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Assessing the Relationship between Economic Growth and Emissions Levels in South Africa between 1994 and 2019

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Abstract: The objective of this study is to establish whether there is any relationship between economic growth and emission levels for pollutants (namely carbon dioxide (CO_2), black carbon (BC), sulfur dioxide (SO_2), and carbon monoxide (CO)) in South Africa, for the period from 1994 to 2019. Data from the world bank, namely gross domestic product (GDP) and CO_2 emissions, were used. BC, SO_2, and CO data were obtained from Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). The linear correlation coefficient and the environmental Kuznets curve (EKC) hypothesis test were used to determine the relationships. The sequential Mann–Kendall (SQMK) test was further used to study the trends. A correlation coefficient of 0.84, which indicates a strong positive linear correlation, between GDP and CO_2 emission was observed. However, the relationship between GDP and CO concentration showed a correlation coefficient of −0.05, indicating no linear relationship between the two variables. The EKC hypothesis showed an N-shape for SO_2 and CO. Overall, the results of this study indicate that emissions levels are generally correlated with economic growth. Therefore, a stringent regulatory system is needed to curtail the high emissions levels observed in this study, given the devastating impacts of global warming already ravaging the world.

Keywords: GDP; sulfur dioxide; black carbon; EKC hypothesis; MERRA-2; sequential Mann–Kendall

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1. Introduction

Economic growth due to industrialization is often associated with negative economic externalities such as air pollution. Industrialization in most developing countries is often associated with high levels of combustion of fossil fuels, resulting in gas emissions such as sulfur dioxide, nitrous oxides, carbon monoxide, and carbon dioxide. These criteria pollutants are associated with direct impacts on human health and ecosystems. Several scholars have investigated the nexus between emissions, economic growth, and energy consumption [1–6]. Significant attention has been paid to the nexus between energy consumption and economic growth [5]. Many studies have also focused on analyzing the relationship between energy consumption and carbon dioxide emission levels. In China, Zhanga and Cheng [7] investigated the energy consumption, carbon emissions, and economic growth relationship and found a unidirectional Granger causality running from gross domestic product (GDP) to energy consumption. Moreover, the study reported that a unidirectional Granger causality was observed from energy consumption to carbon dioxide emissions in the long run. In a similar study, Esso and Kebo [8] observed that energy consumption and economic growth are linked with rising atmospheric pollution in some African countries in the long run.

The relationship between environmental quality and economic growth has mostly been modelled using econometric models, with the environmental Kuznets curve (EKC) model being the most popular [9–12]. The EKC hypothesis proposes that environmental pollution rises rapidly with economic growth until it reaches a turning point and declines with further economic growth. The trend is similar to the Kuznets inverted U-curve used for analyzing income inequality and economic growth. The trends between environmental pollution and income growth can be illustrated by monotonic and non-monotonic curves [13]. Monotonic curves describe situations where environmental pollution increases with increased incomes levels and vice versa, while non-monotonic curves describe more complex trends. Inverted U- and N-shaped curves are among the most widely used non-monotonic curves. Non-monotonic inverted U-shaped curves have remained popular due to their simplicity and theoretical power to describe the positive elasticities between environmental pollution and income. The inverted U-curves can also explain the impacts of structural changes on pollution and consumption, and easily describe the effects of using green technology on the environment as income increases. On the other hand, the N-shaped curve indicates the decline in environmental pollution due to increasing income levels may be temporary, as environmental pollution worsens again with increasing income per capita due to increased material usage [14].

The validity of the EKC has been examined by many scholars, and the results are mixed. Evidence for the environmental Kuznets hypothesis as evinced by an inverted U-shape was observed in some empirical studies [15–19]. However, other studies challenge the validity of the EKC results [20,21]. Other studies urge that the relationship between economic growth and environment studies can be described as N-shaped or U-shaped, or it can take other shapes. While several studies have confirmed the existence of this relationship, many other studies dispute the existence of this correlation. Evidence of the relationship between gas emissions and economic growth has been found mostly with nitrous oxides, and to some extend sulfur dioxide (SO_2) resulting from the combustion of fossil fuels.

While some studies validate the Kuznets hypothesis in industrialized European and Asian countries, little work has been done in sub-Saharan Africa. In particular, very few studies have been done in southern Africa to correlate economic growth and industrial gas emissions. South Africa has undergone many economic cycles since the colonial days of apartheid and after its democratic dispensation in 1994. South Africa's energy needs are primarily satisfied by electricity from coal-fired stations, which generate large quantities of carbon dioxide (CO_2) and SO_2 emissions [22]. The country is the leading greenhouse gas emitter in Africa and ranks high globally. The relationship between CO_2 emissions and economic growth in South Africa has previously been explored in the context of energy utilization and economic policy. Bekun et al. [23] examined the relationship between energy use and economic growth from 1960 to 2016 and observed an inverse U-shaped relationship between economic growth and CO_2. Using the Granger causality test, the authors further attested the existence of a unidirectional causality between energy consumption and CO_2 emissions, suggesting that the country's economic growth is energy-led. A similar study by Hossain [24] focusing on newly industrialized countries that included South Africa observed that economic growth was correlated with higher energy consumption accompanied by higher CO_2 emissions. Odhiambo [25] found bidirectional causality between economic growth and electricity consumption in South Africa.

South Africa's reliance on coal for electricity generation is well established [22]. The country's carbon emissions per capita increased incessantly from 1980 to 2006 due to the establishment of coal-fired stations to meet growing domestic and industrial electricity demands. Winkler [26] noted that the CO_2 emission levels increased by a multiple of seven since 1950, with up to 90% of the emissions originating from the burning of coal. South Africa's emission levels pose a significant threat to climate change and human respiratory health. The emission profile suggests that the country should adopt sustainable green energy sources to mitigate the detrimental environmental impacts. An analysis by Menyah and Wolde-Rufael [22] reveals that the country's energy consumption per capita and CO_2 emissions per capita accelerated faster than real GDP per capita.

