Open Access Library Journal
2024, Volume 11, e12718
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Seasonal and Interannual Variability in Carbon Dioxide Fluxes in the Tropical Atlantic

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How to cite this paper: Ogundare, M.O. and Adekunbi, F.O (2024) Seasonal and Interannual Variability in Carbon Dioxide Fluxes in the Tropical Atlantic. *Open Access Library Journal*, **11**: e12718.
https://doi.org/10.4236/oalib.1112718

Received: November 28, 2024
Accepted: December 27, 2024
Published: December 30, 2024

Abstract

The seasonal and interannual variations of carbon dioxide flux in the tropical Atlantic were investigated from 1994-2023 based on 30 years of sea surface carbon dioxide fugacity (fCO_2ssw) data available in the latest version of the Surface Ocean CO_2 Atlas (SOCATv24). Using monthly mean global atmospheric CO_2 at Mauna Loa, CO_2 exchange between the ocean and atmosphere was calculated. The long-term trend across the tropical Atlantic investigated here showed the influence of sea surface temperature, salinity, and ocean surface CO_2 content on this region's interannual variability of CO_2 flux. Correlation statistics revealed that ocean surface CO_2 content has the greatest influence, where 20 years of data show significant correlations (r-value ≥ 0.5), and ocean surface temperature has the lowest effect. This study showed salinity as the main factor controlling CO_2 uptake demonstrating a significantly positive correlation for eleven of the studied years, and a negative correlation for nine years. Thus, higher salinity decreases and increases CO_2 uptake for the different years respectively. This finding highlights biogeochemical complexity of the interaction between salinity and CO_2 uptake on long-term variability and carbon sink capacity in the tropical Atlantic Ocean.

Subject Areas

Environmental Sciences

Keywords

Seasonal and Interannual Variability, Carbon Dioxide Fluxes, Tropical Atlantic, Salinity

1. Introduction

As a source and sink of carbon dioxide (CO_2) [1] [2] through a variety of biological, physical, and chemical processes, the tropical Atlantic Ocean is vital to the global carbon cycle [3]-[5]. Climatologies of sea-air CO_2 flux [2] [6] [7] have estimated a net efflux of CO_2 to the atmosphere from the surface waters of the tropical Atlantic. The main surface water current influences the sea-air CO_2 flux distribution in the region [8]. The North Brazil Current (NBC) and North Equatorial Counter Current (NECC) were characterized by a permanent CO_2 oversaturation [9], and are attributed to the transport of cold CO_2-rich water from the equatorial upwelling system [10]. The region also acts as a net atmospheric CO_2 sink driven by river discharge for instance Amazon River and due to a seasonal distribution pattern identified in the North Equatorial Current (NEC) [9]. The occurrence of Atlantic Nino; a tropical climate interannual variability mode of sea surface temperature (SST) similar to the El Niño/Southern Oscillation (ENSO) in the Pacific also influences the CO_2 flux distribution in the region [11]. The Atlantic Nino enhances the CO_2 oversaturation in the central tropical Atlantic driven by sea surface temperature (SST) solubility changes in the partial pressure of CO_2 (pCO_2) and weakens it in the western region where freshwater-induced salinity changes drive the CO_2 flux variation [11].

Predicting future climatic trends and appreciating the tropical Atlantic Ocean's contribution to the global carbon budget requires an understanding of the long-term variability of carbon dynamics in the region [12]-[14]. Seasonal fluctuations in carbon dioxide fluxes are largely driven by the equatorial upwelling system, which brings nutrient-rich waters to the surface [15]. The main factors influencing the seasonal variations include patterns of ocean circulation, SST, and biological activity [16] [17]. The upwelling increases biological productivity during boreal summer leading to greater uptake of CO_2 by phytoplankton [18]. Wintertime brings a decrease in phytoplankton productivity due to reduced sunlight and water column mixing [19]. This cyclical pattern of production affects the net exchange of CO_2 between the ocean and the atmosphere [20]. Inter-annual variability in CO_2 flux in the tropical Atlantic is influenced by two climatic phenomena: the Atlantic Meridional Mode (AMM) and ENSO [21]-[23]. The AMM is characterized by variations in air pressure gradients and SST influences CO_2 flux [24]. Biological output and upwelling increase the ocean's capacity to absorb carbon, which is boosted by stronger trade winds during the La Niña phase [25] [26].

