

## Article

# Evolution of Ozone above Togo during the 1979-2020 Period

Koffi Ayassou<sup>1,2\*</sup>, Andrea Pazmiño<sup>1</sup>, Kokou Sabi<sup>2</sup>, Ariane Bazureau<sup>1</sup> and Sophie Godin-Beekmann<sup>1</sup>

<sup>1</sup> LATMOS, UVSQ Univ. Paris Saclay, Sorbonne Université, France

<sup>2</sup> LCA, Université de Lomé, Lomé, BP 1515, Togo

\* Correspondence: koffi.ayassou@latmos.ipsl.fr / ayass91@yahoo.fr

**Abstract:** The objective of this paper is to estimate the trend of Total Ozone Column (TOC) over Togo. Multi Sensor Reanalysis-2 (MSR-2) TOC over the entire territory of Togo were used. Multiple Linear Regression (MLR) method has been applied to retrieve the interannual contributions of different forcings and the long term variability. It was found that the Annual Oscillation (AnO), the Quasi Biennial Oscillation at 30 mb (QBO30), the Solar Flux (SF), and the El Niño–Southern Oscillation (ENSO) have statistically significant influence on the interannual variability of the TOC. The strongest contribution ( $22 \pm 1.4$  DU) is allocated to the AnO while the weakest ( $< 1$  DU) is attributed to the Semi-Annual Oscillations (SAO). Before the peak year of Equivalent Effective Stratospheric Chlorine (EESC) in tropics in 1997 the trend is negative ( $-0.3\% \pm 0.9\%$  per decade) and is not statistically significant. After the peak year, a statistically significant positive trend is observed. The trend of TOC is  $0.6\% \pm 0.2\%$  per decade. The monthly TOC trend over Togo is positive and statistically significant during the rainy season (particularly during the monsoon period) except in April, unlike during the harmatan period (DJF) where the trend is not significant.

**Keywords:** ozone; MLR; Togo; MSR-2; total column ozone; trend

## 1. Introduction

Stratospheric ozone plays an essential role in sustaining life on earth by filtering the most energetic solar ultra-violet (UV) radiations. Prolonged exposure without protection to these UV radiations, causes serious health risks (e.g. skin cancer) [1] and also affects biodiversity, especially crops and the marine ecosystem [2, 3]. Given this important role played by stratospheric ozone, it is therefore necessary to regularly monitor its evolution. Ozone is more produced in the tropical zone and is transported to extratropical zones by the Brewer-Dobson Circulation (BDC) [4, 5, 6]. The trend of the TOC in the tropics after the year of the peak of the EESC is low compared to the extratropical zones [7]. Similarly, a decreasing ozone in the lower stratosphere in the tropical zone since 1998 has been observed [8]. The MLR method applied in several studies of the trend of variability of the TOC [9, 10, 11, 12] is also used in this work to study TOC over Togo during the period 1979-2020. Togo is a West African country located in the intertropical zone between  $6^{\circ}$  N and  $11^{\circ}$  N, and between  $0^{\circ}14'$  W and  $1^{\circ}65'$  E. Being a stakeholder in the Montreal Protocol, Togo has made commitments not only to reduce Ozone Destruction Substances (ODS) emissions, but also to undertake ozone layer observation activities according to its supports funders. This study was carried out, in order to characterise the long-term trend of TOC over Togo and determine the contribution of dynamical and other major forcings to its interannual and decennial variability. The 1979-2020 period is chosen because the MSR-2 ozone data used in this work are not available before and after that period. It is consistent with the period when an important ozone depletion was observed until the mid-1990s followed by an expected increase in ozone on a global scale [13]. Also, the time series corresponds to a moment when the planet is experiencing a phenomenon of global warming caused by the anthropogenic increase of Greenhouse Gas (GHG) emissions, and therefore a warming of the troposphere which in turn cools the stratosphere [14].

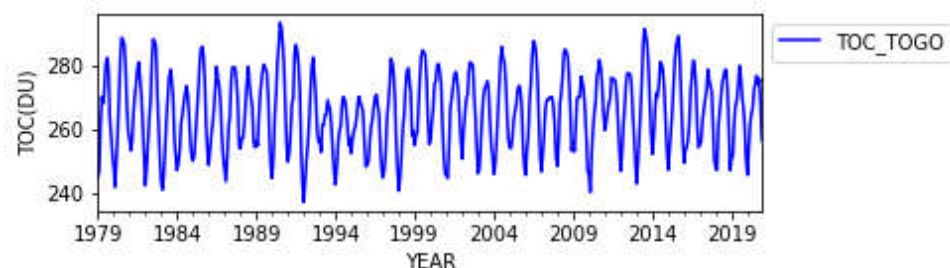
The structure of the paper is as follows: in Section 2 the methodology and data used are presented. The analysis of ozone over Togo is described in Section 4 to determine the contribution of different forcings, and trend since 1997 and monthly trend of ozone according to monsoon and harmattan periods in Togo. Finally, the conclusion of the study is presented in Section 5.

## 2. Data and Methodology

In order to study the interannual and long-term variability of TOC over Togo, a multilinear regression method was applied to MSR-2 [15] data covering the period 1979-2020.

### 2.1. MSR-2 (Multi-Sensor Reanalysis - 2 ) total ozone

MSR-2 ozone data is built on the basis of fourteen (14) satellite data sets [15]. Positioned in polar orbit, the 14 satellites measure in the Huggins UV band (305-340 nm). The first step in data construction is to apply error bias correction to the 14 satellite datasets based on total ozone column measurements from TOC ground-based and UV measurement stations. The correction is made according to the solar zenith angle (SZA), viewing zenith angle (VZA), effective stratospheric temperature, time and offset (with year 2000 reference). The second step is to apply the data assimilation method to satellite datasets to create global ozone data. The assimilation method is that of the sub-optimal implementation of the Kalman filter technique based on the chemistry-transport model TM3-DAM which gives detailed information on the transport and chemistry of ozone in the stratosphere, in order to assimilate the data. The data thus constructed lead to version 2 of the MSR called MSR-2 and they are useful for studies of the TOC in places where measurement stations are lacking such as in Africa, in particular in Togo. The spatial resolution of the data is  $0.5^\circ \times 0.5^\circ$  [16] and corresponds to ozone columns in Dobson Unit (DU). MSR-2 data was chosen for this study because there is the possibility of extracting data specific to the Togolese national territory unlike zonal data. These data have been used to study the trend of total ozone in the southern hemisphere and in the Antarctic [10, 17]. The data collected are monthly average values and cover the 1979-2020 (Figure 1). These data cover the national territory with latitudes between  $6^\circ$  and  $11^\circ$  N, and longitudes between  $0^\circ 14'$  W and  $1^\circ 65'$  E. They were downloaded from the website of the tropospheric emissions monitoring service (TEMIS) of ESA/KNMI at the address: <https://www.temis.nl/protocols/o3total.php> (last access: September 17, 2021).