Satellite data has been proven to be invaluable in monitoring the long-term trends of gas emissions due to industrial combustion of fossil fuels. Many studies have used satellite data to correlate industrial emissions with economic growth. Recently, Ding et al. [27] investigated the existence of EKC using time-series of satellite data of $PM_{2.5}$ emissions over the Beijing–Tianjin–Hebei (BTH) belt in China. The region is characterized by immense pollution due to $PM_{2.5}$ caused by heavy industrialization. The assessment done from 1998 to 2016 confirmed a relationship between economic growth and $PM_{2.5}$ pollutions as evidenced by a typical Kuznets inverted U-shaped curve. Similarly, a more recent study by Dong et al. [28] used satellite data from NASA and economic data from the World Bank to establish the relationship between urbanization and $PM_{2.5}$ pollution, and reaffirmed the existence of the environmental Kuznets inverted U-shaped curve.

Earth observation satellites play a significant role in monitoring gas emissions and aerosol concentrations in the atmosphere. The use of atmospheric monitoring satellites in measuring gas emissions is advantageous because it enables long-term analysis of historical emission data records. While some studies have used satellite data for monitoring atmospheric gas emissions in South Africa, little has been done to correlate the gas emission levels and economic growth using satellite data. Furthermore, most studies on gas emissions and economic growth tend to focus on carbon dioxide (CO_2) emissions. To address this paucity in research, our study investigates the relationship between emissions (i.e., SO_2, CO_2, carbon monoxide (CO), and black carbon (BC)) and economic growth using satellite-derived emission data.

Therefore, in this study, we aim to establish whether there is any relationship between economic growth and emission levels for pollutants (namely CO_2, BC, SO_2, and CO) in South Africa, between 1994 and 2019. After establishing the relationship between the emission levels and economic growth, this study also seeks to test the environmental Kuznets curve hypothesis. As described earlier, the hypothesis proposes that economic growth and environmental pollution have an inverted U-shaped relationship. Furthermore, the study also investigates differences in the spatial distribution of BC, CO, and SO_2 for the years 1994 and 2019.

This study is organized as follows: the description of the study area is given in Section 2, and a discussion of the datasets and methods used in this study are detailed in Section 3. Section 4 presents a discussion of the results obtained, and conclusions are outlined in Section 5.

2. Description of the Study Area

The Republic of South Africa (RSA) is a country on the southernmost tip of the African continent. It covers an area of ~1.22 million km^2 and has a coastline of ~2800 km. Its terrestrial biodiversity can be divided into nine biomes, 31 different river ecoregions and estuaries, and coastal marine habitats in three biogeographical zones around the coast. One of the major threats to biodiversity is habitat loss and degradation, resulting from alternative land uses for urban, industrial, and mining development, agriculture, biofuel production, canalization, and trawling. Most of the country experiences cold and dry periods in the autumn and winter (March–August) seasons, while the hot and wet periods are observed in the spring and summer (September–February) seasons. The weather in this region is also influenced by ENSO (El Niño–Southern Oscillation).

RSA has a diverse economy, with key sectors such as mining, manufacturing, agriculture, construction, and government services contributing the most towards the gross domestic product (GDP). However, the growing population and increasing unemployment over time have contributed negatively to the economic growth of RSA. Table 1 summarizes some indicators that directly and indirectly impact the economic growth of RSA. The growing population in RSA has led to higher electricity demands as more houses and businesses are established. This has led to an increase in harmful emissions in the atmosphere. South Africa is the leading producer of greenhouse gases on the Africa continent due to its advanced industrialization powered by fossil fuels such as coal and petroleum products [29].

Table 1. World Development Indicators for RSA [30].

World Development Indicators	Indicator Value (Start Year)	Indicator Value (End Year)	Change (%)
Population	40,564,059 (1994)	57,779,622 (2018)	+29.80
CO_2 emissions from solid fuel consumption (kt)	299,443.553 (1994)	399,603.991 (2016)	+25.07
Access to electricity (% of population)	57.60 (1996)	91.23 (2018)	+36.86
GDP growth (annual %)	3.200 (1994)	0.787 (2018)	−306.7

3. Data and Methodology

3.1. World Bank Indicators

In this study, three variables, namely GDP in local currency unit (LCU), GDP annual growth, and CO_2 emissions, are employed from the World Development Indicators [30]. GDP is defined as the market value of all final goods and services produced in one period [31]. Therefore, GDP is said to be a measure of economic activity. On the other hand, GDP annual growth is the percentage change in the value of all the goods and services produced in a nation during a specific period compared to an earlier period. GDP annual growth is used to measure the comparative health of an economy over time. CO_2 is one of the greenhouse gases (GHG) attributed to climate change and global warming [32–34]. CO_2 sources occur both naturally (decomposition, ocean release, and respiration) and from human activities (burning of fossil fuels, cement production, and deforestation). The Intergovernmental Panel on Climate Change (IPCC) Special Report [35] showed that the power and industry sectors combined dominate global CO_2 emissions. The IPCC Special Report further showed that the CO_2 emissions in these sectors are generated by boilers and furnaces burning fossil fuels and are typically emitted from large exhaust stacks. To reduce the CO_2 emissions from the power and industry sectors, it is important to understand where these emissions arise and what their geographical relationship is with respect to potential storage opportunities [36]. Other sectors of the economy, such as the residential and transport sectors also contribute towards CO_2 emission. In this study, GDP annual growth data for 1994–2018 and CO_2 data from 1994–2016 were used.

