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ARTICLE

Atmospheric Ozone Variability in Central Brazil: A Spatiotemporal Analysis Across Three Distinct Biomes

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ABSTRACT

This study investigates the spatial and temporal variability of the Total Column Ozone (TCO) across three Brazilian biomes—Cerrado, Pantanal, and Atlantic Forest—between 2005 and 2020. Satellite-derived TCO data from the Ozone Monitoring Instrument (OMI) were used to assess monthly, seasonal, and interannual variations. Linear and polynomial regressions were applied to identify trends and variability, while descriptive and comparative statistics supported biome-specific characterization. The results reveal distinct seasonal cycles, with primary TCO peaks during the dry season (August–October), driven by intense solar radiation and biomass burning, and secondary peaks during the rainy season (March–May), likely influenced by stratospheric ozone transport. The Cerrado exhibited the highest TCO values and variability, followed by the Atlantic Forest and Pantanal. The observed upward TCO trend (~ 0.03 DU/year) is modest and biome-dependent, reflecting both global atmospheric circulation patterns (e.g., Brewer–Dobson, QBO) and localized human impacts such as land use change and fire regimes. Notably, the Pantanal showed the lowest TCO concentrations and interannual fluctuations, likely due to its flat topography and high humidity. This work emphasizes the importance of regionalized ozone monitoring in tropical ecosystems and supports public policy aimed at reducing emissions, protecting

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ARTICLE INFO

Received:16 May 2025 | Revised: 9 July 2025 | Accepted: 16 July 2025 | Published Online: 27 July 2025

DOI: https://doi.org/10.30564/jasr.v8i3.10978

CITATION

Songa, M., de Souza, A., Cardoso, K.R.A., et al., 2025. Atmospheric Ozone Variability in Central Brazil: A Spatiotemporal Analysis Across Three Distinct Biomes. Journal of Atmospheric Science Research. 8(3): 129–142. DOI: https://doi.org/10.30564/jasr.v8i3.10978

biodiversity, and mitigating climate impacts. The integration of satellite-based data and spatiotemporal analysis provides valuable insights for future climate-chemistry modeling in tropical regions.

Keywords: Total Column Ozone; Cerrado; Pantanal; Atlantic Forest; Remote Sensing; Seasonal Variability; Atmospheric Dynamics

1. Introduction

Atmospheric ozone (O_3) is a chemically active trace gas that occurs naturally in both the troposphere and stratosphere. In the troposphere, ozone acts as a pollutant with harmful effects on human health and ecosystems, functioning as a potent oxidizing agent and greenhouse gas [1,2]. Conversely, in the stratosphere, ozone plays an essential role in absorbing harmful ultraviolet (UV) radiation, thereby protecting life on Earth. As both a greenhouse gas and UV absorber, ozone has a significant influence on the atmospheric radiation balance and on climate variability [3,4].

Over recent decades, anthropogenic activities have led to a decrease in the Total Column Ozone (TCO), especially at polar and mid-latitudes [5]. The implementation of the Montreal Protocol and its subsequent amendments have been pivotal in halting and reversing this depletion, with observed signs of stratospheric ozone recovery at high and mid-latitudes [6–9]. Nonetheless, the recovery remains heterogeneous, and uncertainties persist regarding ozone trends in tropical regions [10].

Understanding the spatial and temporal behavior of TCO in tropical biomes is essential to assess the regional impacts of climate variability and anthropogenic pressures. The Cerrado, Pantanal, and Atlantic Forest biomes in Brazil exhibit distinct ecological and climatic characteristics, which affect ozone dynamics. The Cerrado, a tropical savanna, is significantly influenced by seasonal biomass burning, which emits ozone precursors such as nitrogen oxides (NO_x) and volatile organic compounds (Vox) [11,12]. The Atlantic Forest is subject to urban and industrial emissions, particularly in coastal areas, contributing to regional ozone chemistry alterations [13]. The Pantanal, one of the world's largest wetlands, exhibits unique atmospheric behavior due to hydrological seasonality and the long-range transport of pollutants [14,15].

Seasonal variations in TCO are pronounced in Brazil, with maxima during austral spring attributed to enhanced stratosphere-troposphere exchange, and minima during autumn [16]. Atmospheric features such as the South Atlantic Convergence Zone (SACZ) and varying air mass trajectories further modulate ozone distribution across regions [16,17].

The Brewer–Dobson circulation (BDC) is the large-scale meridional overturning circulation of the stratosphere. It is driven primarily by the breaking and dissipation of planetary (Rossby) and gravity waves, which induce upward motion of air in the tropical stratosphere and poleward transport at higher altitudes, followed by descent in the mid- and high latitudes [18,19]. This circulation plays a fundamental role in redistributing ozone globally: ozone is mainly produced in the tropical stratosphere by photolysis of molecular oxygen, then transported poleward and downward by the BDC, leading to higher ozone concentrations at mid- and high latitudes. In the tropics, by contrast, ozone concentrations remain relatively lower due to the continuous upward motion and export of ozone-rich air to other latitudes. Therefore, the BDC is critical for understanding the seasonal and interannual variability of the Total Column Ozone (TCO) observed in different biomes.

This study aims to characterize the seasonal patterns and long-term trends of TCO across the three major biomes of Mato Grosso do Sul from 2005 to 2020. Using satellite-based data from the OMI sensor, we analyze monthly, seasonal, and interannual TCO variations and their potential driving factors. By exploring regional ozone dynamics in relation to meteorological and anthropogenic variables, this study contributes to a deeper understanding of ozone variability in tropical South America and informs climate and environmental policy development.

2. Materials and Methods

2.1. Study Area

The study focuses on three biomes in the state of Mato Grosso do Sul (MS), Brazil: Cerrado, Pantanal, and Atlantic Forest. These biomes exhibit distinct climatic, topographic, and ecological characteristics (**Figure 1**).