**Figure 1.:** Monthly total ozone column over Togo from 1979-2020

### 2.2. Multilinear regression method

The multilinear regression (MLR) method was applied to study the interannual variability and trend of TOC over Togo. The MLR method used in this work is similar to that used in previous works [9, 10, 12]. The method was applied using the R statistical software [18]. In order to take into account, the autocorrelation of the residuals, the Cochrane-Orcutt transformation was applied [19, 20] to the MLR method thanks to the Rcmdr (Rcmdr) library and the package Orcutt of R statistical software allowing to have a valid MLR model.

The equation of the MLR method used is schematized by the relation:

$$Y(t) = K + C_{QBO30}QBO30(t) + C_{QBO10}QBO10(t) + C_{ENSO}ENSO(t) + C_{SF}SF(t) + C_{AnO}AnO(t) + C_{SAnO}SAnO(t) + C_{T1}T1(t) + C_{T2}T2(t) + \epsilon(t) \quad (1)$$

where

- $Y(t)$  is the monthly TOC average
- $t$  designates the month between 1 and 504 i.e. the number of months between 1979 to 2020,
- $K$  denotes the constant (Intercepts) of the model,
- $C_{proxy}$  designates the regression coefficients of different proxies, and
- $\epsilon(t)$  is the total of the residuals of the ozone anomalies.

The regression coefficients have the same unit as the  $Y(t)$ . Each proxy except  $T1$ ,  $T2$ ,  $AnO$  and  $SAnO$  was divided by its amplitude (Max-Min) allowing to have the anomalies of the proxies introduced into the model.

In this equation:

- The explained variable is the monthly average TOC for the time series and constitutes the input value of the MLR;
- The explanatory variables are the Annual Oscillation ( $AnO$ ), Semi-Annual Oscillation ( $SAnO$ ), the anomalies of Solar Flux ( $SF$ ), El Niño–Southern Oscillation ( $ENSO$ ), Quasi Biennial Oscillation at 30 mb ( $QBO30$ ), Quasi Biennial Oscillation at 10mb ( $QBO10$ ) and the linear trend functions ( $T1$ ;  $T2$ ). The  $QBO$ ,  $ENSO$  and  $SF$  explanatory variables linked to the contribution of dynamical and radiative processes on total ozone interannual variability are the usual ones already used in different studies [18, 19].

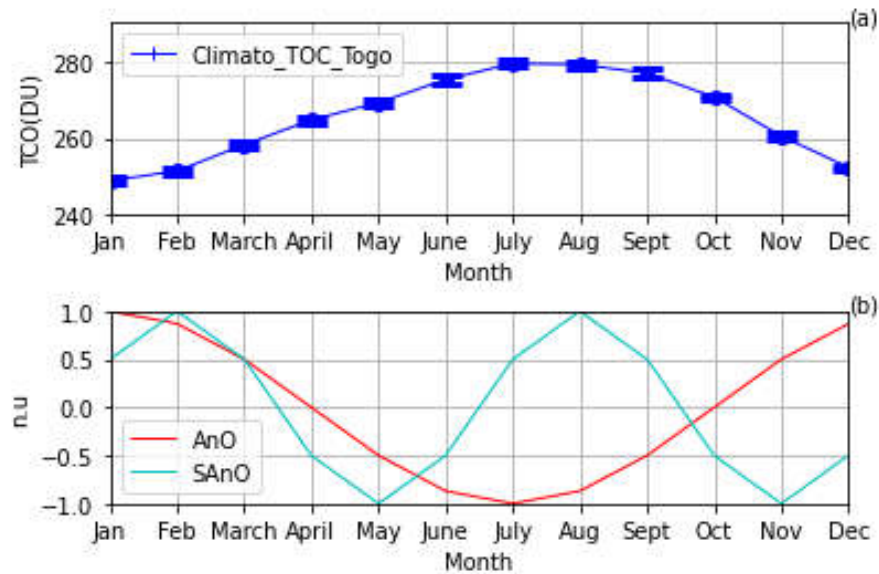
The  $AnO$  term corresponds to the annual variation of ozone and the  $SAnO$  term to the semiannual variation. The  $AnO$  is at the origin of the annual variation of ozone and both the  $AnO$  and  $SAnO$  act on the ozone according to the altitude and to the periods of equinoxes and solstices. Their indexes are defined by the following functions:

$$AnO = \cos\left(\frac{2\pi t}{12} + \frac{2\pi I}{180}\right) \text{ and } SAnO = \sin\left(\frac{2\pi t}{6} + \frac{2\pi I}{180}\right) \quad (2)$$

where

- $t$  is the ranks of the months in the time series.
- $I$  is the phasing coefficient between the TOC time signal and the  $AnO$  or  $SAnO$ .

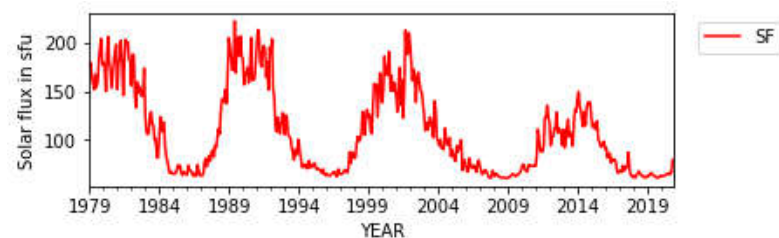
In this study  $I$  is set at -15 to simulate the  $AnO$  from climatological TOC MSR-2 data (Figure 2a).



**Figure 2.** Climatology of TOC (a) and the estimated proxies corresponding to the ANO and SAnO (Eq. 1) to simulate the climatology of TOC (b) in DU above Togo. The TOC is in DU while the AnO and SAnO are in non-unit (n.u.).