3.2. MERRA-2

The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) is an atmospheric reanalysis designed to provide an intermediate dataset and bridge between the first MERRA reanalysis [37] and the project's long-term goal of producing a coupled Earth system reanalysis [38]. MERRA-2 provides data from 1980. It uses the latest V5 Goddard Earth Observing System Model (GOES) data assimilation with an updated grid to point statistical interpolation system [39,40]. Gridded data are released at a 0.625° longitude × 0.5° latitude resolution on 72 sigma–pressure hybrid layers between the surface and 0.01 hPa [41]. MERRA-2 incorporates system changes and fundamental developments in modeling and data assimilation, including (1) assimilation of aerosol observations that can interact with atmospheric radiative processes; (2) constraining mass conservation even with the analysis of water vapor, allowing a global balance between evaporation and precipitation; (3) use of a cube sphere to reduce the effect of grid point singularities at the pole, allowing for improved polar circulation; (4) an updated radiative transfer model to permit the assimilation of data from many more instruments than could have been included in MERRA; and (5) inclusion of new observational forcing for the land model to provide more stable land feedback processes [34,42,43]. MERRA-2 assimilates bias-corrected aerosol optical depth (AOD) from the Moderate Resolution Imaging Spectro-radiometer and the Advanced Very High Resolution Radiometer instruments. Moreover, MERRA-2 assimilates (non-bias-corrected) AOD from the Multiangle Imaging SpectroRadiometer over bright surfaces and AOD from Aerosol Robotic Network sunphotometer stations [43]. One of the advantages of MERRA-2 data is their ability to provide detailed information on how the anthropogenic component of aerosols, and thus radiative forcing, has changed during the modern satellite era, as well as its interaction with the circulation and the climate at large [38]. In this study, BC concentration, CO concentration, and SO_2 concentration were used. A summary of the data used in this study is shown in Table 2.

Table 2. Summary of the data used in this study.

Input Data Source (Temporal Resolution, Spatial Resolution)	Products Used	Period of Analysis
MERRA-2 (monthly; 0.5° × 0.625°)	BC (μg·m^{-3}) SO_2 (μg·m^{-3}) CO (μg·m^{-3})	1994–2019
World bank Indicators	GDP annual growth CO_2 emission (kt)	1994–2018 1994–2016

3.3. Linear Regression

Analysis of variance is used to analyze the effects of one or more independent variables on the dependent variable. The dependent variable must be quantitative. The dependent variable(s) may be either quantitative or qualitative. Unlike regression analysis, no assumptions are made about the relation between the independent variable and the dependent variable(s). Linear regression is a model with a single regressor x that has a relationship with a response y that is a straight line. This simple linear regression model can be expressed as

$$y = mx + c + \varepsilon \tag{1}$$

where the intercept c and the slope m are unknown constants, and ε is a random error component. The coefficient of determination (i.e., R-squared (R^2)) is a measure of how close the data are to the fitted regression line. R^2 close to 1 implies an almost perfect relationship between the model and the data, whereas an R^2 close to 0 implies that just fitting the mean is equivalent to the model fitted. However, R^2 statistics are often well understood and correctly interpreted, although they can also be misleading, given that the precision of the statistic is dependent on sample size [44,45].

3.4. SQ-MK Test

The sequential Mann–Kendall (SQMK) test proposed by Sneyers [46] is used to identify abrupt changes in significant trends [47,48]. This test sets up two series: a progressive $u(t)$ and a retrograde (backward) series $u'(t)$. If they cross each other and diverge beyond the specific threshold value, then there is a statistically significant trend. The point where they cross each other indicates the approximate year at which the trend begins [49]. The threshold values in this study are ±1.96 (p = 0.05), with the crossing point estimating the year at which the trend begins. The SQMK test has the following steps:

i. At each comparison, the number of cases $x_i > x_j$ is counted and indicated by n_i, where x_i (i = 1, 2, . . . , n) and x_j (1,2, . . . , n) are the sequential values in a series, respectively.

ii. The test statistic t_i is calculated by

$$t_i = \sum_{j=1}^{i} n_j \tag{2}$$

iii. The mean $E(t)$ and the variance var(t_i) of the test statistic are calculated by

$$E(t) = \frac{n(n-1)}{4} \tag{3}$$

$$\mathrm{var}(t_i) = \frac{i(i-1)(2i+5)}{72} \tag{4}$$

iv. Sequential progressive value can be calculated as

$$u(t) = \frac{t_i - E(t)}{\sqrt{\mathrm{var}(t_i)}} \tag{5}$$

Similarly, the values of $u'(t)$ are computed backwards, starting from the end of the series. In this study, SQMK was performed on CO, BC, SO_2, and CO_2 emissions, and GDP annual growth.

3.5. Environmental Kuznets Curve Hypothesis

The environmental Kuznets curve (EKC) hypothesizes a relationship between environmental degradation and GDP per capita. Environmental pressure increases in the early stages of economic growth due to the increased release of pollutants [50], but beyond some level of GDP per capita, economic growth leads to environmental improvement. This implies that environmental emissions per capita are an inverted U-shaped function of GDP per capita.

The EKC has been the dominant approach among economists to modeling ambient pollution concentrations and aggregate emissions. To test the EKC hypothesis, we use regression analysis of the modelled EKC economic growth and environmental pollution. The quadratic form of EKC is given by Equation (6).

$$Y_t = \beta_0 + \beta_1 X_t + \beta_2 (X_t)^2 + U_t \tag{6}$$

The EKC hypothesis holds that if $\beta_1 > 0$ and $\beta_2 < 0$, and both are statistically significant, then a turning point and an inverse U–shaped relation could exist. The cubic form of EKC is given by Equation (7).

$$Y_t = \beta_0 + \beta_1 X_t + \beta_2 (X_t)^2 + \beta_3 (X_t)^3 + U_t \tag{7}$$

Equation (7) describes a relationship with two potential turning points. If $\beta_1 > 0$, $\beta_2 < 0$, and $\beta_3 > 0$, then an N-shaped function exists. The N-shaped curve indicates that the environmental degradation starts rising again after a reduction to a specific level. The inverted N-shaped graph means that the environmental deterioration starts falling again after an increase to a certain level.