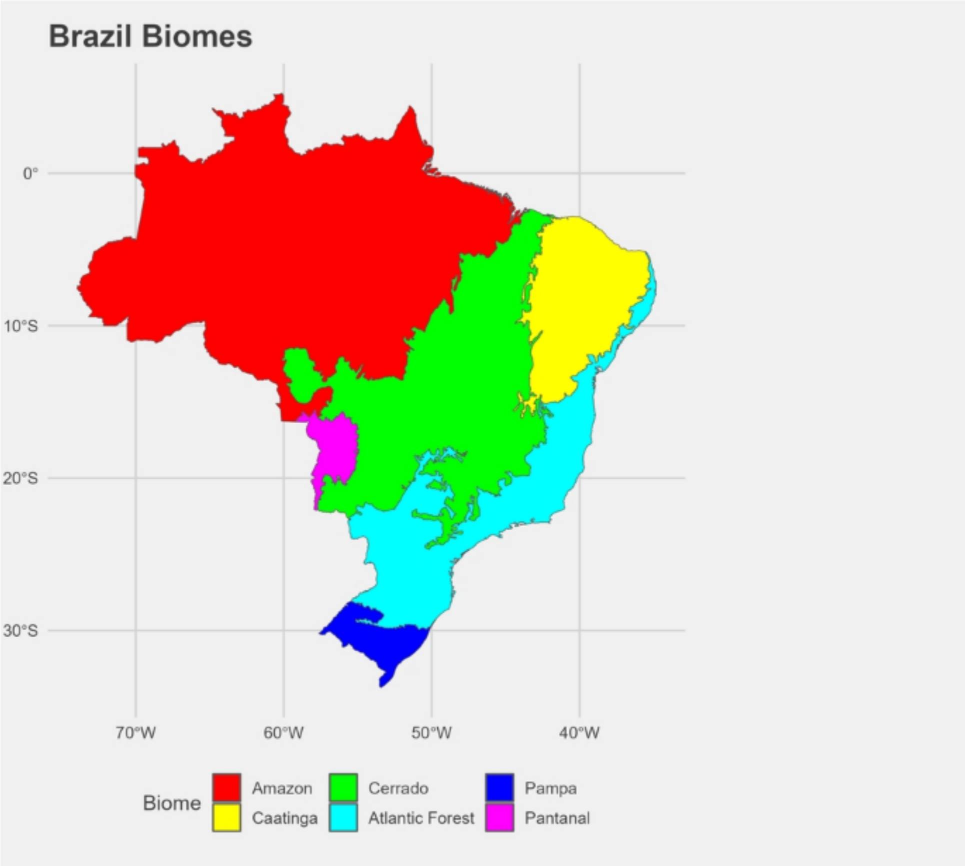

Figure 1. Location of South America and Brazil, Highlighting the State of Mato Grosso do Sul and Its Three Main Biomes: Cerrado (red), Pantanal (blue), and Atlantic Forest (purple). The Dashed Green Line Indicates the Approximate Boundary of Mato Grosso do Sul.

Cerrado – Located approximately between 17°S and 23°S and 52°W and 56°W, the Cerrado features a tropical seasonal climate (Aw – Köppen), with a pronounced dry winter and a rainy summer. Elevations range from 200 to 1,000 meters. The vegetation includes savanna formations with grasses, shrubs, and scattered trees. It covers about 61% of MS (~ 220,000 km²) [20,21].

Pantanal – Spanning from 17°S to 21°S and 55°W to 58°W, the Pantanal lies at low elevations (80–150 m). It exhibits a humid tropical climate (Aw – Köppen) with distinct flood and dry periods. Vegetation includes floodable fields, aquatic species, and patches of seasonal forest. It comprises about 25% of MS (~ 137,000 km²) [22,23].

Atlantic Forest – Found mainly in southeastern MS (22°S to 24°S; 53°W to 55°W), the Atlantic Forest ranges from 300 to 1,100 meters in elevation. It has a humid tropical and subtropical climate (Cfa and Cwa – Köppen) with well-distributed rainfall. Vegetation is dominated by dense evergreen forests with a rich diversity of flora. This biome covers approximately 14% of MS (~ 50,000 km²) [24,25].

2.2. Data Collection and Processing

TCO data were obtained from the Ozone Monitoring Instrument (OMI), onboard NASA's Aura satellite, available through the Earth Observing System Data and Information System (EOSDIS). Monthly mean TCO values (in Dobson Units – DU) were extracted for each biome from January 2005 to December 2020. Representative grid cells were selected for each biome to ensure spatial coverage and consistency.

Monthly, seasonal, and annual averages of the Total Column Ozone (TCO) were calculated to characterize temporal variability. Monthly averages were obtained by computing the arithmetic mean of all daily TCO values within each month for every biome, ensuring that short-term fluctuations were smoothed into representative monthly means. Annual averages were then derived from the arithmetic mean of the 12 monthly values for each year, so that all months contributed equally to the annual statistic regardless of the number of valid daily observations. Seasonal means were computed for the four standard climatological seasons in the Southern Hemisphere: DJF (summer), MAM (autumn), JJA (winter), and SON (spring). To analyze long-term behavior, the time series were further smoothed using a 13-month moving average, which reduces high-frequency variability and highlights broader temporal trends.

Linear regression was employed to estimate temporal trends, and trend magnitude was expressed in DU/year. The net TCO change over the 15-year period was obtained by multiplying the trend slope by 15. Additionally, percentage variability was calculated to assess interannual fluctuations.

Statistical analyses were performed to examine spatial differences among biomes, including mean, standard deviation, skewness, kurtosis, and coefficient of variation. Comparative graphs and tables were used to visualize trends and seasonal cycles.

This methodological approach allows for a comprehensive understanding of ozone behavior across distinct Brazilian biomes, facilitating the interpretation of spatial–temporal dynamics in the context of environmental variability and anthropogenic influence.

3. Results

3.1. Trend Analysis

Trends derived from linear regression of the monthly TCO time series from 2005 to 2020 (**Figure 2**) are presented in **Figure 2**(**a**)–(**c**). The analysis reveals an apparent upward trend in the Total Column Ozone (TCO) across the Cerrado, Pantanal, and Atlantic Forest biomes. However, the linear trends are not homogeneous across all regions. The estimated mean increase of approximately 0.03 DU per year over the 15-year period aligns with expected behavior in tropical regions, where ozone variability is typically less pronounced than in mid- and high-latitudes.

