The higher intensities of rainfall and relative humidity during the wet season constitute greater hindrance to optical satellite imaging than during the dry season. Theoretically, it is known that the presence of these climatic conditions reduce the quantity of measurements obtainable from optical sensors such as SCIAMACHY. However, the distribution of meteorological stations within the sections of the Niger Delta region (two stations within each section) limits the statistical (regression) analysis to establish the level of dependence of the availability of column measurements within each section on these two climatic conditions. A seasonal evaluation of the total number of column measurements available within each of the sections of the Niger Delta region clearly indicates the climate of the Niger Delta have impact of availability of CO column measurements as evidenced by the greater number of column measurements during the dry season than during the wet season throughout the three-year period of study (Fig. 5).

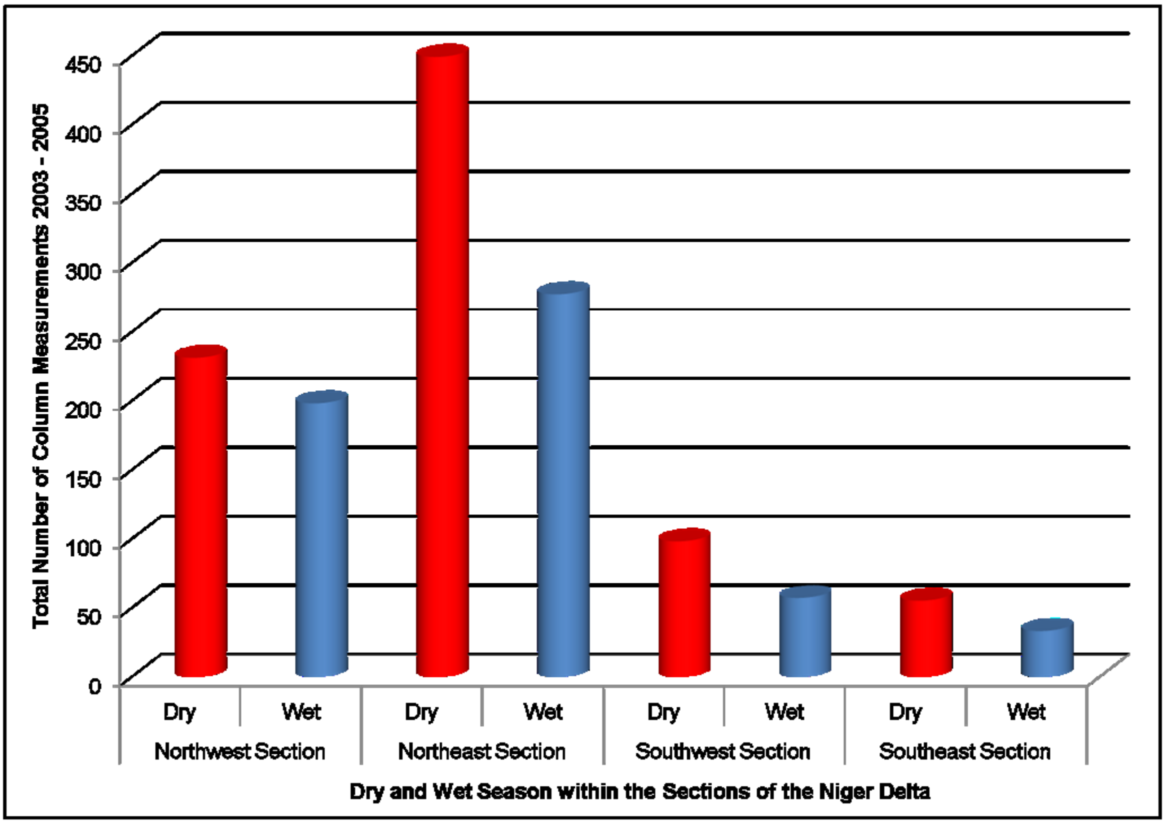


Fig 5 Seasonal variations of the total number of CO column measurements within the sections of the Niger Delta from 2003 to 2005

Despite the low intensity of rainfall and low relative humidity which characterize the dry season in the Niger Delta, it was observed that there were sparse column measurements during some months of the dry season resulting in very high values of mean sampling distances between column measurements. As a result of this, there was low reliability or unreliable estimates during the months of December 2003, November 2004 to January 2005 and November 2005. This is indicative of the fact that the availability of column measurements is affected by other factors which also negatively affect the quality of data retrieved using the WFM-DOAS algorithm.