4. Results and Discussions

4.1. CO_2 Emissions and GDP Annual Growth

From 1994 to 2016, CO_2 emissions in South Africa were on an increasing trend. Figure 1a shows an increasing linear trend of CO_2 emissions during the 1994–2016 period. However, from 1994 to 1998, a decrease in CO_2 emissions is observed. This is the period when a political transition was taking place with new resolutions and laws being put into effect. The uncertainty in the new government resulted in several companies closing down and thus resulted in the reduction of CO_2 emissions. This also resulted in a decrease in GDP annual growth from 1994 to 1998 (Figure 1b). Overall, GDP annual growth showed a linearly decreasing trend from 1994 to 2018. This decrease was due to many factors, such as increasing population and unemployment. The SQ-MK results in Figure 1c,d tell a very interesting story on the trends of CO_2 emissions and GDP annual growth, respectively. The first democratic term in South Africa was in the period from 1994 to 1999. The first term shows a decrease in CO_2 emissions and negative GDP growth. The decrease in CO_2 emissions could be from the uncertain economy, which was relatively new. Several economic activities slowed down, which impacted CO_2 emissions and GDP annual growth. The second democratic term was from 1999 to 2004. This is the turning point of both the CO_2 emissions and GDP annual growth. The turning point (increase) of CO_2 emissions is observed from the year 2000. A slight increase in CO_2 emissions, in this case, indicates a recovery in the economy, with more activities in the manufacturing and processing activities contributing to the increase in CO_2 emissions. This observation is supported by Figure 1d, which shows an increase in GDP annual growth in the second democratic term. The turning point is in the year 1998, and it increases until 2005. South Africa's Electrification Programme [51] picked up momentum in the late 1990s. The essence of the program was to electrify most of South Africa. This needed more power stations to produce electricity. In fact, decommissioned power stations from the past were refurbished and brought back to an operational state. This increased the amount of CO_2 emitted. Owing to the stable economic, political, and energy state, more factories started operating, and hence contributing to the increase in CO_2 emissions and GDP annual growth during that period. The third democratic term was from 2004 to 2009. During this period, there is a sharp increase in CO_2 emission and a negative annual GDP growth.

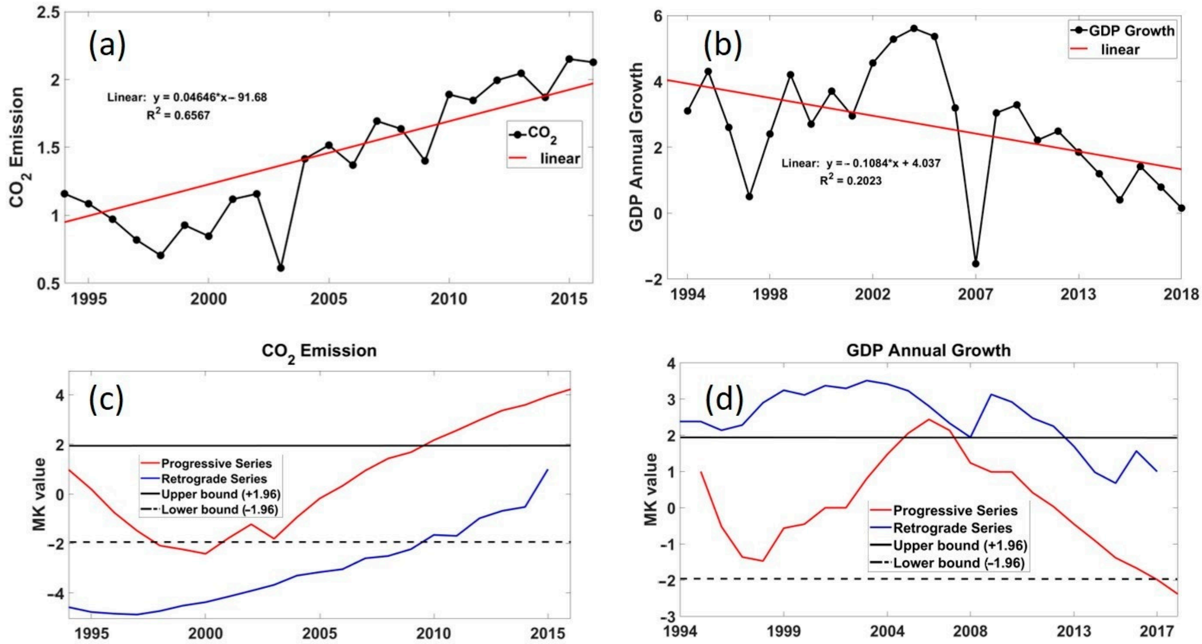

Figure 1. Linear trends of (**a**) CO_2 emissions and (**b**) GDP annual growth in South Africa. SQ-MK trends in (**c**) CO_2 emissions and (**d**) GDP annual growth in South Africa.

4.2. Emissions: Linear and SQ-MK Trends

Chemical processes in some economic activities such as electricity production, manufacturing, and mining result in harmful substances' emissions into the atmosphere. Electricity production, in particular, results in the emission of CO_2 and SO_2 gases. Figure 2a,c show a time-series of these gases from 1994 to 2016 and 2019, respectively. An increasing linear trend is observed over time. The high demand for electricity for both households and manufacturing and processing industries are the main drivers for the escalating emissions. Most of South Africa's power stations are coal-based [52], which leads to the formation and emission of large amounts of CO_2 and SO_2 gases. However, the increasing rate of emissions of CO_2 and SO_2 are rather vast. Apart from the obvious reason that more CO_2 is produced during electricity production than SO_2, another contributor to the CO_2 emissions could be the increase in the number of operating vehicles post-1994. The free movement and the opening of the economy for all South Africans resulted in more people affording and purchasing vehicles and moving freely across the country. On the other hand, non-ferrous mining and smelting are the other contributors to SO_2 emissions. However, both these activities have not increased significantly post-1994; hence, the slower increasing rate is observed. Similar to the CO_2 linear trend, BC concentration increased rapidly over time (see Figure 2b). There are several known sources of BC emissions from activities such as biomass burning (from wildfires and agriculture), oil and gas processing, transportation, domestic burning, and shipping. The rapidly increasing rate of BC concentration in this study is likely associated with domestic burning and transportation. With the increase in population (Table 1), unemployment, and the slow implementation of South Africa's Electrification Programme, most people rely on domestic burning for cooking and heating [53]. This is mostly dominant in rural and semi-urban areas. The high dependence on domestic burning contributes to the increase in BC concentration over time. Road, air, and water transportation also contributed towards the increase in the BC concentration. However, it is known that the biggest emission from transportation is CO. Therefore, CO would be a better parameter to use in order to track if there is any effect due to transportation activities. Figure 2d shows no trend in CO over time, implying that there was limited change in emissions from transport activities. The trend for CO concentration shows that it was not a significant pollutant post-1994.