This study examines the seasonal and inter-annual variability of CO_2 flux in the tropical Atlantic between 1994 and 2023 to understand the drivers of long-term changes in CO_2 uptake utilizing observational data of sea surface fugacity of CO_2 in the region from the latest version of Surface Ocean CO_2 Atlas (SOCATv24).

2. Methodology

Sea surface fugacity of CO_2 (fCO_2ssw) in the tropical Atlantic available in the latest version of Surface Ocean CO_2 Atlas (SOCATv24) was extracted from 1994 to 2023

(**Figure 1**). Using the monthly mean Mauna Loa global atmospheric CO_2 records in ppm, the fugacity in µatm was calculated using the SST in SOCATv24 following the method of [27].

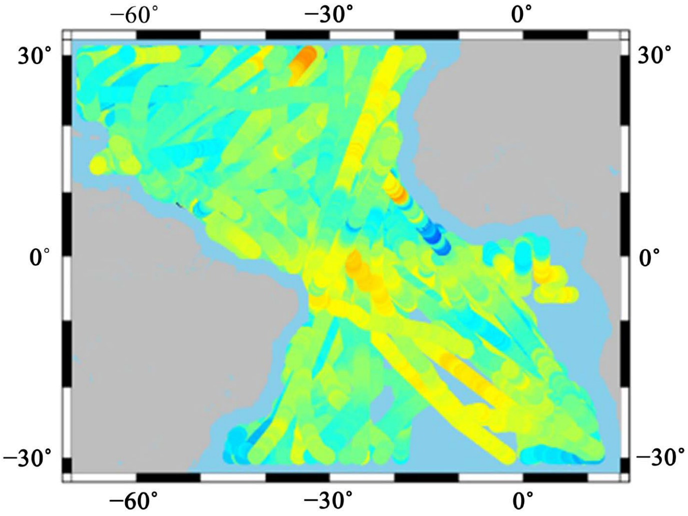

Figure 1. Available Sea surface fugacity of CO_2 (fCO_2ssw) in the tropical Atlantic from 1994 to 2023.

$$fCO_2atm = pCO_2atm \times \exp\left[-1636.75 + 12.0408 \text{ x } SST - 0.0327957 \times SST^2 + 0.0000316528 \times SST^3 + 2\left(57.7 - 0.118 \times SST\right)\right]/82.0578 \times SST$$

where pCO_2atm is the partial pressure of CO_2 computed following [28].

The sea-air CO_2 exchange ($dfCO_2$) was calculated thus: fCO_2ssw-fCO_2atm

Where;

fCO_2ssw = sea surface fugacity of CO_2.

fCO_2atm = atmospheric fugacity of CO_2 fCO_2atm.

Monthly mean climatology of fCO_2ssw, $dfCO_2$, SST, and sea surface salinity (Sal) was computed to examine the spatial distribution, and the western region where more fCO_2ssw occur was analysed for seasonal variation and decadal trend.

3. Results and Discussion

3.1. Spatial, Inter-Annual, and Seasonal Distributions

The spatial distribution of fCO_2ssw (**Figure 2(A)-(ZD)**) shows fewer data in the first decade (**figure 2(A)-(J)**; 1994-2003). Data density increases in the second decade (**Figure 2(K)-(T)**; 2004-2013) through the third decade (**Figure 2(U)-(ZD)**; 2014-2023) and concentrates more in the northwestern basin. Notably, the ocean time-series monitoring program in the tropical Atlantic include the CARIACO (CArbon Retention In A Colored Ocean) (10˚30'N, 64˚40'W) station and PIRATA (Prediction and Research moored Array in the Tropical Atlantic, [29]) mooring (6˚S, 10˚W). Also, the amount of CO_2 in the surface ocean increases over the years; ranging from 300 to 450 µatm. The higher values occur especially from 2019 to 2023 (**Figure 2(Z)-(ZD)**).