A consideration of climatic factors and anthropogenic activities during the dry season reveals that the Niger Delta region experiences haze and reduced visibility due to the influx of dust blown into Nigeria from over the Sahara Desert by the continental air mass (Akinro et al. 2008; Uyigue and Agho, 2007). The degree of the dust haze varies and is higher over the inland areas than over the coastal areas because of the Inter-tropical Convergence Zone (ITCZ), which limits the inland extent of the moist tropical maritime air mass. This results in lower intensities of rainfall and relative humidity during this period as compared with the wet season. Furthermore, due to low rainfall intensity, the dry season is a period in which forest removal takes place for construction activities and farmers' preparation for the next planting season (Akinro et al. 2008). The practice of biomass burning in the Niger Delta (Chokor, 2004) results in the emission of air pollutants including smoke and particulates (Langmann et al. 2009; Lim et al. 2004). The smoke and dust particles from biomass burning and construction works combine with the dust particles from the Sahara Desert to form a layer of cloud condensation nuclei (CCN), which may exist for a longer period in the atmosphere in the absence of rainfall to remove them (Cattani et al. 2006; Kaskaoutis et al. 2011; Keil and Haywood, 2003; Lim et al. 2004). The presence of the CCN above cloud layers has been identified as an obstruction to an optical satellite sensor's ability to retrieve cloud properties accurately. Cloud properties are required for cloud correction when using algorithms to retrieve useful information from satellite sensors (Cattani et al. 2006; Haywood et al. 2004). The combination of these climatic factors and their contributions to the formation and presence or removal of CCN over the Niger Delta may be responsible for the inability of the WFM-DOAS retrieval algorithm to adequately correct for cloud interferences during some months of the dry season over the Niger Delta. This accounts for the lack of adequate number of column measurements over the Niger Delta in November (2004 and 2005), December (2003 and 2004) and January 2005.

4.3. Climatic effects on spatial distribution of concentrations

Based on the periods with reliable estimates, the spatial distribution of CO total column concentrations shows that prevailing wind, rainfall and atmospheric water vapor have effects on concentrations. Due to the rainfall and atmospheric water vapor content, chemical oxidation and wet deposition of CO molecules are higher during the wet season than during the dry season. Consequently, concentrations are lower during the wet season than during the dry season. However, Fig. 4 shows a sharp increase in the mean concentration of CO in August 2003. A comparison of the rainfall in July, August and September 2003 (Table 6) shows that the rainfall amount recorded over the majority of the meteorological stations was least in August. This shows that the rate of wet deposition of CO in August 2003 reduced considerably, thereby resulting in the sharp increase in the concentrations observed in the month.

Table 6: Comparison of rainfall amount over meteorological stations in July, August and September 2003

Station	**Total Rainfall Amount (mm)**		
	July 2003	**August 2003**	**September 2003**
Akure	77.4	58.7	320.8
Ondo	61.0	81.4	556.6
Owerri	439.5	379.2	NA
Uyo	475.0	274.3	388.8
Benin	177.1	142.1	57.3
Calabar	332.4	385.0	309.1
Port Harcourt	480.9	206.4	535.3
Warri	353.2	213.6	436.1

The major anthropogenic activities that release carbon monoxide in the Niger Delta are road transportation, domestic cooking and lighting, industries, construction, and oil and gas exploration (EC-JRC/PBL, 2010). The majority of roads in the region are inland where the urban and semi-urban areas are located. These areas are also the industrialized parts of the Niger Delta. However, the majority of oil and gas exploration activities occur in the rural areas in the delta of the River Niger, located in the coastal part of the region (ERML, 1995). The observation of the spatial distribution of the concentrations of CO is generally higher downwind of areas of anthropogenic activities. During the dry season, high CO concentrations are observed in some parts of the coastal areas due to the weakness of the south westerly and the stronger influence of the north easterly winds (Adaramola and Oyewola, 2011), which restricts the transport of CO molecules inland, even though the mean wind direction in the Niger Delta is south westerly. During the rainy season, concentrations of CO are higher over inland areas due to the transport of pollutants by the south westerly, and due to the higher rates of wet deposition over the coastal areas than over the inland areas. Consequently, during the wet season, the effects of the release of CO in the oil rich, industrialized and urban areas of the Niger Delta are likely to be greater further inland away from the region. However, during the dry season, the effects of the emission of CO from within the Niger Delta are higher over the inland parts of the region due to the north easterly continental air mass that blows coastward. The individual impacts of precipitation, humidity and wind direction have not been fully assessed in this study. However, it can be inferred from the spatial distribution that the health-based effects of carbon monoxide released from anthropogenic and natural activities in the Niger Delta are likely greater inland than along the coastal areas.