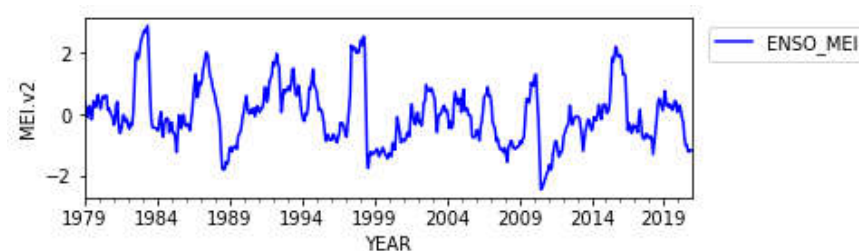
Regarding the solar flux, it measures the variation of solar activity that influences the ozone content. The SF at 10.7 cm wavelength is used [18, 10, 20, 21] and is represented in Figure 3.

According to Labitzke et al. and Gray et al. [22, 23], the ozone balance is influenced by the variation in the activity of the sun through the radiative and photochemical forcing that it induces [24].



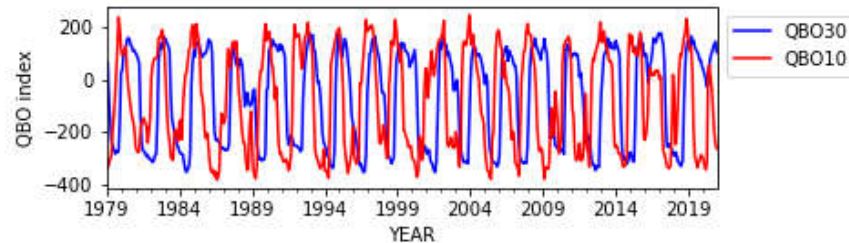
**Figure 3.** Solar Flux (SF) index at 10.7 cm wavelength in sfu (solar flux unit) with  $1 \text{ sfu} = 10^{-22} \cdot \text{m}^{-2} \cdot \text{Hz}^{-1}$

The indexes of ENSO forcing are represented in Figure 4. The ENSO influences the change in atmospheric circulation by reinforcing these positive and negative anomalies in ocean surface temperature [25, 26]. This results in the reinforcement of the transport of ozone towards the subtropics leading to a decrease in ozone in the east of the Pacific and an increase in the west [27, 28]. In these works, the MEI (Multivariate ENSO Index) indexes of ENSO are used [29, 18, 21].



**Figure 4.** Multivariate ENSO Index version 2 (MEI.v2).

The QBO manifests in the tropical stratosphere as a reversal of the zonal winds with descending cycles with mean period of 28 months also with important impacts on the global circulation of the atmosphere. QBO30 is used in these works because it influences ozone variability in the tropics and mid-latitudes [30, 18, 31, 32]. The QBO30 is combined with the QBO10 to optimize the phase contribution of the QBO. Their indexes are shown in Figure 5.



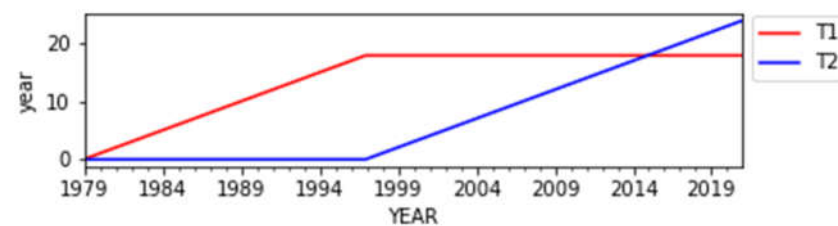
**Figure 5.** Quasi-biennial Oscillation at 30 mb (QBO30) and at 10 mb (QBO10) index.

The two linear functions T1 and T2 (Figure 6) represent the trend for the period before and after the turnaround year in 1997 corresponding of peak of EESC in the tropics. As an approximation, they are represented by a linear function of time and considered as piecewise linear trends (PWL) with the year of change set in 1997 [11, 33].

$$T1 = \begin{cases} \frac{t}{12} & 0 < t \leq T_0 \\ T_0 & T_0 < t \leq T_{end} \end{cases} \text{ and } T2 = \begin{cases} 0 & 0 < t \leq T_0 \\ \frac{(t-T_0)}{12} & T_0 < t \leq T_{end} \end{cases} \quad (3)$$

Where  $T_0$  is the last month of the year preceding the year in which the EESC started by decreasing so here corresponds to the month of December 1996 (216<sup>th</sup> month of the time series) and  $T_{end}$  to the last month of the series (504<sup>th</sup> month).

The proxy for the trend is expressed in "year" and the regression coefficient in "DU per year"



**Figure 6.** Trend functions T1 and T2 (see Eq. 3) as a function of the year.

The sources of the other proxies apart from T1, T2, AnO, and SAnO are presented in Table 1.

**Table 1.** Proxies used in this paper are present in column 1 and corresponding sources and characteristics in column 2 and 3 respectively.

Proxy	Source	Characteristics
QBO 30 and 10	Freie Universität Berlin Department of Earth Sciences/Institute of Meteorology/Atmospheric Dynamics <a href="https://www.geo.fu-berlin.de/met/ag/strat/produkte/qbo/qbo.dat">https://www.geo.fu-berlin.de/met/ag/strat/produkte/qbo/qbo.dat</a>	Monthly mean quasi-biennial oscillation at 30mb and at 10 mb
ENSO_MEI	NOAA Physical Science Laboratory <a href="https://psl.noaa.gov/enso/mei/data/meiv2.data">https://psl.noaa.gov/enso/mei/data/meiv2.data</a> Last acces : September 17, 2021	Monthly average of ENSO Multivariate ENSO Index Version 2
SF	The National Research Council Canada Dominion Radio Astrophysical ,Observatory in Penticton <a href="ftp://ftp.geolab.nrcan.gc.ca/data/solar_flux/monthly_averages/solflux_monthly_average.txt">ftp://ftp.geolab.nrcan.gc.ca/data/solar_flux/monthly_averages/solflux_monthly_average.txt</a> <a href="ftp://ftp.seismo.nrcan.gc.ca/spaceweather/solar_flux/monthly_averages/solflux_monthly_average.txt">ftp://ftp.seismo.nrcan.gc.ca/spaceweather/solar_flux/monthly_averages/solflux_monthly_average.txt</a> Last access: November 25, 2021	Monthly averages of solar flux at 10.7 cm wavelength

3. Evaluation of the MLR model

With the Cochrane-Orcutt transformation, the autocorrelation coefficient of the MLR model is ~ 0.2. This value of autocorrelation coefficient is close to zero showing a negligible autocorrelation between the residuals and thus making the model more robust and therefore applicable.