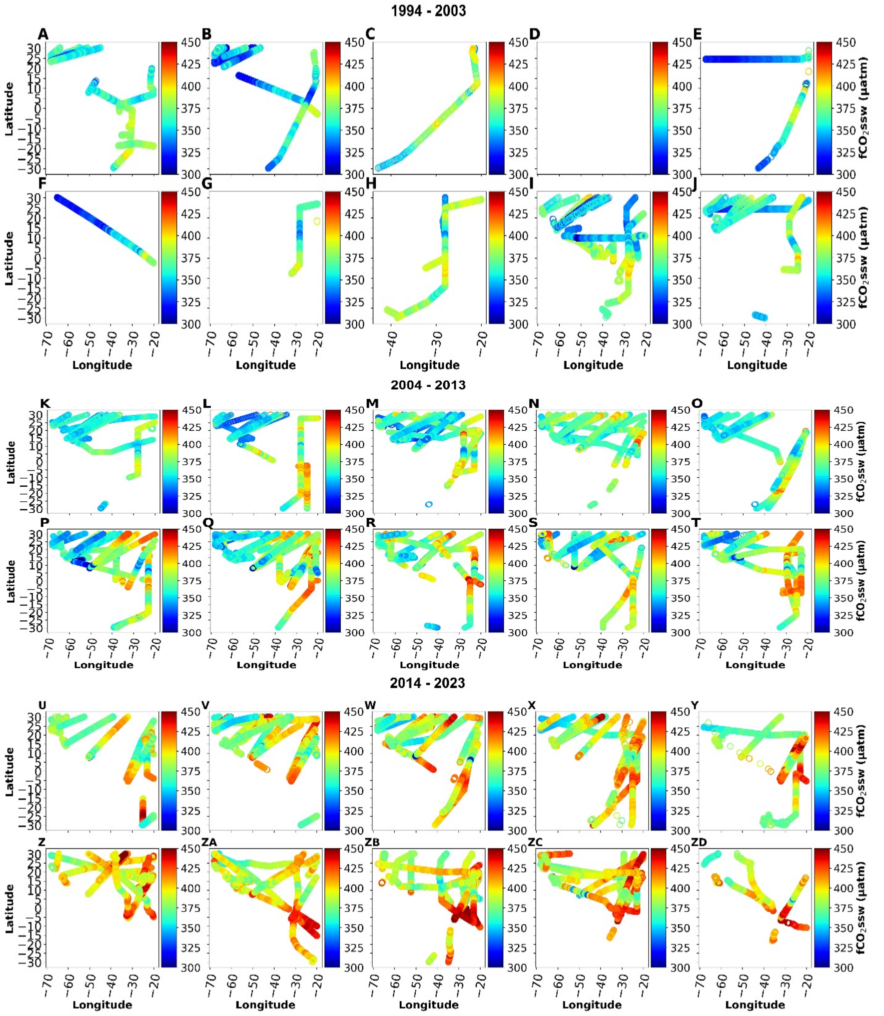

Figure 2. Spatial distribution of sea surface fugacity of CO_2 (fCO_2ssw) (1994-2023) using SOCATv24.

The sea-air CO_2 exchange (Figure 3(A)-(ZD)) generally shows increasing ocean uptake (negative values of dCO_2) over the years. This pattern corroborates the findings of [9] that reported certain regions of the eastern tropical Atlantic as weak CO_2 sinks.