Fig. 3(a-i) shows the spatial distribution of CO monthly variations for the periods with reliable estimates. The variations indicate higher CO concentrations over the western and northern parts of the Niger Delta region. Seasonal wind regimes and anthropogenic activities in areas outside the Niger Delta region contribute to the observed spatial distributions. To the west of the Niger Delta region is the highly industrialized Lagos and Ogun States in Southwest Nigeria. These areas have many manufacturing industries, including cement factories. Fig. 3b, c, g and h represent spatial distributions during the wet season, which is characterized by the moisture-laden south westerly winds. The high-intensity rainfalls that accompany the south westerly winds contribute to high rate of wet deposition of atmospheric CO in the coastal part of the Niger Delta, and the wind regime also transport CO molecules westwards to combine with molecules released from industrial and transport sources in Southwest Nigeria. During the dry season, however, the spatial distribution of CO indicates higher concentrations over the northern and inland part of the Niger Delta than the coastal part (Fig. 3a, d, e, f, and i). To the north of the Niger Delta is the part of Nigeria where subsistence and mechanized agriculture are practiced on the large scale. This area is characterized by biomass burning during the dry season (Akinro et al. 2008; Chokor, 2004). The CO emissions from biomass burning are then transported by the dry north easterly winds into the northern and inland parts of the Niger Delta. Consequently, high concentrations of CO usually occur over the inland part of the region during the dry season. Due to the dryness of this wind regime, wet deposition of CO molecules rarely occur in the inland part of the region. However, there is minimal wet deposition only at the coastal areas where there is little rainfall during the dry season.

5. Conclusions

The ability of SCIAMACHY satellite sensor to produce adequate column measurements to interpolate reliable concentration estimates of carbon monoxide over the Niger Delta region is affected by rainfall, relative humidity, cloud and dust haze. Areas with higher intensities of these climatic conditions have less available sensing windows, thereby affecting the number of columns available over such areas. These atmospheric interferences also impede the retrieval of useful information from satellite sensors. Spatially, the coastal areas of the Niger Delta have higher intensities of the impacting climatic conditions than the inland areas. Therefore, the satellite sensor provides considerably more measurements over the inland areas than the coastal areas. On account of the two climatic seasons observed over the Niger Delta, the wet or rainy season from April to October has higher intensities of rainfall and relative humidity than the dry season from November to March. Consequently, there are more measurements during the dry season than the rainy season. However, dust haze, which is due to the influence of the continental air mass blowing into Nigeria from the Sahara Desert during the dry season also have negative influence on the availability of CO column measurements from SCIAMACHY. This has been observed during the months of November, December and January. However, the extent of the impact of dust haze has not been extensively assessed in this paper. Although there are algorithms that correct for cloud and atmospheric water vapor content during the process of extracting pollutant concentrations from raw satellite data, these do not seem to have improved the quality of useful information obtained from SCIAMACHY in the Niger Delta. The measurements have greater quality when taken under cloud-free conditions. Based on the assessment of reliability presented in this paper, it can be concluded that measurements from SCIAMACHY satellite sensor can provide adequate data to generate reliable estimates of CO concentrations only on a monthly basis. However, the level of reliability that can be placed on the estimates depends on the time of the year and proximity to the coast. SCIAMACHY sensor was able to produce enough data to measure and generate reliable continuous CO total column concentration estimates over the low-latitude Niger Delta region during the dry season than during the rainy season. Similarly, higher reliability estimates are obtainable in the inland areas than the coastal areas. This is indicative of the sensor's (and / or its successor's) relevance to support air pollution measurement and monitoring within the low latitudes, where the majority of developing countries are located. These developing countries are faced with economic constraints to establish networks of air quality ground monitoring stations. The integration of satellite sensors measurements could enhance the cost-effectiveness of establishing a monitoring scheme in such developing countries.

For the areas with high intensity of the climatic conditions that affect the SCIAMACHY CO measurements, the possibility of combining measurements from different satellite sensors could be explored in order to improve the number of column measurements available for interpolation. Ghude et al. (2009) demonstrated the combination and inter-comparison of GOME and SCIAMACHY measurements to determine global trend of NO_2 concentrations from 1996 to 2006. Future study could explore the effects of combining measurements from different satellite sensors over low-latitude regions in order to generate more reliable interpolated CO concentration estimates.