The relevance of the values of the coefficients will be validated on the basis of the value of the adjusted R<sup>2</sup> coefficient of determination which should be close to 100%, and the p-value of the model which should be less than 0.05

**Table 2.** General characteristics of the model.

R <sup>2</sup>	R <sup>2</sup> adjusted	p-value
76%	75%	< 5.37 * Exp(-147)

The adjusted R<sup>2</sup> which takes into account the explanatory variables (proxies) and which gives the percentage of the variability explained by the model after the Cochrane-Orcutt transformation is 75% which is close to 100%. The model after the Cochrane-Orcutt transformation then explains 75% of the variability of the TOC over Togo. Similarly, the p-value of the model is much less than 0.01 (Table 2).

The MLR model uses the same dynamical and radiative forcings as those of the Trend-Run used by Toihir et al. [18] except QBO10. It is different from that used by Weber et al. [12] in the sense that the proxies used are not the same and the year of the peak of the EESC considered here is 1997 whereas it is 1995 for the model used by them. Indeed, in their first model, they used two aerosol terms (Mt. Pinatubo 1992 and El Chichón 1983), the solar cycle term, QBO10, QBO50 and ENSO apart from the two independent linear trend terms. In the second version of their model, they included the Arctic (AO) and the Antarctic Oscillation (AAO), and the BDC (100 hPa eddy fluxes in the Northern and Southern Hemisphere). Otherwise, our model is different from the LOTUS (Long-term Ozone Trends and Uncertainties in the Stratosphere) model which is written in Python language and which makes it possible to evaluate the trend of the vertical profile of ozone [37].



In view of the previously discussion, the model resulting from the Cochran-Orcutt transformation, applied is adapted to estimate the contribution of proxies, thus showing the quality of the results of the contributions of the forcings and the trend obtained.

#### 4. Ozone above Togo

The regression coefficients of the forcings after model applications are summarized in Table 3.

**Table 3.** Regression coefficients of the forcings (DU).

AnO	QBO 30	SF	ENSO	SAnO	QBO10
-15.38±0.71	9.39±0.29	6.62±0.17	-5.22±0.18	0.59±0.71	0.98±0.31

Table 4 gathers the contributions in absolute value and in percentage of the proxies which are significant and therefore influence the TOC above Togo. The contribution of the different forcings was estimated by the formula  $C_x \times 2\sigma_x$  where  $C_x$  is the regression coefficient of the forcings noted X and  $\sigma_x$  designates the standard deviation of the time series of each normalized forcing [38].

**Table 4.** Contributions of the forcings to interannual variability (DU).

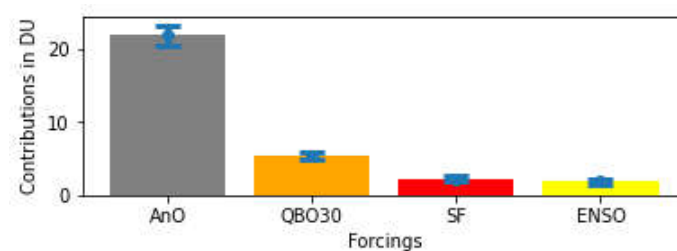
AnO	QBO 30	SF	ENSO
21.84±1.42***	5.35±0.57***	2.25±0.34***	1.88±0.36***
70%	17%	7%	6%

\*\*\*: Statistically significant at >2 sigma

It should be noted that the SAnO (0.84±1.42 DU) and the QBO10 (0.60±0.61DU) do not have a significant contribution to the TOC above Togo.

##### 4.1. Contributions of different proxies

In absolute value, according to Table 4 and Figure 7 the strongest contribution is given by the AnO (21.84 ± 1.42 DU) while the smallest is given by SAnO (0.84 ± 1.42 DU). In fact, AnO characterizes the mechanism reflecting the seasonal variations of weather and climate, which are the engine of the annual distribution of ozone therefore we can conclude that the variability of TOC above Togo is most strongly influenced by the seasonal variability. The contribution of the AnO is followed by that of the QBO30. After the QBO30, the dynamic forcing that controls more the variability of the TOC is the SF. The ENSO contribution follows that of the solar flux.



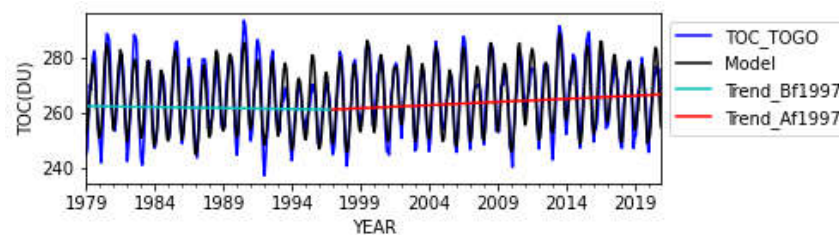
**Figure 7.** Forcings contribution at  $2\sigma$  indicated by the error bars.

This result obtained is consistent with that obtained by Zerefos et al. [39] where they showed that if the contributions of the other proxies, i.e. those of the AnO, the QBO, and the SF are removed from the TOC time signal in tropical areas, a significant part would

be explained by ENSO. It is also in line with that obtained by Poulain et al. [40] where they found that the interannual variability of TOC is contributed about 20% by QBO and 5 to 20% by ENSO in the tropics since in our study 17% (close to 20%) of the contribution is given by the QBO30 and 6% is given by the ENSO (Table 4).

#### 4.2. Trends

The regression coefficients for proxies T1 and T2, at 2 sigmas are respectively  $-0.09 \pm 0.12$  DU. year<sup>-1</sup> and  $0.17 \pm 0.08$  DU. year<sup>-1</sup>. Figure 8 represents the trends before (red line) and after (cyan line) 1997 obtained by the model. According to this figure; the interannual variability of the TOC (blue curve) is well represented by the model (black curve).



**Figure 8.** Evolution of the monthly average ozone over Togo observed by MSR-2, simulated by the MLR model and the trends estimated by the model before and after 1997.