The eastern tropical Atlantic basin demonstrates alternating behaviour, acting as a CO_2 sink in some years and a CO_2 source in others. Climate phenomena like the Atlantic Niño and Intertropical Convergence Zone (ITCZ) migration, as well as the Amazon River outflow, all contribute to these shifts [30]-[32]. The general increase in the region's ocean CO_2 uptake over the years has been associated with some peculiarities about the ocean circulation in the region, river plumes formation with freshwater input and deep-water formation by high-saline sea-water parcels and the migration of the ITCZ in high precipitation regimes [33] [34]. [35] observed strong interannual sea-air CO_2 fluxes in the southwestern tropical Atlantic from 2006-2013, particularly in boreal spring which they attributed to dynamics in the Amazon River plume spatial extent. Furthermore, on interannual timescales, primary production fueled by the extensive river plume modulated and significantly resulted in a drawdown of CO_2.

However, the distribution shows a source of CO_2 (positive values of dCO_2; around 0 - 15 µatm) to the atmosphere in some regions in most of the years (**Figure 3**). This agrees with studies that have shown the tropical Atlantic as a source of CO_2 to the atmosphere [36]-[39]. A combination of physical and biological processes characterizes the temporal dynamics of dCO_2 flux in the tropical Atlantic. On an annual basis, the tropical Atlantic acts as a net source of CO_2 to the atmosphere with significant seasonal variability [40].

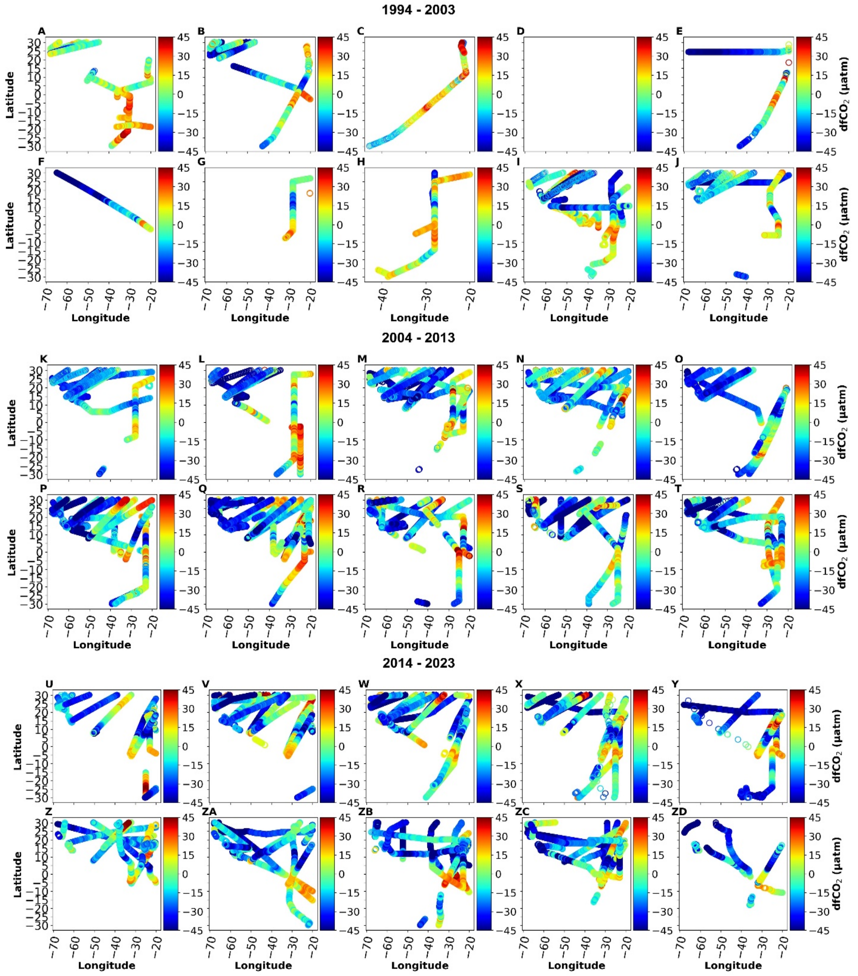

Figure 3. Distributions of sea-air CO_2 flux ($dfCO_2$) (sea - air CO_2 exchange) (1994-2023) using SOCATv24.