References

Akinro, A.O., Opeyemi, D.A., and Ologunagba, I.B. (2008). Climate change and environmental degradation in the Niger Delta region of Nigeria: its vulnerability, impacts and possible mitigations. *Research Journal of Applied Sciences* 3 (3), 167-173.

Attorre, F., Alfo', M., De Sanctis, M., Francesconi, F., and Bruno, F. (2007). Comparison of interpolation methods for mapping climatic and bioclimatic variables at regional scale. *International Journal of Climatology* 27 (13): 1825-1843.

Azpurua, M., and Dos Ramos, K. (2010). A comparison of spatial interpolation methods for the estimation of average electromagnetic field magnitude. *Progress in Electromagnetic Research M* 14, 135-145.

Barker, T., Bashmakov, I., Bernstein, L., Bogner, J.E., Bosch, P.R., Dave, R., et al. (2007). Technical summary. In Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. and Meyer, L.A., (Eds.) *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report on Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, USA: Cambridge University Press, pp. 25-93.

Bovensmann, H., Burrows, J.P., Buchwitz, M., Frerick, J., Noel, S., Rozanov, V.V., Chance, K.V., Goede, A.P.H. (1999). SCIAMACHY: mission objectives and measurement modes. *Journal of the Atmospheric Sciences* 56 (2), 127-150.

Buchwitz, M., de Beek, R., Noel, S., Burrows, J.P., Bovensmann, H., Schneising, O., et al. (2006). Atmospheric carbon gases retrieved from SCIAMACHY by WFM-DOAS: version 0.5 CO and CH_4 and impact of calibration improvements on CO_2 retrieval. *Atmospheric Chemistry and Physics* 6 (9), 2727-2751.

Buchwitz, M., Khlystova, I., Bovensmann, H., and Burrows, J.P. (2007). Three years of global carbon monoxide from SCIAMACHY: comparison with MOPITT and first results related to the detection of enhanced CO over cities. *Atmospheric Chemistry and Physics* 7 (9), 2399-2411.

Buchwitz, M. (2009). SCIAMACHY WFM-DOAS (WFMD) Methane, Carbon Monoxide, and Carbon Dioxide Columns: Algorithm Description and Product Specification [online]. Report number: IUP-SCIA-WFMD-ADPS-0004 Version 4.Bremen, Germany: Institute of Environmental Physics (IUP) University of Bremen.

Caruso, C. and Quarta, F. (1998). Interpolation methods comparison. *Computers & Mathematics with Applications* 35 (12), 109-126.

Cattani, E., Costa, M.J., Torricella, F., Levizzani, V., and Silva, A.M. (2006). Influence of aerosol

Acknowledgement

The Nigerian National Space Research and Development Agency (NASRDA), Abuja, Nigeria funded this study.

particles from biomass burning on cloud microphysical properties and radiative forcing. *Atmospheric Research* 82 (1-2), 310-327.

Chokor, B.A. (2004). Perception and response to the challenge of poverty and environmental resource degradation in rural Nigeria: Case study from the Niger Delta. *Journal of Environmental Psychology* 24 (3), 305-318.

Dils, B., De Mazi\`ere, M., M\uller, J.F., Blumenstock, T., Buchwitz, M., de Beek, R., Et al. (2006). Comparisons between SCIAMACHY and ground-based FTIR data for total columns of CO, CH_4, CO_2 and N_2O. *Atmospheric Chemistry and Physics* 6 (7), 1953-1976.

Environmental Resource Managers Limited, ERML (1997). *Niger Delta Environmental Survey Final Report Phase I: Volume 1 – Environmental and Socio-Economic Characteristics*. Nigeria.

European Commission, Joint Research Centre (JRC) / Netherlands Environmental Assessment Agency (PBL) (2010). *Emission Database for Global Atmospheric Research (EDGAR)*. European Communities.

European Environment Agency (EEA) (1999). Chapter 3.12: *Urban Areas - Environment in EU at the Turn of the Century*. Copenhagen: European Environment Agency, EEA.

Forster, P., Ramaswamy, V., Artaxo, P., Bernsten, P., Betts, R., Fahey, D.W., et al. (2007). Changes in atmospheric constituents and in radiative forcing. In Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Eds.) Climate Change 2007: *The Physical Science Basis. Contribution of the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, pp.129-234.