Thus, according to the model, the TOC has a statistically insignificant negative trend before 1997 above Togo. The decrease is a weak value of  $0.3\% \pm 0.9\%$  per decade ( $2\sigma$ ). After 1997, the trend is positive and statistically significant. The rate of increase is  $0.6\% \pm 0.2\%$  per decade ( $2\sigma$ ). This trend close to 1% is different from that obtained in the report of the World Meteorological Organization (WMO) in 2018 [41], which reports that the trends of ozone in the tropical band are almost zero during the period 1997-2016. This difference of 0.6% could be due to the spatial coverage because this study is limited between 6°N and 11°N while for the WMO, it is a larger region between 20°S–20°N. Another hypothesis could be related to the temporal coverage of the data used because the time series of the study covered shorter period. The trend obtained is close to that obtained by Weber et al. [12] from the merged GSG and GTO dataset where the trend is estimated at  $0.3\% \pm 0.3\%$  per decade after 1995 in the tropics at latitudes between 20°–20°S. It is different from the trends close to zero obtained in the tropics at latitudes between 20°–20°S after 1995; by the same authors from NASA, NOAA and WOUDC merged data. This difference would be due to the spatial coverage of the data, and to the considered time series.

Despite this positive trend estimated after 1997, it is quite low ( $< 1\%$ ) and it might not be linked exclusively to the evolution of ozone in the stratosphere and attributed directly to the success of the implementation of the Montreal Protocol. According to Ball et al. [42], the influence of a consequent increase in tropospheric ozone in the tropics may hide an ever-existing decrease in the lower stratosphere. Indeed, a significant decrease in ozone in the tropics (20° S – 20° N) around 35 hPa has been observed by Godin-Beekmann et al. [43] and an increase in tropospheric ozone over the tropics was found by the work of Thompson et al. [44] and Leventidou et al. [45]. Furthermore, the positive value observed for this trend could be related to the cooling of the upper stratosphere resulting from the increase in greenhouse gas (GHG) emissions, which slows the gas phase ozone loss mechanisms in that region (Chapter 5 of the WMO report, 2018) [40]. Thus, a complementary study could be made to elucidate the phenomena of the lower stratosphere using measurements of ozone profiles by satellites above Togo and to study the trend in each layer of the atmosphere to explain the origin of this weak observed trend.



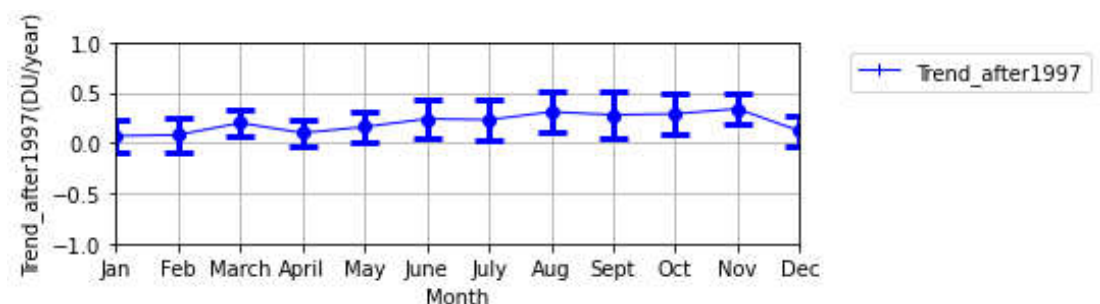
#### 4.3. Trend by months

In order to determine the months during which there is a potential recovery of the ozone layer and to make a link between the variability of the TOC and the monsoon and harmattan winds in Togo, the trend for each month was estimated. Table 4 presents the contribution of the different interannual variability forcings, the monthly trend of the TOC since 1997, the adjusted  $R^2$  determination coefficient and the autocorrelation coefficient. All these results are obtained by applying the Cochran-Orcutt transformation in the MLR model.

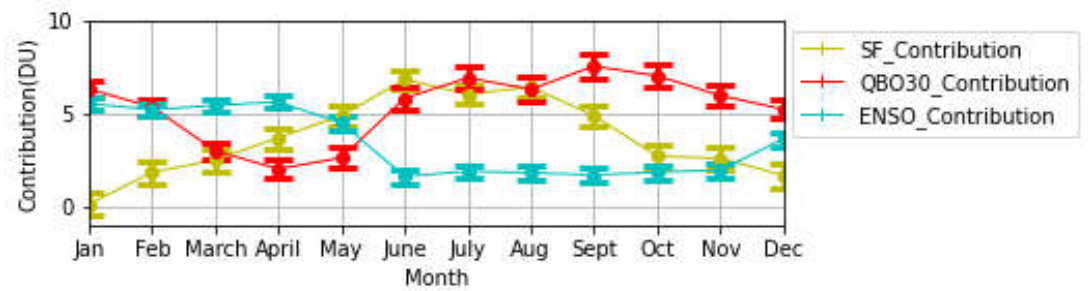
**Table 5.** Contribution of forcings (QBO30, ENSO, SF) in DU and trends after 1997 in DU.year<sup>-1</sup> for each month. Values are given at  $2\sigma$ . Bold lines refer to harmattan months while bold and italic lines refer to monsoon months in Togo. Adjusted  $R^2$  represents the percentage of the variability explained by the model after the Cochran-Orcutt transformation and  $\rho$  is the autocorrelation coefficient.