Figure 4 shows the box-whiskers plot of the of dCO_2 and generally shows a regular seasonal variation pattern for the CO_2 flux with higher CO_2 uptake for most of the years from January to March (boreal winter-early spring), which decreases and relapses into CO_2 source during July and August and sometimes also in September, *i.e.*, during boreal spring-summer (July to September) and the uptake picking up again from October.

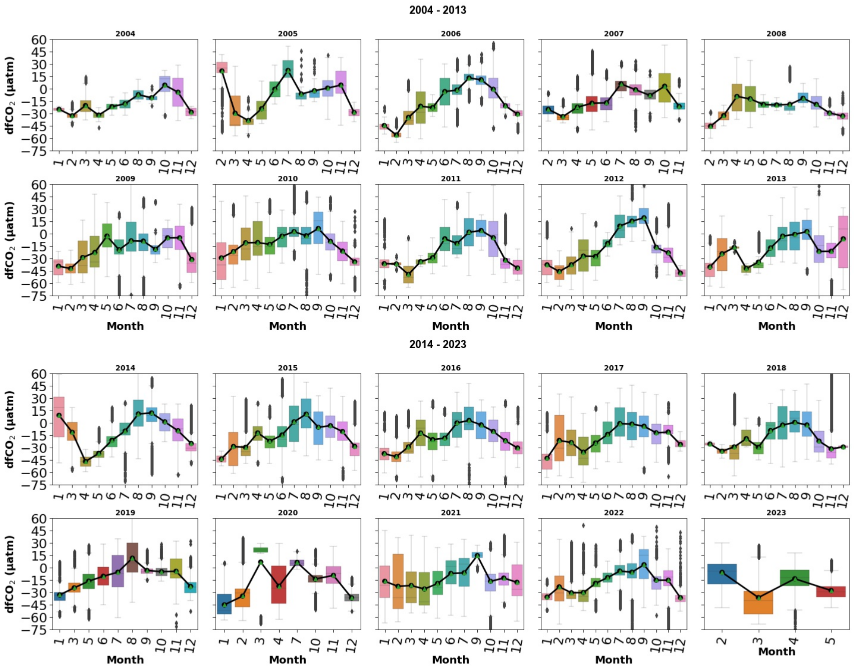

Figure 4. Box-Whisker plots showing the monthly mean of sea-air CO_2 flux ($dfCO_2$) (sea-air CO_2 exchange) (1994-2023) using SOCATv24 for seasonal variation pattern.

[11] has also shown a seasonal variability of high chlorophyll concentration during the cold season and low chlorophyll concentration during the warm season in the eastern tropical Atlantic (12˚W - 12˚E) especially in the coastal upwelling in the Gulf of Guinea and in the equatorial upwelling. This biological productivity could also potentially explain the winter uptake and summer source of CO_2 observed. When upwelling is strongest in the equatorial Atlantic, [39] reported a peak in CO_2 outgassing during boreal summer. These patterns are similar to observations for the period (1994-2023) in this study, as the tropical Atlantic acted as a CO_2 source to the atmosphere mainly in boreal summer (*i.e.*, July-September) (**Figure 4**) when SST was warmest (**Figure 5**). In contrast, during boreal winter-early spring (January-March) the tropical Atlantic acts as a CO_2 sink (**Figure 4**).