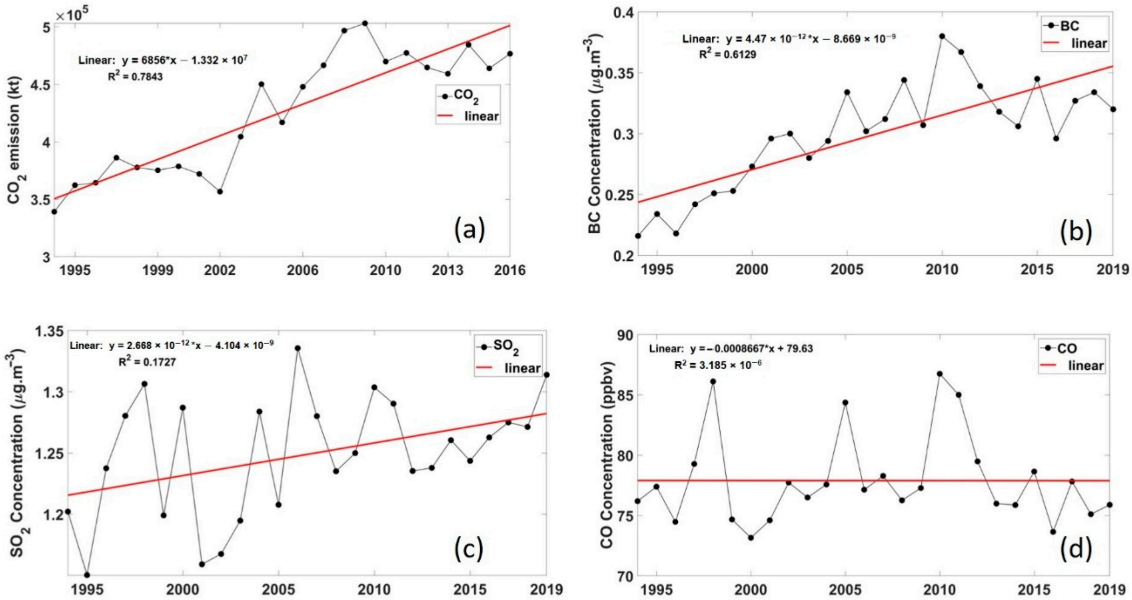

Figure 2. Linear trends for (**a**) CO_2 emission (kt), (**b**) BC concentration, (**c**) SO_2 concentration, and (**d**) CO concentration.

The SQ-MK trends in Figure 3 are in agreement with linear trends observed in Figure 2. Figure 3a shows the SQ-MK trends of CO_2 emissions from 1994 to 2016. A slight decrease in CO_2 emission is observed from 1994 to 2002, which indicates a slowdown in industrial activities (such as manufacturing, processing, and electricity production). Consequently, this has a negative impact on GDP growth. However, an increase in CO_2 emission is observed from 2002 onwards. This is due to an increase in CO_2-related activities such as electricity production and manufacturing. In Figure 3b, the increase in BC starts from the year 1995. Venter et al. [54] showed that a majority of BC in South Africa was due to household combustion from semi-formal and informal settlements at a local scale. With an increasing population in South Africa [55] and increasing unemployment, most people live in dire environments without electricity; hence, they depend on open fires for cooking and heating. However, the BC emission seems to stabilize from 2014 to 2019. This could be due to (1) cleaner energy being used and (2) an increased number of electrified households, thus declining biomass burning. The SO_2 concentration shows a decreasing trend from 1995 to 2004 (see Figure 3c). This indicates lesser emissions from coal-fired power stations. Lesser demands from industries and mines could be the reason for the lower production of electricity. Most companies closed down and relocated to other countries between 1995 and 2004. Political unrest and government transition were the main drivers behind this. However, from 2004 to 2019, an increase in SO_2 concentration is observed. This increase is from the full operations of coal-fired power stations for electricity production. The demand for electricity during this period is from (1) electrification of some rural areas, (2) development of new semi-urban areas, and (3) establishment of new industries. There is no clear trend for CO concentration (see Figure 3d).

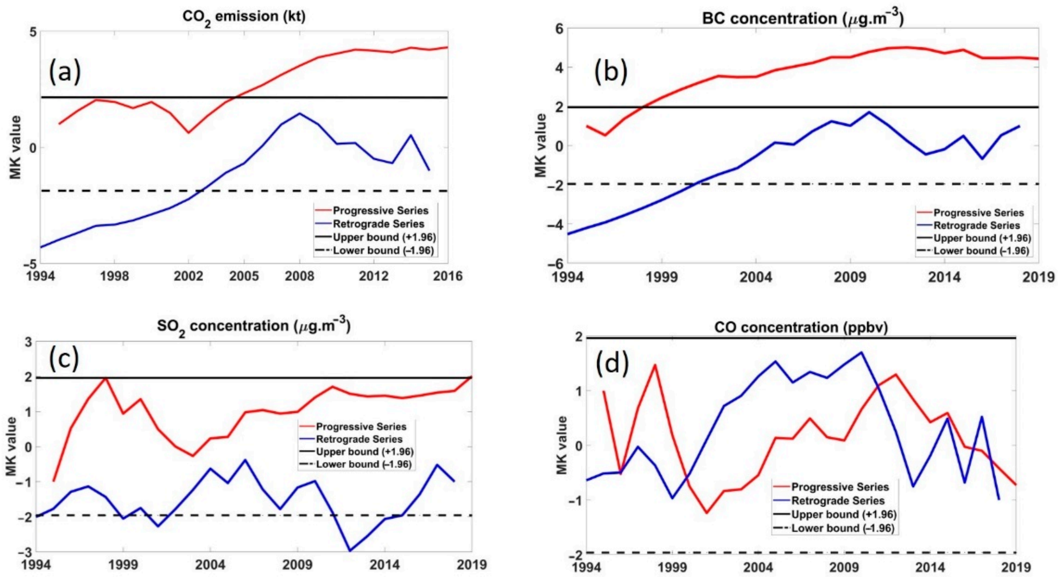

Figure 3. SQ-MK trends for (**a**) CO_2 emission (kt), (**b**) BC concentration, (**c**) SO_2 concentration and (**d**) CO concentration.