	QBO30mb	ENSO	SF	Trend	Adjusted $R^2$	$\rho$
<b>January</b>	<b>6.31 ± 0.46</b>	<b>- 5.54 ± 0.36</b>	<b>-0.12 ± 0.60</b>	<b>0.07 ± 0.16</b>	55%	<b>0.20</b>
<b>February</b>	<b>5.36 ± 0.46</b>	<b>- 5.21 ± 0.36</b>	<b>1.84 ± 0.64</b>	<b>0.08 ± 0.18</b>	55%	<b>0.00</b>
March	2.99 ± 0.48	- 5.44 ± 0.36	2.50 ± 0.59	0.20 ± 0.14	64%	0.10
April	2.02 ± 0.53	- 5.63 ± 0.36	3.70 ± 0.56	0.10 ± 0.13	68%	0.20
May	2.62 ± 0.58	- 4.49 ± 0.36	4.89 ± 0.53	0.16 ± 0.16	56%	0.10
<b>June</b>	<b>5.82 ± 0.62</b>	<b>- 1.62 ± 0.37</b>	<b>6.83 ± 0.55</b>	<b>0.24 ± 0.20</b>	<b>48%</b>	<b>0.00</b>
<b>July</b>	<b>6.92 ± 0.64</b>	<b>1.89 ± 0.37</b>	<b>6.04 ± 0.50</b>	<b>0.23 ± 0.20</b>	<b>54%</b>	<b>0.40</b>
<b>August</b>	<b>6.31 ± 0.65</b>	<b>1.82 ± 0.37</b>	<b>6.43 ± 0.58</b>	<b>0.31 ± 0.20</b>	<b>56%</b>	<b>0.00</b>
September	7.55 ± 0.63	1.69 ± 0.37	4.89 ± 0.59	0.28 ± 0.24	55%	0.20
October	7.03 ± 0.62	- 1.85 ± 0.37	2.71 ± 0.60	0.29 ± 0.20	53%	0.30
November	5.97 ± 0.57	- 1.95 ± 0.37	2.59 ± 0.62	0.34 ± 0.16	53%	0.00
<b>December</b>	<b>5.23 ± 0.51</b>	<b>- 3.63 ± 0.37</b>	<b>1.68 ± 0.65</b>	<b>0.12 ± 0.16</b>	<b>37%</b>	<b>0.10</b>

According to Table 5 and Figure 9, trends of  $\sim 0.20$  DU in average per year are obtained and are statistically significant at  $2\sigma$  for the periods June-July-August (JJA), September-October-November (SON), March and May which correspond to  $\pm 1$  month to periods of rain in Togo. The contributions of QBO30 and ENSO are significant throughout the year. As for the solar flux, its contribution is significant throughout the year except during the month of January. These trends observed in the rainy season could be linked to the lightning triggered during the rainy season in Togo which generates NO<sub>x</sub> (LNO<sub>x</sub>) contributing to the photochemical production of ozone in the lower stratospheric layer [46]. This same relationship between the TOC trend and NO<sub>x</sub> was established in the work of Tohir et al. [18] to explain the strong TOC trend observed at the Bauru site.



**Figure 9.** Trend in the variability of ozone per month ( $2\sigma$ ) in Togo after 1997.



**Figure 10.** Seasonal contribution of ENSO.

Finally, from this part of the work, it is to be concluded that the monthly trend of TOC is positive and significant in rainy season (particularly in monsoon period) except in April but it is not significant in harmattan period.

## 5. Conclusion

This work, which is a contribution to the observation of the total ozone column is the first study that targets the evolution of ozone above Togo. In this study the long-term and interannual variability of the TOC were analysed. This study has, quantified the influence of the different forcings on the interannual variability of the TOC. As expected, the set of standard proxies considered in this study were presented a significant contribution at  $>2\sigma$  except QBO10 and SAnO. In addition, the study quantified the trends before and after the year of the peak of EESC in the stratosphere in 1997. Thus, before the year of the peak, the trend is weak and statistically insignificant. After the year of the peak, a statistically significant positive trend is observed which cannot be directly associated with the success of the implementation of the Montreal Protocol. The recovery rate of the total ozone column is  $0.6\% \pm 0.2\%$  per decade which therefore shows a smaller increase of total ozone column above Togo compared to the extra areas tropical regions where the rate is above 1% ( $1.74\% \pm 0.40\%$ ) according to the work of Tohir et al. [18]. It is possible that this weak trend obtained is due to certain factors such as a decrease in ozone at 35 hPa observed by Godin-Beekmann et al. [42] and an increase in tropospheric ozone over the tropics [44, 47, 45, 48]. Thanks to this study, it was also shown that the variability of the TOC during the year is positive and significant in rainy month except April. As perspectives of this work, a complementary study could be made to elucidate the phenomena of the lower stratosphere above Togo and to study the trend in each layer of the atmosphere.

**Author Contributions:** Conceptualization, K.A., A.P. and K.S.; methodology, K.A. and K.S.; software, A.B.; validation, A.P., K.S. and S.G-B.; formal analysis and investigation, A.K.; resources, A.P.; data curation, A.B.; writing original draft preparation, A.K.; writing review, editing, and supervision A.P.; visualization, A.K, A.P and K.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** The APC was funded by CNRS (Centre National de la Recherche Scientifique)

**Data Availability Statement:** The data collected are monthly average values and cover the 1979-2020. These data cover the national territory with latitudes between  $6^\circ$  and  $11^\circ$  N, and longitudes between  $0^\circ$  14 'W and  $1^\circ$  65'E. They were downloaded from the website of the tropospheric emissions monitoring service (TEMIS) of KNMI / ESA at the address: <https://www.temis.nl/protocols/o3total.php> (last access: September 17, 2021).

**Acknowledgments:** This work was carried out thanks to the scholarship funded by the Cooperation and Cultural Action Service of the French Embassy (SCAC) in Togo, so the authors warmly thank the SCAC and Campus France which is the executing organization of the scholarship.