The seasonal migration of the ITCZ over the tropical Atlantic also influences the CO_2 system and causes significant outgassing of CO_2 to the atmosphere in the western tropical Atlantic region relative to the eastern part during the boreal spring-summer. This pattern is associated with the effects of the ITCZ on surface currents and wind patterns [39]. In the eastern tropical Atlantic (6˚S - 6˚N, 10˚W - 10˚E) from 2006-2011 [39] reported significant interannual variations which tended from a CO_2 source from 2006-2009 to a net-zero state in 2010.

Generally, the tropical Atlantic exhibits warm temperatures with the SST climatology ranging between 21 and 30 degC (**Figure 5**) and the warmest temperatures occur mostly during boreal summer; July-August, and sometimes in September (**Figure 5**). It is also generally a region of high salinity with the Sal climatology ranging between 35 and 37 PSU (Figure not shown). The high SST and surface salinity are evidence of the South Equatorial Current (SEC) that carries relatively high temperature and high salinity waters (T~28 degC and S~36 PSU) in the region and the high salinity could also be associated with the high evapouration rate over precipitation occurring throughout the year in the northeastern Brazil region [41].

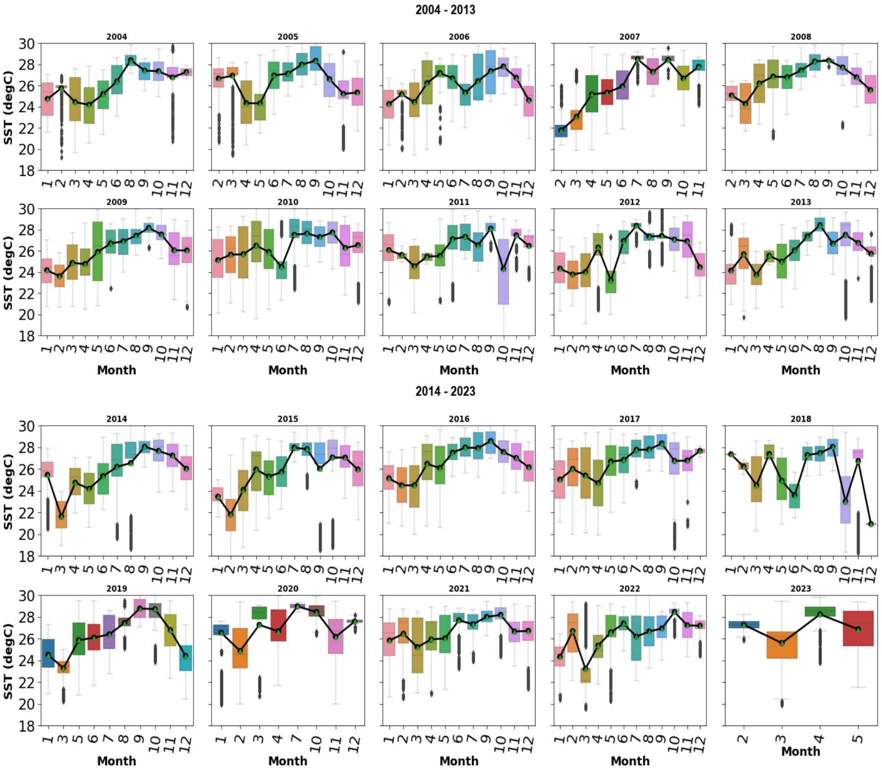

Figure 5. Box-Whisker plots with a monthly mean of SST (2004-2023) from SOCATv24 for seasonal variation pattern.

3.2. Decadal Trend Variability

Both fCO_2sww (Figure 6; upper panel) and fCO_2atm (Figure 6; middle panel) show increasing decadal trend of 0.002 - 0.006 $\mu atmyr^{-1}$ and 0.005 - 0.007 $\mu atm\ yr^{-1}$ respectively, over three decades with fCO_2atm increasing faster than fCO_2sww in each decade. The lower panel shows decreasing CO_2 uptake (−0.002 - 0.0005 $\mu atmyr^{-1}$) over the decades. All trends are significant at p-value < 0.00001.