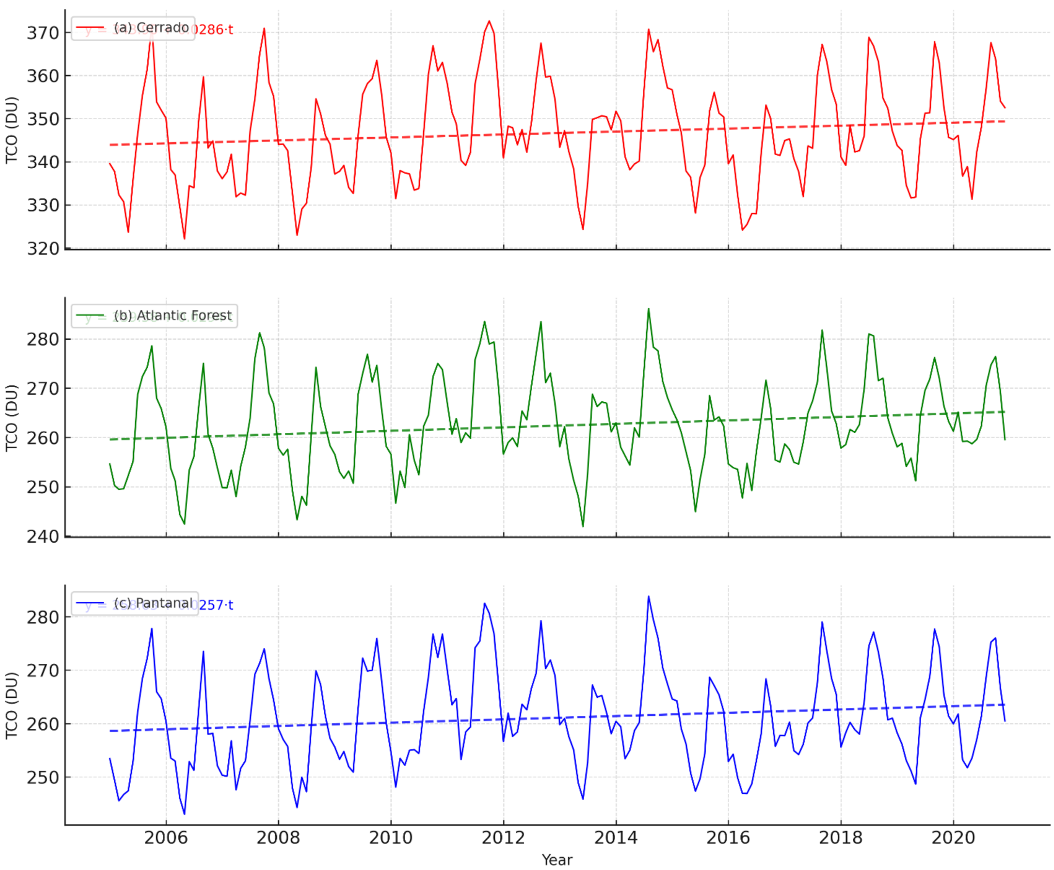

Figure 2. Monthly Mean TCO Time Series from 2005–2020 with Their Linear Fits for (**a**) Cerrado (CER), (**b**) Atlantic Forest (ATF) and (**c**) Pantanal (PAN) Biomes.

Despite this observed increase, global assessments suggest a slight decline in the stratospheric ozone layer, potentially indicating progressive thinning.

3.2. Seasonal and Interannual Variability

The Total Column Ozone (TCO) in the Cerrado, Pantanal, and Atlantic Forest biomes exhibits clear seasonal and interannual variability, shaped by both large-scale atmospheric processes and localized environmental factors.

The time series from 2005 to 2020 (**Figure 2**) reveals a modest but consistent upward trend (~0.03 DU/year), with the Cerrado showing the highest TCO levels (~ 346.7 DU) (**Figure 2**(**a**)), followed by the Atlantic Forest (~262.4 DU) (**Figure 2**(**b**)) and Pantanal (~ 261.1 DU) (**Figure 2**(**c**)), as summarized in **Table 1**.

Table 1. Descriptive Statistics of Annual TCO for the Biomes (2005–2020).

Statistic	Cerrado (CER)	Atlantic Forest (ATF)	Pantanal (PAN)
Mean (DU)	346.66	262.43	261.12
Standard Deviation	11.69	9.45	9.01
Median	345.73	261.24	260.23
Coefficient of Variation (%)	3.37	3.60	3.45
Maximum	372.64	286.14	283.81
Minimum	322.10	241.92	243.04
Range	50.53	44.22	40.77
Skewness	0.21	0.23	0.31
Kurtosis	−0. 617	−0. 547	−0. 623
Sample Variance	136.74	89.39	81.11
95% Confidence Interval	± 1.67	± 1.35	± 1.29

The descriptive statistics of the TCO for the biomes of Mato Grosso do Sul (**Table 1**) reveal consistent differences among the analyzed regions. The Cerrado exhibited the highest mean values (346.66 DU), approximately 80–100 DU higher than those observed in the Atlantic Forest (262.43 DU) and Pantanal (261.12 DU). This spatial hierarchy is associated with the greater incidence of solar radiation in the Cerrado, coupled with extensive land-use changes that favor ozone formation and accumulation in the atmospheric column. In contrast, the high relative humidity of the Atlantic Forest and Pantanal acts as a limiting factor, enhancing the removal of ozone precursors and resulting in lower absolute levels.

Interannual variability, expressed by the standard deviation, was more pronounced in the Cerrado (11.69), while the Atlantic Forest (9.45) and Pantanal (9.01) showed lower dispersion. However, the coefficients of variation were low across all biomes (3.3–3.6%), highlighting the relative stability of the time series. The amplitude was highest in the Cerrado (50.53 DU), confirming its greater sensitivity to atmospheric oscillations and the impacts of seasonal biomass burning. The statistical distribution displayed near-zero skewness and negative kurtosis, indicating an approximately symmetric and flattened distribution without extreme events.

The analysis of the time series of normalized standard deviations (**Table 2**) complements these findings, showing low interannual variability (< 5%) across all biomes, a typical feature of tropical regions. The Cerrado presented the highest absolute TCO levels but the lowest relative variability, suggesting interannual robustness even under conditions of intense UV radiation and anthropogenic pressure. The Atlantic Forest displayed low variability, strongly influenced by high humidity and dense vegetation cover, which promotes precursor scavenging. The Pantanal, in contrast, showed episodes of higher oscillation between 2011 and 2014 (variability up to 3–4%), a period linked to severe droughts and widespread biomass burning, possibly intensified by ENSO events.