4.3. Pollutants and GDP Correlation

The association between GDP and the pollutants is shown in Figure 4. A correlation coefficient of 0.84, which indicates a strong positive linear correlation, between GDP and CO_2 emission is observed in Figure 4a. This indicates that as GDP increases, CO_2 emissions also increase almost proportionally. The activities mostly responsible for the CO_2 emissions' increase are in the electricity production, manufacturing, and mining sectors. The relationship between GDP and BC concentration showed a correlation coefficient of 0.68 (see Figure 4b), which indicates a moderate positive linear correlation. This result shows that there is some sort of relationship between GDP and BC concentration, especially in the beginning, but over time the relationship is lost as the BC concentration saturates (see Figure 3b). The saturation in BC concentration is due to the decrease in domestic burning. A correlation coefficient of 0.40 between GDP and SO_2 concentration is observed in Figure 4c. This indicates a positive weak correlation. This result suggests that there is a small relationship and influence between the two variables. The relationship between GDP and CO concentration showed a correlation coefficient of -0.05 (see Figure 4d), indicating no linear relationship between the two variables. As much as the linear relationship correlation gives us some useful information regarding GDP and pollutants, the EKC hypothesis (see Section 3.5) is the best method to use.

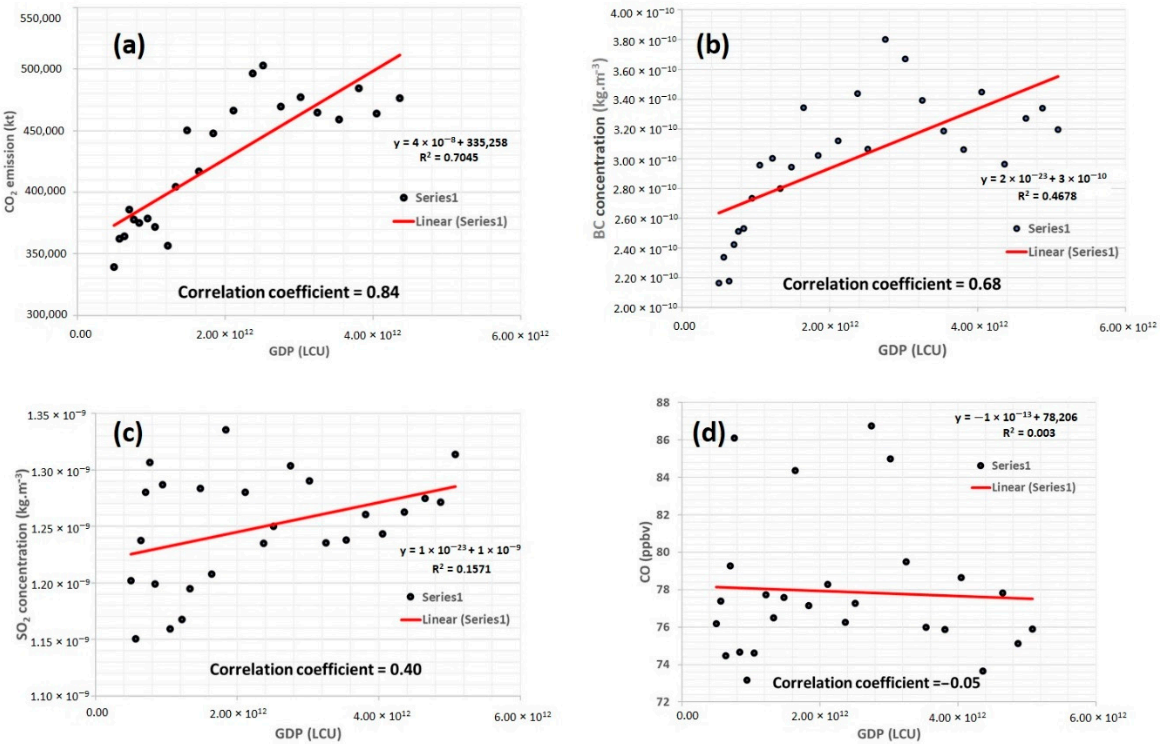

Figure 4. Scatter plots for (**a**) GDP and CO_2, (**b**) GDP and BC, (**c**) GDP and SO_2, and (**d**) GDP and CO.

4.4. EKC Relationship between GDP per Capita and Pollutants

While most studies on economic growth and greenhouse gas emissions in South Africa have focused on CO_2 emissions, this study fills a fundamental gap in studying the trends of four harmful constituent emissions, namely SO_2, CO, CO_2, and BC. Figure 5 shows the relationship between GDP per capita and pollutants emission using the EKC hypothesis. SO_2 results in Figure 5a show evidence of an N-shape relationship. These findings are consistent with Grossman and Krueger [56] and Panayotou [57]. The reduction in emission level for SO_2 as observed on the EKCs (see Figure 5a) is caused by a number of factors that includes the technological effects due to innovation, the introduction of renewable and clean energy sources into the energy mix, adoption of the smart city concepts in urban centers, emission regulatory controls, carbon taxes, and carbon trading. The need for green energy sources to support sustainable development is significantly pressurizing governments to reduce emission levels. While the emission levels currently show a downward trend, there is a greater need to decouple the emission levels from economic growth by using cleaner energy sources. Since coal is unavoidable in the near future, the use of clean coal with smaller sulfur content is recommended. Furthermore, as the South African economy continues to grow, there is a need to shift from a heavy industry structure to one that is more service-orientated, as this will also reduce the emission levels in the long run.