Significant interest has been geared towards the long-term fCO_2ssw trends in the tropical Atlantic due to its role in global carbon cycling. Observations in the past few decades have shown a consistent increase in fCO_2ssw largely due to the uptake of anthropogenic CO_2. From 1970 to 2007, [8] recorded a mean rate of fCO_2ssw increase of about 1.5 $\mu atmyr^{-1}$ including the tropical Atlantic, indicating that this ocean basin is keeping pace with rising atmospheric CO_2 levels. Interestingly, over a three-decade period, this study also observed an increasing trend in seawater and atmospheric fCO_2 rate at 0.002 - 0.006 $\mu atm\ yr^{-1}$ and 0.005 - 0.007 $\mu atm\ yr^{-1}$ respectively in agreement with global trends and with fCO_2 increasing faster in the atmosphere than seawater in each decade.

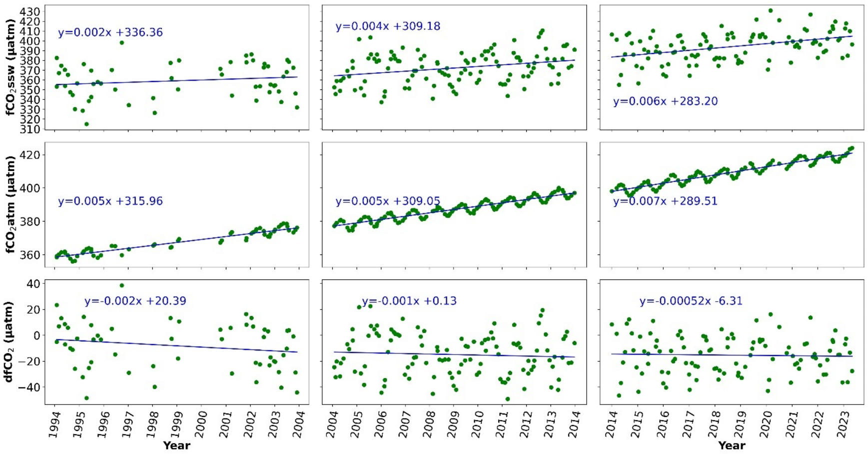

Figure 6. Decadal trend using the monthly mean of; upper panel: sea surface fugacity of CO_2 (fCO_2ssw), middle panel: atmospheric fugacity of CO_2 (fCO_2atm) and lower panel: sea-air fCO_2 exchange ($dfCO_2$).

When compared to other ocean basins the tropical Atlantic is peculiar in its CO_2 flux trend as it shows regional dynamics and responses to global change [42]. On the one hand, in contrast to the Southern Ocean which went through a decline in CO_2 uptake during the 1990s followed by an increase in the 2000s, the tropical Atlantic has consistently showed outgassing trends. On the other hand, the Indian Ocean has experienced increased CO_2 uptake in its southern region with the tropical areas undergoing a stable flux pattern [43].

3.3. Drivers of Inter-Annual Variability

The annual regressions r-values for correlating the CO_2 uptake with fCO_2ssw, SST, and Sal (**Figure 7**) show positive correlation values for every year with fCO_2ssw (**Figure 7(A)**) indicating increasing fCO_2ssw leads to a source of CO_2 to the atmosphere from the surface ocean with significant r-values (r-values ≥ 0.5) for most of the years. With SST, both positive and negative correlations occur for different years (**Figure 7(B)**) indicating increasing SST leads to a source of CO_2 to the atmosphere in some years while in some other years it leads to an increase in CO_2 uptake, respectively. The increased uptake with increasing SST is observed for 1999, 2000, 2002, 2005, and 2011 with significant r-values only for 1999 and 2000. For the source of CO_2 to the atmosphere with increasing SST, the r-values are significant only for 1995, 1996, 2001, and 2003. The correlation with Sal (**Figure 7(C)**) also shows positive and negative correlations for different years indicating increasing Sal leads to a source of CO_2 to the atmosphere for some years and an increase in CO_2 uptake in some other years, respectively. Increased uptake with decreasing salinity (negative correlation) occurred for most of the years and with significant r-values (**Figure 7(C)**). For dCO_2 correlating both positively and negatively with SST and Sal annually is an indication of opposing mechanisms acting for the ocean CO_2 source and sink. Potentially, the increasing Sal could be associated with the surface equatorial current waters and possible upwelling of cool nutrient-rich high saline waters as occurs along the Central American coast [36].