Overall, **Tables 1** and **2** indicate that, despite the relative stability of the Total Column Ozone in tropical latitudes, there are marked differences among the biomes. The Cerrado appears more prone to absolute fluctuations, the Atlantic Forest maintains a regime of low oscillation, and the Pantanal exhibits higher vulnerability to hydroclimatic extremes. These results reinforce the combined influence of global drivers (e.g., Brewer–Dobson circulation, Quasi-Biennial Oscillation) and regional factors (biomass burning, humidity, land-use change) on TCO dynamics, emphasizing the importance of continuous monitoring to better understand variability and to support environmental management strategies.

Table 2. Time Series of TCO with Normalized Standard Deviations by Year for Each Biome.

	TCO (DU)		
	CER	**ATF**	**PAN**
Mean	346.73	269.44	261.23
SD	5.22	4.31	4.08
Median	346.92	262.8	261.73
CV	1.51%	1.60%	1.56%
Max	355.9	269.83	268.85
Min	337.28	256.4	254.68
Range	18.63	13.43	14.17
Skewness	−0.154	0.032	0.059
Kurtosis	−0.453	−1.174	−0.551
Sample Variance	27.25	18.61	16.64
Confidence Level (95.0%)	2.89	2.39	2.26

Monthly TCO values display well-defined seasonal patterns across all biomes (**Figure 3**), with primary peaks occurring between August and October, coinciding with the dry season and heightened fire activity, particularly in the Cerrado and Pantanal. A secondary peak is typically observed from March to May, likely influenced by stratospheric ozone transport associated with the Brewer–Dobson circulation and convective uplift (**Figure 4**). Minimum TCO values tend to occur in January, during the peak of the austral summer, when convective activity and ozone redistribution are intensified.

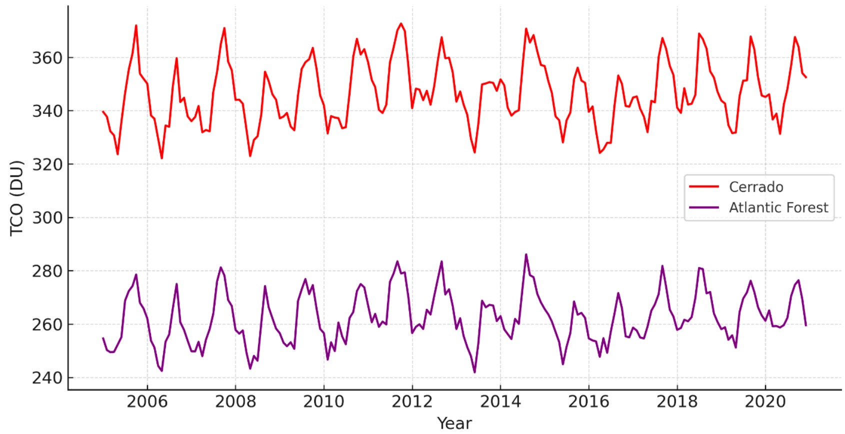

Figure 3. Temporal Variation of the Total Column Ozone (TCO) in the Cerrado (CER) and Atlantic Forest (ATF) Biomes Over the Period from 2005 to 2020.

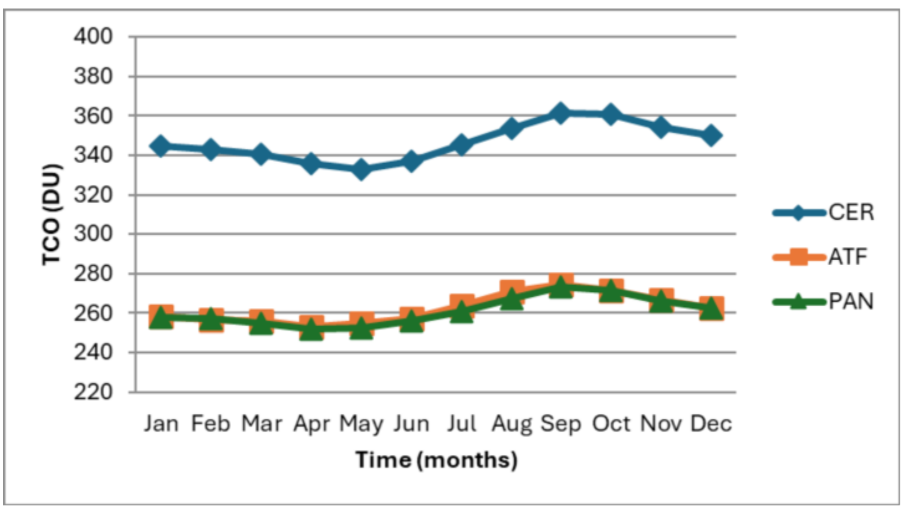

Figure 4. Average Monthly Variability of the TCO in the Pantanal, Cerrado, and Atlantic Forest Biomes.

Figure 4 shows the monthly behavior of the Total Column Ozone (TCO) for the Cerrado, Atlantic Forest, and Pantanal biomes during the period 2005–2020. In all three biomes, a clear seasonal pattern is observed. Minimum TCO values occur between February and April, while maximum values are recorded from August to October. The Cerrado consistently exhibits the highest TCO levels, ranging from approximately 340 to 365 DU. The Atlantic Forest presents intermediate values, between ~ 255 and 275 DU, with well-defined seasonal variation. The Pantanal shows the lowest TCO values, generally between 250 and 270 DU, and a comparatively smaller seasonal amplitude.

Figure 5 illustrates the annual variation in Total Column Ozone (TCO) across the Pantanal, Cerrado, and Atlantic Forest biomes from 2005 to 2020. The analysis reveals that in several years, TCO values fell below the recommended threshold for tropical regions (260 DU) and remained consistently below the global average standard of 300 DU.