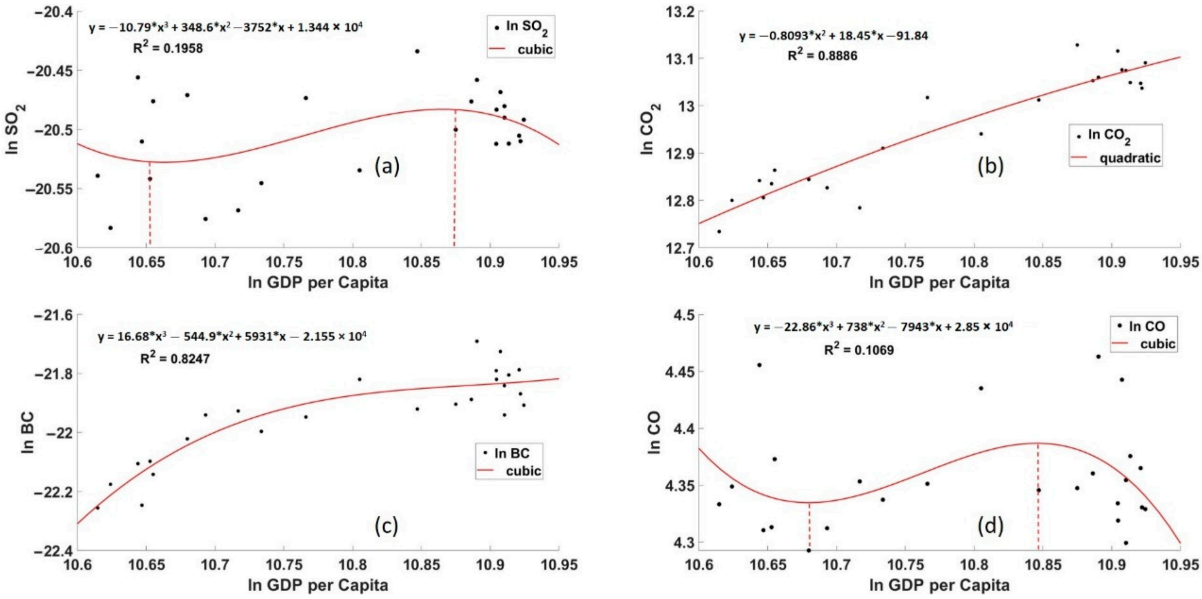

Figure 5. The relationship between GDP per capita and (**a**) SO_2, (**b**) CO_2, (**c**) BC, and (**d**) CO.

The CO_2 results in Figure 5b suggest an inverted U-shape; however, there seems to be greater linearity in emission levels and economic growth. In some way, the CO_2 trends in Figure 5b seem to have some similarity with the environmental Daly curve, where the emissions levels increase with economic growth. For CO_2, the increase in emissions with economic growth is explained by the scaling effects related to the expansion of power generation capacity using fossil fuels to meet the increasing energy demands of heavy industries and domestic electricity needs. South Africa is heavily reliant on coal for its electricity generation. The domestic power needs for South Africa are further exacerbated by rapid urbanization. The rapid proliferation of informal settlements in South African cities add an additional dimension to the emission challenges in the country. The relationship between energy, CO_2 emissions, and economic growth in South Africa has been studied by some scholars previously. Bekun et al. [23] investigated the relationship between CO_2 emissions and economic growth and found an inverse relationship. The scholars further established a unidirectional causality from energy consumption to carbon dioxide. Their study validates the energy-induced economic growth hypothesis in South Africa. Earlier studies by Odhiambo [25] and Eggoh et al. [58] affirmed a distinct bidirectional causality between energy consumption and economic growth in South Africa. Similar studies also concluded a long-run and unidirectional causal relationship between energy consumption and CO_2 gas emissions and economic growth in South Africa [22,59]. A recent study by Shikwambana and Tsoeleng [55] revealed that cooking fires from informal settlements add a significant amount of BC and CO emissions in urban environments. Furthermore, South Africa has many rapidly growing small towns that demand a fair share of energy. The high emission levels are also further caused by the aging infrastructure and obsolete technology used by the old coal-fired power generation stations. The BC trend in Figure 5c shows a logarithmic curve where BC stabilizes (i.e., no change over time) with economic growth. CO (see Figure 5d), on the other hand, shows a N-shape relationship. De Bruyn et al. [13] showed that for the N-shape, beyond a certain GDP per capita value, increased GDP per capita might once again lead to a positive relationship between economic growth and environmental degradation.

4.5. Spatial Distribution of Pollutants and Meteorological Conditions over South Africa

The spatial distributions of BC, CO, and SO_2 over South Africa for the years 1994 and 2019 and their difference are shown in Figure 6. Figure 6a shows a hotspot of high BC concentration (~0.9 $\mu g \cdot m^{-3}$) in the northeastern parts of South Africa (27° S, 27° E).

Generally, BC results from incomplete combustion processes such as fossil fuel and biomass burning. Therefore, this high BC concentration is from industrial processing activities and a high volume of vehicles in the area. In 2019, Figure 6b, a higher BC concentration of ~1 $\mu g \cdot m^{-3}$ is observed. This is confirmed by Figure 6c, which shows an increase in the BC concentration in the northeastern parts of South Africa. The increase in the BC concentration is from (1) the increase in vehicle volume on the road influenced by a growing economy, and (2) the increasing economic growth permitting more industrial plants for processing and manufacturing to operate. However, in 2019, a significant increase in BC (see black box in Figure 6b) is observed on the east coast of South Africa. This is confirmed by Figure 6c, which shows an increase in BC concentration. The area highlighted by the black box (29° S, 30° E) consists of numerous sugar cane plantations. An increase in sugar cane burning during harvest time might be the cause for the increase in BC concentration in this area. Some of the benefits of sugar cane burning are (1) the fire increases the yield of sugar recovered per ton of sugar cane by the factories and improves the overall quality of the sugar produced, (2) it allows more efficient harvesting of sugar cane in the field, and (3) it reduces wear and tear on field and factory equipment.