Frankenberg, C., Platt, U., and Wagner, T. (2005). Retrieval of CO from SCIAMACHY onboard ENVISAT: detection of strongly polluted areas and seasonal patterns in global CO abundances. *Atmospheric Chemistry and Physics* 5 (6), 1639-1644.

Ghude, S.D., Van der A, R.J., Beig, G., Fadnavis, S., and Polade, S.D. (2009). Satellite derived trends in NO_2 over the major global hotspot regions during the past decade and their inter-comparison. *Environmental Pollution* 157 (6), 1873-1878.

Gloudemans, A.M.S., Schrijver, H., Kleipool, Q., van den Broek, M.M.P., Straume, A.G., Lichtenberg, G., van Hees, R.M., Aben, I., Meirink, J.F. (2005). The impact of SCIAMACHY near-infrared instrument calibration on CH4 and CO total columns. *Atmospheric Chemistry and Physics Discussion* 5: 1733-1770.

Gottwald, M., Bovensmann, H., Lichtenberg, G., Noel, S., von Bargen, A., Slijkhuis, S., et al. (2006). *SCIAMACHY, Monitoring the Changing Earth's Atmosphere*. Bonn, Germany: DLR, Institut für Methodik der Fernerkundung (IMF).

Gupta, P., Christopher, S.A., Wang, J., Gehrig, R., Lee, Y., and Kumar, N. (2006). Satellite remote sensing of particulate matter and air quality assessment over global cities. *Atmospheric Environment* 40 (30), 5880-5892.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G. and Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25, 1965-1978. Doi: 10.1002/joc.1276.

Hooninger, G., von Friedeburg, C., and Platt, U. (2004). Multi-axis differential optical absorption spectroscopy (MAX-DOAS). *Atmospheric Chemistry and Physics* 4, 231-254.

Huston, M.A., and Marland, G. (2003). Carbon management and biodiversity. *Journal of Environmental Management* 67: 77-86.

Johnston, K., Ver Hoef, J.M., Krivoruchko, K., and Lucas, N. (2001). *Using ArcGIS Geostatistical Analyst*. Redlands, CA USA: ESRI.

Joyce, L.A., Price, D.T., McKenney, D.W., Siltanen, R.M., Papadopol, P., Lawrence, K., and Coulson, D.P. (2011). *High resolution interpolation of climate scenarios for the conterminous USA and Alaska derived from general circulation model simulations*. Gen Tech Report RMRS-GTR-263. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 87 p.

Kampas, M., and Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution* 151, 362-367.

Kanaroglou, P.S., Soulakellis, N.A., and Sifakis, N.I. (2002). Improvement of satellite derived pollution maps with the use of a geostatistical interpolation method. *Journal of Geographical Systems* 4 (2), 193-208.

Kaskaoutis, D.G., Kharol, S.K., Sifakis, N., Nastos, P.T., Sharma, A.R., Badarinath, K.V.S., Kambezidis, H.D. (2011). Satellite monitoring of the biomass-burning aerosols during the wildfires of August 2007 in Greece: Climate implications. *Atmospheric Environment* 45 (3), 716-726.

Kassteele, J. (2006). Statistical Air Quality Mapping. Doctorate, Wageningen University, The Netherlands. Available from: http://edepot.wur.nl/121778.

Keil, A. and Haywood, J.M. (2003). Solar radiative forcing by biomass burning aerosol particles during SAFARI 2000: A case study based on measured aerosol and cloud properties. *Journal of Geophysical Research* 108 (D13), 8467.

Kumar, A., Maroju, S., and Bhat, A. (2007). Application of ArcGIS geostatistical analyst for interpolating environmental data from observations. *Environmental Progress* 26 (3), 220-225.

Lamsal, L.N., Martin, R.V., van Donkelaar, A., Steinbacher, M., Celarier, E.A., Buscela, E., Dunlea, E.J., and Pinto, J.P. (2008). Ground level nitrogen dioxide concentrations inferred from the satellite-borne Ozone Monitoring Instrument. *Journal of Geophysical Research* 113 (D16), D16308.

Langmann, B., Duncan, B., Textor, C., Trentmann, J., and van der Werf, G.R. (2009). Vegetation fire emissions and their impact on air pollution and climate. *Atmospheric Environment* 43 (1), 107-116.

Leroux, M. (2001). *The Meteorology and Climate of Tropical Africa*. Chichester, UK: Praxis Publishing Limited.