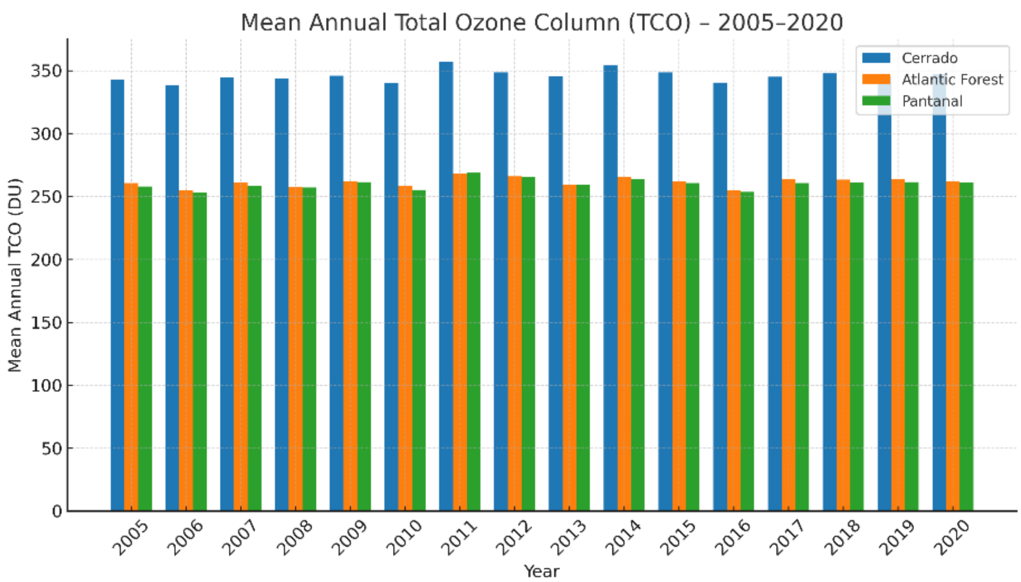

Figure 5. Comparative Analysis of TCO in the Pantanal, Cerrado, and Atlantic Forest Biomes.

3.3. Spatial Distribution of TCO Across Biomes

The spatial behavior of TCO exhibits notable differences among the biomes. The Cerrado recorded the highest TCO values throughout the study period, followed by the Atlantic Forest, while the Pantanal registered the lowest averages. These patterns suggest that geographic location, vegetation characteristics, and regional meteorological dynamics influence the spatial distribution of ozone in the atmospheric column.

Cerrado: This biome presented the highest average TCO values, ranging from approximately 330 to 360 DU. These elevated levels may be attributed to a greater incidence of ultraviolet radiation, which enhances photochemical ozone formation. Additionally, the large-scale conversion of native vegetation for agriculture likely alters local emissions of ozone precursors.

Atlantic Forest: TCO values typically ranged from 245 to 275 DU and frequently fell below the tropical standard of 260 DU. High relative humidity and dense forest cover in the region may enhance the removal of ozone precursors from the atmosphere, leading to reduced ozone formation.

Pantanal: This biome recorded the lowest TCO values, possibly due to its topographic features and climatic conditions that facilitate the dispersion of ozone. The influence of humid air masses and the region's hydrological regime may also suppress ozone formation and retention in the atmospheric column.

3.4. Trends and Extremes During the Study Period

According to the dataset, the highest and lowest annual TCO values were recorded in 1990 (267.33 DU) and 2007 (245.19 DU), respectively. These values reflect inter-annual fluctuations that may be linked to variations in ozone precursor emissions, stratospheric transport processes, and ozone-depleting mechanisms.

Throughout the 2005–2020 study period, the Cerrado consistently exhibited the highest TCO levels, with the Atlantic Forest presenting intermediate values and the Pantanal the lowest. This spatial hierarchy aligns with findings by De Souza et al. (2022), who emphasize the role of solar radiation, humidity, and land use in modulating tropospheric and stratospheric ozone variability.

The persistence of TCO values below the global average (300 DU) across all biomes underscores the importance of long-term monitoring to better understand the driving forces behind ozone variability. The elevated ozone concentrations in the Cerrado may be driven by intense UV radiation and land use changes, while the Pantanal's lower values result from higher humidity levels and unique atmospheric circulation patterns.

Further research is essential to deepen the understanding of how meteorological and anthropogenic factors interact to influence ozone dynamics in Brazilian biomes, especially in the context of ongoing environmental change and policy development.

The analysis of annual variability (%) of the Total Column Ozone (TCO) across the Cerrado, Atlantic Forest, and Pantanal reveals a generally stable interannual behavior, with fluctuations mostly below 2%. (**Figure 6**) The Cerrado exhibited the lowest variability, reflecting its relative atmospheric stability despite strong photochemical activity driven by intense solar radiation. The Atlantic Forest also displayed reduced variability, likely due to high humidity and dense vegetation, which promote ozone scavenging and buffer annual oscillations. In contrast, the Pantanal presented slightly higher peaks, particularly between 2011 and 2014, when variability approached 3–4%. These anomalies coincide with years of intense droughts and widespread biomass burning in central South America, conditions often linked to El Niño–Southern Oscillation (ENSO) events and enhanced stratosphere–troposphere exchange [13,17]. The overall low variability (< 5%) confirms that ozone in tropical latitudes is relatively stable compared to mid- and high latitudes, where stronger seasonal dynamics prevail. However, the episodic increases in the Pantanal highlight the sensitivity of this biome to hydroclimatic extremes and fire regimes, underscoring the interplay between large-scale circulation processes such as the Brewer–Dobson circulation and local anthropogenic pressures.