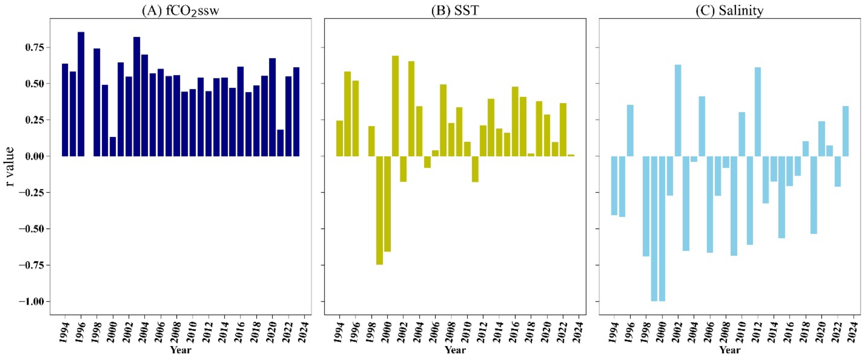

Figure 7. r-values of regression correlation against sea-air fCO_2 exchange ($dfCO_2$) with (A) sea surface fugacity of CO_2 (fCO_2ssw) (B) SST, (C) Sal.

The year-to-year dCO_2 variability influenced by both SST and salinity (**Figure 7(B)-(C)**, respectively) corroborates previous findings that SST variability and Sal are influenced by changes in the position of the ITCZ and are the main processes causing the interannual pattern in the region.

4. Conclusion

The long-term variability of CO_2 flux in the tropical Atlantic remains poorly understood due to the sparseness of spatio-temporal CO_2 data. Monthly climatology of sea surface fugacity of CO_2 in the tropical Atlantic from 1994 to 2023 from the latest version of Surface Ocean CO_2 Atlas (SOCATv24) revealed the spatio-temporal sparseness of CO_2 data in the regions especially in the Gulf of Guinea within the eastern tropical Atlantic. Few data were available in the first decade and data density increased through the second decade to the third with the data concentrating in the western basin. The tropical Atlantic has been studied in regional isolation of portions in the eastern, western, and central tropical Atlantic. The long-term variability of the combined regions with more data density (entire fCO_2ssw observations in the western region) studied here shows the influence of sea surface temperature and salinity and the amount of CO_2 in the surface ocean on the year-to-year variability of CO_2 flux. Correlation statistics show the most influence from the amount of CO_2 in the surface ocean; with 20 years of data showing a significant correlation (r-values ≥ 0.5) and the least influence from surface ocean temperature; showing significant correlation values for only 6 years of the data. Salinity shows significant correlation values for 11 years of data out of which negative correlations occur for 9 years which means increasing salinity increases CO_2 uptake. This pattern negates the uptake of CO_2 hinged on the biological productivity enhanced by the effect of the river discharge in the region and is accompanied by a freshening effect (reduced salinity). This reveals the interaction between salinity and CO_2 uptake is biogeochemically complex, typically increased salinity is associated with reduced CO_2 uptake due to lower biological productivity however in the western tropical Atlantic discharge of the Amazon River carries high load of carbon dioxide from organic matter respiration that is as well associated with high nutrients that fuels increased primary production leading to enhanced CO_2 uptake. This mechanism has implications for long-term carbon uptake in the region.

Conflicts of Interest

The authors declare no conflicts of interest.

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