Levelt, P.F., van den Oord, G.H.J., Dobber, M.R., Malkki, A., Huib V., de Vries, J., Stammes, P., Lundell, J.O.V., and Saari, H. (2006). The ozone monitoring instrument. *Geosciences and Remote Sensing, IEEE Transactions on* 44 (5), 1093-1101.

Li, C., Hsu, C.N., and Tsay, S-C. (2011). A study on the potential applications of satellite data in air quality monitoring and forecasting. *Atmospheric Environment* 45 (22), 3663-3675.

Lim, H.S., MatJafri, M.Z., and Abdullah, K. (2004). Retrieval of air quality using a newly simulated algorithm from aerosol optical depth. In: Anonymous: Map Asia 2004. Beijing, China, 26 – 29 August, 2004. Website: http://www.geospatialworld.net/index.php?option=com_content&view=article&id=15486&catid=130%3Aenvironment-air-pollution&Itemid=41.

Lyon, S.W., Seibert, J., Lembo, A.J., Steenhuis, T.S. and Walter, M.T. (2008). Incorporating landscape characteristics in a distance metric for interpolating between observations of stream water chemistry. *Hydrological and earth System Sciences* 12, 1229-1239.

Martin, R.V. (2008). Satellite remote sensing of surface air quality. *Atmospheric Environment* 42 (34), 7823-7843.

Olaniran, O.J. (1986). On the classification of tropical climates for the study of regional climatology: Nigeria as a case study. Geografisca Annaler. *Series A, Physical Geography* 68 (4), 233-244.

Osterman, G., Bowman, K., Eldering, A., Fisher, B., Herman, R., Jacob, D., et al. (2007). *Earth Observing System (EOS) Tropospheric Emission Spectrometer (TES): Level 2 (L2) Data user's Guide, Version F04_04 Data*. Report number: D-8042. Pasadena, California: Jet Propulsion Laboratory, California Institute of Technology.

Platt, U. and Stutz, J. (2008). *Differential optical absorption spectroscopy: principles and applications*. Springer, Verlag Berlin Heidelberg. 597 pp.

Richter, A. (2006). Differential optical absorption spectroscopy as a tool to measure pollution from space. *Spectroscopy Europe* 18 (6), 14-21.

Shim, C., Li, Q., Luo, M., Kulawik, S., Worden, H., Worden, J., et al. (2009). Satellite observations of Mexico City pollution outflow from the Tropospheric Emissions Spectrometer (TES). *Atmospheric Environment* 43 (8), 1540-1547.

Sifakis, N. (1999). *Identification of priority areas and prospect analysis for the use of Earth Observation Data for EEA State of the Environment Reporting*. Report number: Contract #3010/SER/9700212.Copenhagen, Denmark: European Environment Agency, EEA.

Stutz, J. and Platt, U. (1996). Numerical analysis and estimation of the statistical error of differential optical absorption spectroscopy measurements with least-squares methods. *Applied Optics* 35 (30), 6041-6053.

United Nations Development Programme, UNDP (2006). *Niger Delta Human Development Report*. Abuja, Nigeria. United Nations Development Programme.

United Nations Environment Programme, UNEP (2005). *Urban Air Quality Management Toolbox*. Nairobi, Kenya: United Nations Environment Programme.

United States Environmental Protection Agency, USEPA (2006). *Air and Radiation*. National Ambient Air Quality Standards (NAAQS). Website: http://www.epa.gov/air/criteria.html

Uyigue, E. and Agho, M. (2007). *Coping with Climate Change and Environmental Degradation in the Niger Delta of Southern Nigeria*. Benin City, Nigeria: Community Research and Development Centre (CREDC).

World Meteorological Organization, WMO (1995). *Manual on Codes*. Report number: WMO No. 306.Geneva, Switzerland: World Meteorological Organization.

Ziemke, J.R., Chandra, S., Duncan, B.N., Froidevaux, L., Bhartia, P.K., Levelt, P.F., and Waters, J.W. (2006). Tropospheric ozone determined from Aura OMI and MLS: Evaluation of measurements and comparison with the Global Modeling Initiative's Chemical Transport Model. *Journal of Geophysical Research* 111 (D19), D19303.

Zimmerman, D., Pavlik, C., Ruggles, A., and Armstrong, M. (1999). An experimental comparison of ordinary and universal kriging and inverse distance weighting. *Mathematical Geology* 31 (4), 375-390.