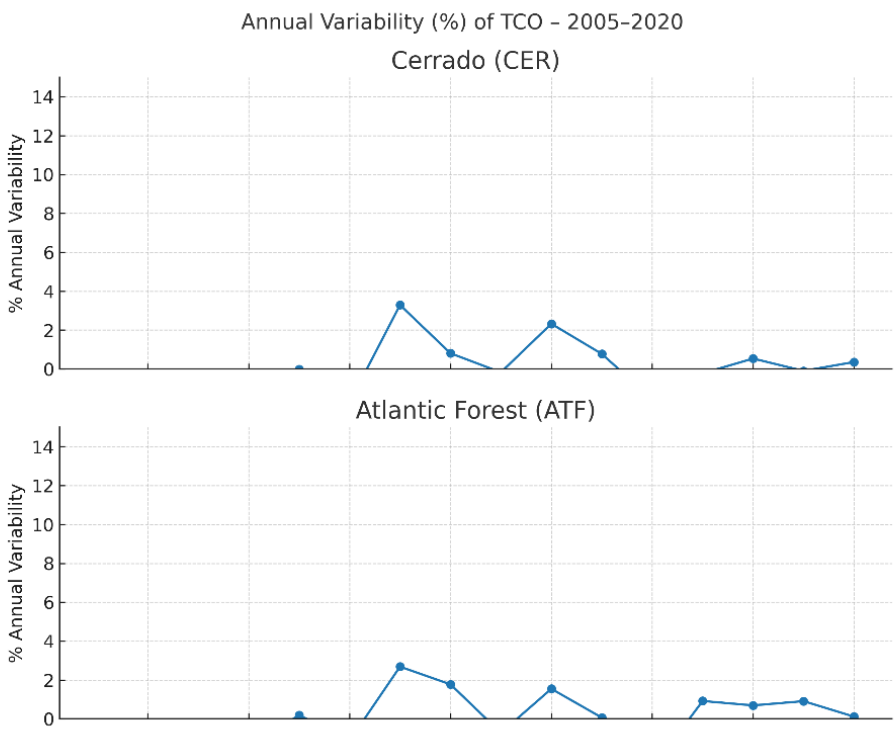

Figure 6. *Cont.*

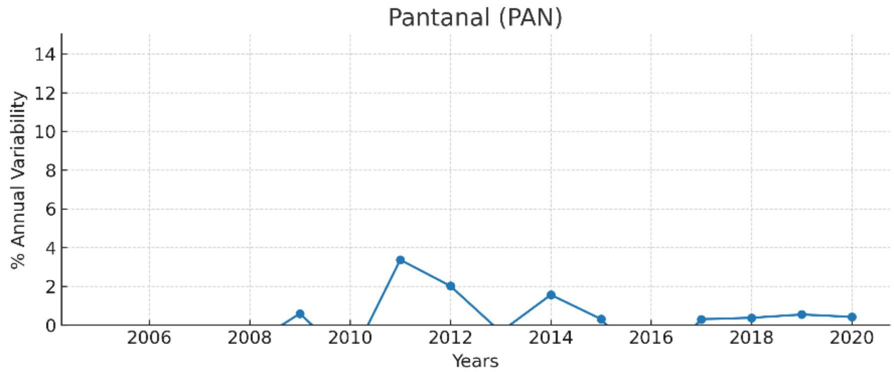

Figure 6. Annual Variability of the Total Column Ozone (TCO) in the Pantanal, Cerrado and Atlantic Forest Biomes.

Figure 7 shows the monthly variability of the Total Column Ozone (TCO) in the three biomes analyzed (Cerrado, Atlantic Forest, and Pantanal) for the period 2005–2020 (**Figure 7**(**a**)–(**c**)), with confidence intervals represented by error bars.

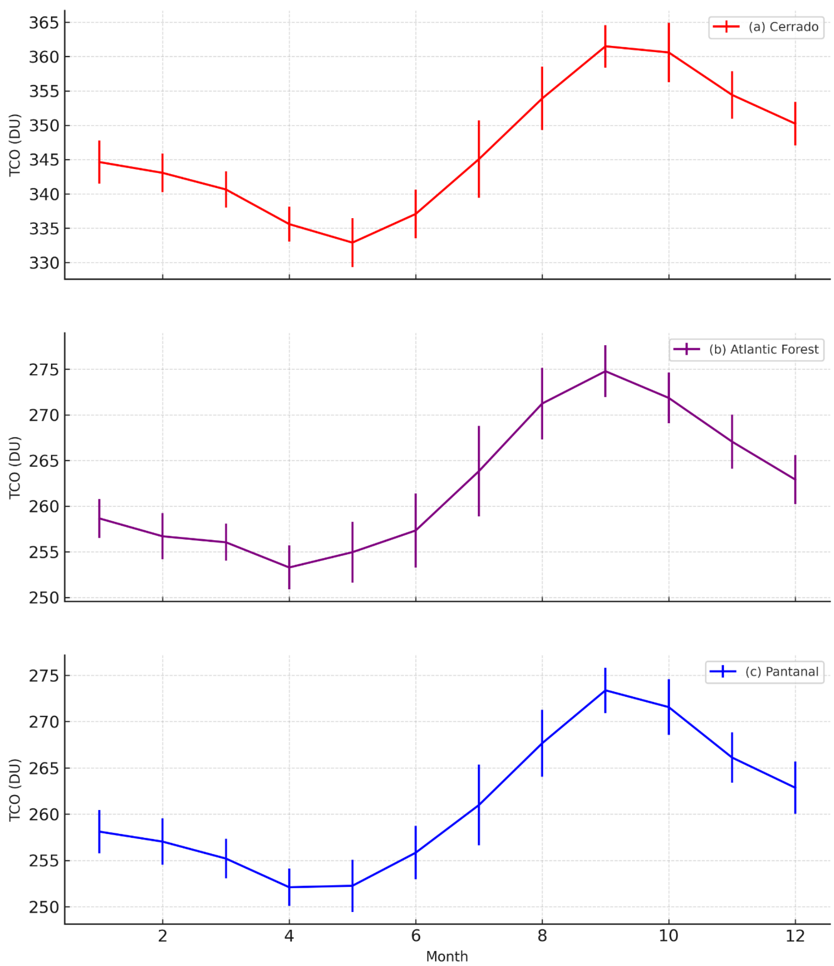

Figure 7. Monthly variability of the Total Column Ozone (TCO) in the State of Mato Grosso do Sul, Brazil, for the Period 2005–2020. (**a**) Cerrado (CER), (**b**) Atlantic Forest (ATF), and (**c**) Pantanal (PAN). The Error Bars Represent Confidence Intervals of the Mean Values. Although the Three Biomes Display a Similar Seasonal Cycle, with Minimum Values in Autumn (March–May) and Maximum Values in Late Winter and Early Spring (August–October), Significant Differences are Observed in Absolute TCO Levels, with the Cerrado Exhibiting Values 80–100 DU Higher than Those of the Atlantic Forest and Pantanal.