**Conflicts of Interest:** The authors declare that they have no conflict of interest.

## References

- [1] OMS, "Climate change and human health," OMS, 1996.
- [2] V. G. Kakani, K. R. Reddy, D. Zhao and K. Sailaja, "Field crop responses to ultraviolet-B radiation:a review," *Elsevier*, vol. 120, p. 191 – 218, 2003.
- [3] M. Vernet, E. A. Brody, O. Holm-Hansen and B. G. Mitchell, "The Response of Antarctic Phytoplankton to Ultraviolet Radiation : Absorption, Photosynthesis, and Taxonomic Composition," *AGU*, vol. 62, pp. 143-158, 1994.
- [4] N. Butchart, "The Brewer-Dobson circulation," *Rev. Geophys*, vol. 52, p. 157–184, 2014.
- [5] N. R. P. Harris, E. Kyrö, J. Staehelin, D. Brunner, S.-B. Andersen, S. Godin-Beekmann, S. Dhomse, P. Hadjinicolaou, G. Hansen, I. Isaksen, A. Jrrar, A. Karpetchko, R. Kivi, B. Knudsen, P. Krizan, J. Lastovicka, J. Maeder, ... and C. Zerefos, "Ozone trends at northern mid- and high latitudes – a European perspective," *Geophys. Ann.*, vol. 26, p. 1207–1220, 2008.
- [6] M. Weber, S. Dikty, J. P. Burrows, H. Garny, M. Dameris, A. Kubin, J. Abalichin and U. Langematz, "The Brewer-Dobson circulation and total ozone from seasonal to decadal time scale," *Atmos. Chem. Phys.*, vol. 11, p. 11221–11235, 2011.
- [7] P. Braesicke and J. Neu, "Update on Global Ozone: Past, Present, and Future chapter 3," World Meteorological Organization, Geneva, 2018.
- [8] W. T. Ball, J. Alsing, D. J. Mortlock, J. Staehelin, J. D. Haigh, T. Peter, F. Tummon, R. Stübi, A. Stenke, J. Anderson, A. Bourassa, S. M. Davis, D. Degenstein, S. Frith, ... and E. V. Rozanov, "Evidence for a continuous decline in lower stratospheric ozone offsetting ozone layer recovery," *Atmos. Chem. Phys.*, vol. 18, p. 1379–1394, 2018.
- [9] H. Bencherif, A. Tohir, N. Mbatha, V. Sivakumar, D. du Preez, N. Bègue and G. Coetzee, "Ozone Variability and Trend Estimates from 20-Yearsof Ground-Based and Satellite Observations at IreneStation, South Africa," *Atmosphere*, p. 11, 2020.
- [10] A. Pazmiño, S. Godin-Beekmann, A. Hauchecorne, C. Claud and S. Khaykin, "Multiple symptoms of total ozone recovery inside the Antarctic," *Atmos. Chem. Phys.*, vol. 18, pp. 7557-7572, 2018.
- [11] P. J. Nair, S. Godin-Beekmann, J. Kuttippurath, G. Ancellet, F. Goutail, A. Pazmiño, L. Froidevaux, J. M. Zawodny, R. D. Evans, H. J. Wang, J. Anderson and M. Pastel, "Ozone trends derived from the total column and vertical profiles at a northern mid-latitude station," *Atmos. Chem. Phys*, vol. 13, pp. 7081-7112, 2013.
- [12] M. Weber, C. Arosio, M. Coldewey-Egbers, V. E. Fioletov, S. M. Frith, J. D. Wild, K. Tourpali, J. P. Burrows and D. Loyola, "Global total ozone recovery trends attributed to ozone-depleting substance (ODS) changes derived from," *Atmos. Chem. Phys.*, vol. 22, p. 6843–6859, 2022.
- [13] S. Montzka, S. Reimannander, A. Engel, K. Kruger, O. Simon, W. Sturges, D. Blake, M. ., F. P. Dorf, L. Froidevaux, K. Jucks, K. Kreher, M. Kurylo III, A. Mellouki, J. Miller, O. Nielsen, V. Orkin, R. Prinn, ... and D. P. Verdon, "Ozone-Depleting Substances (ODSs) and Related Chemicals chapter 1," Geneva, switzerland, 2010.
- [14] V. Ramaswamy, M. D. Schwarzkopf, W. J. Randel, B. D. Santer, B. J. Soden and a. G. L. Stenchikov, "Anthropogenic and natural influences in the evolution of lower stratospheric cooling," *Science*, vol. 311, p. 1138–1141, 2006.
- [15] R. J. van der A, M. A. F. Allaart and H. J. Eskes, "Multi sensor re-analysis of total ozone," *Atmos. Chem. Phys*, vol. 10, p. 11277–11294, 2010.
- [16] R. J. v. d. A, M. A. F. Allaart and H. J. Eskes, "Extended and refined multi sensor reanalysis of total ozone for the period 1970-2012," *Atmos. Meas. Tech.*, vol. 8, p. 3021–3035, 2015.
- [17] J. W. Krzyścin and D. B. Baranowski, "Signs of the ozone recovery based on multi sensor reanalysis of total ozone for the period 1979–2017," *Elsevier*, vol. 199, pp. 334-344, 2019.
- [18] Team, R Core, *R: A Language and Environment for Statistical Computing*, Vienna: R Foundation for Statistical Computing, 2022.
- [19] G. Tiao, G. Reinse, D. XU, J. Pedrick, X. Zhu, A. Miller, I. J. Deluis, C. Mateer and D. Wuebbles, "Effects of correlation and temporal sampling schemes on estimates of trend and spatial correlation," *J. Geophys. Res.*, vol. 95, pp. 507-517, 1990.
- [20] D. Cochran and G. H. Orcutt, "Application of least squares regression to relationships containing autocorrelated error terms," *J. Am. Stat. Assoc*, vol. 44, pp. 32-61, 1949.
- [21] A. M. Tohir, T. Portafaix, V. Sivakumar, H. Bencherif, A. Pazmino and N. Bègue, "Variability and trend in ozone over the southern tropics and subtropics," *Annales Geophysicae*, vol. 36, pp. 381-404, 2018.
- [22] M. Coldewey-Egbers, D. G. Loyola, C. Lerot and M. V. Roozendaal, "Global, regional and seasonal analysis of total ozone trends derived from the 1995–2020 GTO-ECV climate data record," *Atmospheric Chemistry and Physics*, 2022.