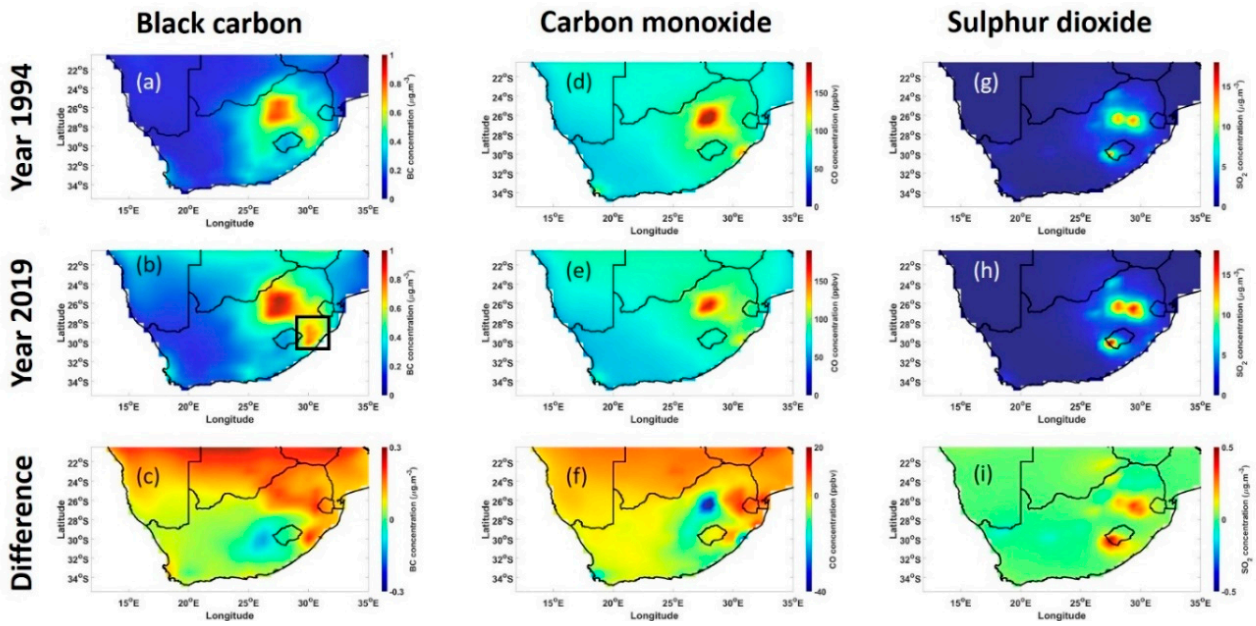

Figure 6. Spatial distribution of (**a**–**c**) black carbon, (**d**–**f**) carbon monoxide and (**g**–**i**) sulphur dioxide in 1994, 2019 and the difference between 2019 and 1994.

The highest concentration of CO (~170 ppbv, parts-per-billion-volume) is observed in the northeastern parts of South Africa in the year 1994 (see Figure 6d). Generally, the main sources of CO are cars, trucks, and other vehicles or machinery that burn fossil fuels. Trucks transport coal to the power stations around the Highveld area, therefore the high volume of trucks contributes significantly to the high CO concentration. Industries in the area burning fossil fuels for the processing and manufacturing of goods also contributes to the CO concentration. However, in 2019, a decrease in CO concentration in the area is observed (see Figure 6e). Figure 6f shows that the decrease is as much as ~−40 ppbv, which is very significant. The decrease in CO concentration can be attributed to declining economic growth, which has resulted in many industries shutting down or cutting down production, which in turn has resulted in the decline in CO emissions.

Two SO_2 hotspots (see Figure 6g) are observed on the Highveld of South Africa (27° S, 29° E), and one hotspot is observed on the border of Lesotho and South Africa. The SO_2 concentration at the Highveld in 1994 is between 9 $\mu g \cdot m^{-3}$ and 11 $\mu g \cdot m^{-3}$. The main sources of the SO_2 are the coal-fired power stations. Shikwambana et al. [38] give an in-depth discussion on the distribution of SO_2 in this area. In 2019 (see Figure 6h), an increase in SO_2 concentration (~0.5 $\mu g \cdot m^{-3}$) in the Highveld is observed. This is confirmed by Figure 6i. Although the increase might not seem significant, it does contribute negatively to the air quality. The increase could be caused by the addition of old coal-fired power stations on the energy grid to meet the energy demand.

5. Summary

The results of this study indicate that emissions levels are generally correlated with economic growth. This is consistent with econometric propositions such as the environmental Kuznet hypothesis, which indicates that environmental pollution increases proportionally with economic growth until an inflexion point at which an inverse relationship takes place. Growing industrial and domestic energy demands necessitated South Africa to enhance its power generation capacity by expanding coal-fired power stations. Kusile and Medupi coal-fired power stations were recently constructed to augment the power supply in the country, and are subsequently injecting massive amounts of SO_2 and CO_2 into the atmosphere. Notably, there is increasing pressure for renewable green energy sources in South Africa and for independent power producers to supplement the power utility (i.e., Eskom). This emerging trend is widening the energy mix for South Africa to include solar, hydro, and wind energy. While the shift to green and cleaner energy sources is gaining momentum in South Africa, the emission levels will predictably remain high in the foreseeable future due to the high dependence on fossil fuels for power generation. South Africa, a signatory to the Paris Agreement (i.e., a treaty led by the United Nations Framework Convention on Climate Change), is facing increasing pressure to reduce its greenhouse gas emissions from coal-powered stations. To ensure compliance, the country needs to increase reliance on clean energy sources, such as renewable energy alternatives like solar, hydro, and wind energy. Nuclear energy is another alternative energy source as it does not emit greenhouse gases. The technological effects noted in the EKC hypothesis are also likely to impact future emissions trends. A stringent regulatory system is also needed to curtail the high emissions levels observed in this study, given the devastating impacts of global warming that are already ravaging the world.

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