In the Cerrado, mean TCO values range between 335 and 365 DU, standing out as the highest among the biomes analyzed. A well-defined seasonal cycle is observed, with decreasing values from March to May and a progressive increase from June onward, reaching a maximum between August and October.

In the Atlantic Forest, TCO values vary between 250 and 275 DU. The seasonal pattern is similar to that of the Cerrado, with minimum values during autumn (March to May) and maximum values in late winter and early spring (August to September).

The Pantanal exhibits the lowest TCO values, ranging from 250 to 270 DU. Its seasonal variability follows the same trend as the other biomes, with a decrease in autumn and an increase from winter onward, also peaking between August and September.

The graphs highlight that, although the three biomes display a similar seasonal cycle, there are significant differences in absolute TCO values. The Cerrado presents concentrations about 80–100 DU higher than those in the Atlantic Forest and Pantanal, suggesting the influence of regional factors such as higher solar radiation incidence and land-use changes.

3.5. Analysis of Seasonal Variation of the Total Column Ozone (TCO) in the Pantanal, Cerrado, and Atlantic Forest Biomes

The seasonal variation of the Total Column Ozone (TCO) across the Pantanal, Cerrado, and Atlantic Forest biomes reveals distinct ozone distribution patterns, shaped by the interplay between large-scale atmospheric circulation and regional forcings such as biomass burning, pollutant transport, and climate variability [10,17]

3.5.1. Seasonal Variation and Mean TCO in the Biomes

In Mato Grosso do Sul, a well-defined seasonal cycle emerges, with maximum TCO values recorded between August and October and minimum values between December and February. This pattern reflects shifts in atmospheric circulation, stratospheric–tropospheric exchange, and seasonal differences in ozone sources and sinks [5,19].

Pantanal: The Pantanal is strongly influenced by seasonal fires during the dry season (June–October), which release significant amounts of ozone precursors. Its flat topography also favors vertical mixing processes that can facilitate ozone redistribution between atmospheric layers [13,14].

Cerrado: The Cerrado, subject to intense land-use pressures such as deforestation and extensive burning (particularly July–October), exhibits elevated ozone production. Biomass burning enhances tropospheric ozone formation and promotes its dispersion to higher altitudes [10,26,27].

Atlantic Forest: In the Atlantic Forest, higher humidity and dense forest cover tend to limit photochemical ozone formation relative to other biomes. However, long-range transport of pollutants and the influence of oceanic air masses play a key role in shaping ozone variability in this region [10,27].

3.5.2. Maximum and Minimum TCO Values

The TCO cycle shows consistent seasonal extremes: September (Maximum TCO): This period coincides with enhanced stratospheric subsidence and reduced ozone destruction, resulting in elevated TCO levels. At the same time, widespread fires in the Cerrado and Pantanal increase emissions of aerosols and ozone precursors, further amplifying ozone concentrations [17,28].

January (Minimum TCO): During austral summer, intense convective activity and dominant low-pressure systems enhance vertical transport and redistribution of ozone, leading to lower TCO. Higher humidity also promotes chemical reactions that accelerate ozone depletion [5,18].

3.5.3. Interannual Variability and Large-Scale Drivers

Although standard deviations are relatively low—indicating that TCO seasonality is a robust and recurring feature—interannual variability is influenced by large-scale phenomena. The Quasi-Biennial Oscillation (QBO), El Niño–Southern Oscillation (ENSO), and the Brewer–Dobson Circulation exert significant control over vertical and horizontal ozone transport, modulating the magnitude of seasonal cycles across years.

Overall, the TCO in the Pantanal, Cerrado, and Atlantic Forest biomes follows a tropical climatological pattern, with maxima at the end of the dry season and minima during the summer. These results emphasize the dual influence of regional climatic drivers (biomass burning, humidity, hydrology) and global-scale atmospheric dynamics in shaping ozone variability. Understanding this interaction is essential for interpreting ozone trends and assessing environmental risks linked to atmospheric composition in tropical South America[5,28].

Figure 8 shows the seasonal averages of the Total Column Ozone (TCO) for the Cerrado, Atlantic Forest, and Pantanal during the study period. The Cerrado consistently exhibits the highest TCO values, ranging between approximately 335 and 355 DU across all seasons, indicating a greater ozone concentration in the atmospheric column over this biome.

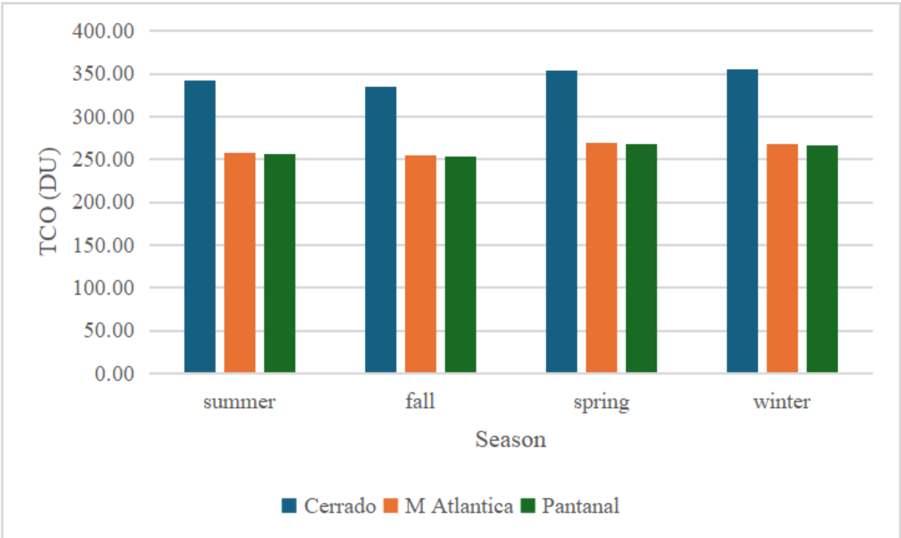

Figure 8. The Average of the Seasonal Values for the Three Biomes.

In the Atlantic Forest and the Pantanal, TCO values are similar, ranging from 250 to 270 DU, with only minor differences between the two biomes. In both regions, the seasonal pattern mirrors that of the Cerrado, with the lowest values observed in autumn (fall) and the highest in winter and spring.