- [23] R.D.Bojkov and V.E.Fioletov, "Total ozone variations in the tropical belt: An application for quality of ground based measurements," *Meteorol. Atmos. Phys.*, vol. 58, p. 223–240, 1996.
- [24] K.-F. Li, X. Jiang, M.-C. Liang and Y. L. Yun, "Simulation of solar-cycle response in tropical total column ozone using," *Atmos. Chem. Phys.*, vol. 12, p. 1867–1893.
- [25] K. LABITZKE, "The global signal of the 11-year solar cycle in the stratosphere: observations and models:Differences between solar maxima and minima," *Meteorologische Zeitschrift*, vol. 10, no. 2, pp. 83-90, 2001.
- [26] L. J. Gray, J. Beer, M. Geller, J. D. Haigh, M. Lockwood, K. Matthes and U. Cubasch, "Solar influences on climate," *Rev. Geophys.*, vol. 48, 2010.
- [27] B. E. Soukharev and L. L. Hood, "Solar cycle variation of stratospheric ozone: Multiple regression analysis of long-term satellite data sets and comparisons with models," *J. Geophys. Res.*, vol. 111, 2006.
- [28] D. Jin and B. P. Kirtman, "The impact of ENSO periodicity on North Pacific SST variability," *Clim. Dyn.*, vol. 34, p. 1015–1039, 2010.
- [29] H. A. Dijkstra, "The ENSO phenomenon: theory and mechanisms," *Adv. Goesci.*, vol. 6, pp. 3-15, 2006.
- [30] M. Shiotani, "Annual, quasi-biennial, and El Nino-Southern Oscillation (ENSO) time-scale variations in equatorial total ozone," *J. Geophys. Res.*, vol. 97, pp. 7625-7633, 1992.
- [31] W. J. Randel, R. R. Garcia, N. Calvo and D. Marsh, "ENSO influence on zonal mean temperature and ozone in the tropicallower stratosphere," *Geophys. Res. Lett.*, vol. 36, 2009.
- [32] D. A. D. W. J. R. A. E. Bourassa<sup>1</sup>, J. M. Zawodny, E. Kyrölä, C. A. McLinden<sup>5</sup>, C. E. Sioris and C. Z. Roth, "Trends in stratospheric ozone derived from merged SAGE II and Odin-OSIRIS satellite observations," *Atmos. Chem. Phys.*, vol. 14, p. 6983–6994, 2014.
- [33] M. A. Olsen, G. L. Manney and J. Liu, "The ENSO and QBO impact on ozone variability and stratosphere-Troposphereexchange relative to the subtropical jets," *Journalof Geophysical Research: Atmospheres.*, vol. 124, p. 7379–7392, 2019.
- [34] Z. Han, Chongping, J. and Z. Libo, "QBO Signal in total ozone over Tibet," *Adv. Atmos. Sci.*, vol. 17, p. 562–568, 2000.
- [35] W. Chehade, M. Weber and J. P. Burrows, "Total ozone trends and variability during 1979–2012 from merged data sets of various satellites," *Atmos. Chem. Phys.*, vol. 14, p. 7059–7074.
- [36] G. C. Reinsel, E. Weatherhead, G. C. Tiao, A. J. Miller, R. M. Nagatani, D. J. Wuebbles and L. E. Flynn, "On detection of turnaround and recovery in trend of ozone," *J. Geophys.*, vol. 107, 2002.
- [37] I. Petropavlovskikh, S. Godin-Beekmann, D. Hubert, R. Damadeo, B. Hassler and V. S. (Eds.), "SPARC/IO3C/GAW, 2019: SPARC/IO3C/GAW Report on Long-term Ozone Trends and Uncertainties in the Stratosphere.," 2019.
- [38] W. Steinbrecht, B. Hassler, H. Claude, P. Winkler and R. S. Stolarski, "Global distribution of total ozone and lowerstratospheric temperature variations," *Atmos. Chem. Phys.*, vol. 3, p. 1421–1438, 2003.
- [39] C. S. Zerefos, A. F. Bais, I. C. Ziomas and R. D. Bojkov, "On the relative importance of Quasi-Biennial Oscillation and El Niño/Southern Oscillation in the Revised Dobson Total Ozone Records," *J. Geophys. Res.*, vol. 97, p. 10135–10144, 1992.
- [40] V. Poulain, S. Bekki, M. Marchand, M. P. Chipperfield, M. Khodri, F. Lefèvre and S. Dhomse, "Evaluation of the Inter-Annual Variability of Stratospheric Chemical Composition in Chemistry-Climate Models Using Ground-Based Multi Species Time," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 145, pp. 61-84, 2016.
- [41] WMO (World Meteorological Organization), "Scientific Assessment of Ozone Depletion: 2018, Global ozone research and monitoring.Project-report No.58," Geneva, Switzerland, , 2018.
- [42] W. T. Ball, "Evidence that tropical total column ozone no longer represents stratospheric changes," in *QOS 2021*, 2021.
- [43] S. Godin-Beekmann, N. Azouz, V. Sofieva, D. Hubert, I. Petropavlovskikh, P. Effertz, G. Ancellet, D. A. Degenstein, D. Zawada, L. Froidevaux, S. Frith, J. Wild, S. Davis, W. Steinbrecht, ... and R. Sussman, "Updated trends of thozone vertical distribution in the in the 60°S-60°N latitude range based an LOTUS regression model," *Atmos. Chem. Phys.*, vol. 22, p. 11657–11673, 2022.
- [44] A. M. Thompson, R. M. Stauffer, K. Wargan, J. C. Witte, D. E. Kollonige and J. R. Ziemke, "Regional and Seasonal Trends in Tropical Ozone From SHADOZ Profiles: Reference for Models and Satellite Products," *Journal of Geophysical Research: Atmospheres* 126, e2021JD034691, vol. 126, 2021.
- [45] E. Leventidou, M. Weber, K.-U. Eichmann, J. P. Burrows, K.-P. Heue and A. M. Thompson, "Harmonisation and trends of 20-year tropical tropospheric ozone data," *Atmos. Chem. Phys.*, vol. 18, p. 9189–9205, 2018.

- 
- [46] S. VERMA, P. K. Y. ADAVA, D. M. L. AL, R. K. M. ALL, H. A. K. UMAR and S. PAYRA, "Role of Lightning NO<sub>x</sub> in Ozone Formation: A Review," *Pure Appl. Geophys.*, vol. 178, p. 1425–1443, 2021.
- [47] D. Tarasick, I. E. Galbally, O. R. Cooper, M. G. Schultz, G. Ancellet, T. Leblanc, T. J. Wallington, J. Ziemke, X. Liu, M. Steinbacher, J. Staehelin, C. Vigouroux, J. W. Hannigan, O. García, ... and J. L. Neu, "Tropospheric Ozone Assessment Report: Tropospheric ozone from 1877 to 2016, observed levels,trends and uncertainties," *Elem Sci Anth*, vol. 7, no. 39, 2019.
- [48] A. Gaudel, O. R. Cooper, G. Ancellet, B. Barret, A. Boynard, J. P. Burrows, C. Clerbaux, P.-F. Coheur, J. Cuesta, E. Cuevas, S. Doniki, G. Dufour, F. Ebojie, G. Foret, O. Garcia, M. J. Granados-Muñoz, J. W. Hannigan, F. Hase, B. Hassle, ... and J. Ziemke, "Tropospheric Ozone Assessment Report: Present-day distribution and trends of tropospheric ozone relevant to climate and global atmospheric chemistry model evaluation.," *Elem Sci Anth*, vol. 6, no. 39, 2018.