Overall, the three biomes display a similar seasonal cycle, characterized by minimum TCO in autumn and maximum TCO in winter and spring. However, the absolute magnitude of TCO differs substantially, with the Cerrado exhibiting values approximately 80–100 DU higher than those of the Atlantic Forest and Pantanal. This difference suggests the influence of regional factors, such as higher solar radiation and significant land-use and land-cover changes in the Cerrado, which may favor ozone production and accumulation.

4. Discussion

The results reveal a consistent seasonal cycle of TCO across the three biomes, with minima in autumn (March–May) and maxima in winter–spring (August–October). In terms of magnitude, the Cerrado maintains the highest absolute TCO values (≈ 80–100 DU above the Atlantic Forest and Pantanal), while the Pantanal and Atlantic Forest display similar levels and smaller seasonal amplitudes. This spatial hierarchy and seasonal pattern agree with tropical climatology observed in Brazil and support the interpretation that variability is modulated by both large-scale processes and regional forcings (e.g., biomass burning, humidity, atmospheric circulation, and transport).

From a dynamical perspective, the observed seasonality is consistent with the combined influence of the Brewer–Dobson circulation (BDC) and the Quasi-Biennial Oscillation (QBO), which control, respectively, the meridional–vertical transport of stratospheric ozone and the modulation of tropical winds[18,19]. Ascending motion in the tropics and subsidence in mid-latitudes, typical of the BDC, favor TCO maxima in late winter and spring, whereas the combination of deep convection and enhanced mixing in summer contributes to TCO minima (WMO, 2018)[5]. Furthermore, ENSO events and regional circulation anomalies may intensify interannual extremes—an imprint that appears in our 2005–2020 dataset and has also been reported in analyses for other Brazilian regions[16,17].

Regional controls help explain the differences among biomes. Higher solar radiation and anthropogenic pressure from land-use change in the Cerrado favor elevated ozone levels [10], while greater humidity and dense forest cover in the Atlantic Forest tend to dampen seasonal amplitude [12]. In the Pantanal, the hydrological regime and the transport of aerosols/precursors during the dry season modulate variability, with regional biomass burning and long-range transport playing a significant role [13,14]. These interpretations are consistent with recent studies mapping the spatiotemporal variability of TCO in central-western and northeastern Brazil [26–28].

Linking TCO climatology to biological implications, there is extensive evidence from southeastern and southern Brazil that episodes of tropospheric ozone—associated with vehicular/industrial emissions and photochemical formation under intense radiation—cause foliar injury, reduced photosynthesis, and productivity losses in both cultivated and native species. Studies with sensitive bioindicators (e.g., *Nicotiana tabacum* cv. Bel-W3) in urban and peri-urban areas of São Paulo and Curitiba have documented visible lesions and physiological responses consistent with chronic O_3 exposure; research on Atlantic Forest species (deciduous and evergreen trees) also reports differential sensitivity among species and associations with urban–industrial corridors. These regional findings resonate with our results: even with relatively stable TCO, seasonal atmospheric conditions that favor O_3 production/accumulation in the lower troposphere (winter–spring in the Southeast/South) coincide with periods of greater biological risk for vegetation [12]; see also biomass burning and aerosol series in Sena [17].

Finally, the convergence between (i) robust seasonal patterns of TCO across the MS biomes and (ii) ecophysiological evidence from the Southeast and South underscores the need to integrate ozone climatology, emission inventories, and plant biomonitoring into risk assessments. This is consistent with international recommendations for monitoring stratospheric recovery and ecosystem effects at tropical latitudes [5].

5. Conclusions

This study provides a comprehensive assessment of the spatial and temporal variability of the Total Column Ozone (TCO) across three distinct biomes in Mato Grosso do Sul, Brazil: Cerrado, Atlantic Forest, and Pantanal, over the period 2005–2020. The results demonstrate a consistent seasonal cycle in all biomes, with minimum values during autumn and maxima in winter and spring. However, significant differences in absolute magnitudes were observed. The Cerrado maintained the highest TCO levels, approximately 80–100 DU greater than those of the Atlantic Forest and Pantanal, which exhibited lower values and reduced seasonal amplitude.

These differences highlight the combined influence of large-scale atmospheric dynamics, including the Brewer–Dobson circulation and the Quasi-Biennial Oscillation, alongside regional forcings such as biomass burning, land-use change, and hydrological regimes. The findings are consistent with climatological patterns reported for tropical latitudes and reinforce the role of both global-scale drivers and local processes in modulating ozone variability.

Furthermore, the convergence between climatological evidence from central Brazil and ecological studies in the Southeast and South regions, where tropospheric ozone has been shown to cause significant damage to vegetation, emphasizes the importance of integrating ozone monitoring with ecological risk assessments. Such integration is crucial for advancing environmental policies, particularly in the context of climate change, land-use transformation, and the recovery of the stratospheric ozone layer.

In summary, this work contributes to the understanding of ozone climatology in tropical South America, providing baseline information that may support future research and guide strategies for air quality management and ecosystem protection.

Author Contributions

Conceptualization, M.S., A.S., K.R.A.C. and J.F.O.J.; methodology, M.S., A.S., K.R.A.C. and J.F.O.J.; software, M.S., A.S., K.R.A.C. and J.F.O.J.; validation, M.S., A.S., K.R.A.C. and J.F.O.J.; formal analysis, M.S., A.S., K.R.A.C. and J.F.O.J.; investigation, M.S., A.S., K.R.A.C. and J.F.O.J.; resources, M.S., A.S., K.R.A.C. and J.F.O.J.; data curation, M.S., A.S., K.R.A.C. and J.F.O.J.; writing—original draft preparation, M.S., A.S., K.R.A.C. and J.F.O.J.; writing—review and editing, M.S., A.S., K.R.A.C. and J.F.O.J.; visualization, M.S., A.S., K.R.A.C. and J.F.O.J.; supervision, M.S., A.S., K.R.A.C. and J.F.O.J. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data from this study are available upon request to the corresponding author.

Acknowledgments

The authors would like to express their sincere gratitude to the universities for their institutional support in the development of this research. We are also thankful to the administrative and academic teams of both institutions for providing the necessary infrastructure, technical assistance, and encouragement that significantly contributed to the successful completion of this work.

Conflicts of Interest

The authors declare no conflict of interest.

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