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# Assessment of the Latitudinal Behavior of Total Column Ozone at Nine Discrete 1º-Wide Latitude Bands, from TOMS and OMI Data

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**Abstract:** Total Ozone Mapping Spectrometer (TOMS) and Ozone Monitoring Instrument OMI Version 8 data, from November 1978 to February 2013, have been used to retrieve the shape and amplitude of the daily mean of the total column ozone (TCO) and their associated dispersion over eleven selected 1°-wide latitude bands. Their inter-annual variation at 44.5° S, 23.5° S, 23.5° N, 44.5° N and 59.5° N shows a quasi-regular periodic behavior. However, Polar Regions exhibit abrupt changes, whereas at the Equator a complex perturbation of periodicity is highlighted, which could be associated to the effect of the quasi-biennial oscillation (QBO). The discrete 1°-wide latitude bands show a stabilization of TCO levels from the late nineties, but they do not display a generalized recovery. Indeed, at the Equator, between 1997 and 2013, a 1.4% per decade decrease in the total column ozone is exhibited, which may be significant given that during the 1987-1994 period the decrease was only of 0.5%. Additionally, the discrete bands reveal the appearance of a perturbation of the inter-annual ozone variations at 59.5º S, in contrast to regular behavior in the Northern Hemisphere and at other latitudes. The perturbation apparently begins in the 1980-1984 time series and is clear and systematic after 1998.

**Keywords:** Total column ozone, inter-annual variation, TOMS data, OMI data.

## INTRODUCTION

The depletion of the ozone layer in the stratosphere revealed in the early seventies [1-4], the Antarctic ozone hole discovered by Farman *et al*. [5] and the ozone losses discovered at middle latitudes [6-10], have turned the inter-annual ozone variations into a research topic of the utmost importance.

The effects of stratospheric ozone variations and changes are essential to model and assess the global change [11, 12]. Modeling studies confirm the fact that ozone loss is a dominant mechanism leading to the cooling-off of the lower stratosphere [13-17].

NASA's Total Ozone Mapping Spectrometer (TOMS) has provided long-term records of ozone. Aboard satellite Nimbus-7, TOMS provided daily global measurements of TCO from November 1st, 1978 to May 6th, 1993. Aboard Meteor-3, TOMS covered a time span from August 22nd, 1991 to November 25th, 1994. An eighteen-month interruption occurred until July 22nd, 1996, when the program had no on-orbit capability. ADEOS TOMS was launched on August 17th, 1996 and provided data until June 29th, 1997, but could not produce continuous daily measurements. Earth Probe was launched on July 2nd, 1996 to provide supplemental measurements, but was boosted to a higher orbit to replace the failed ADEOS. Earth Probe covered a time span from July 2nd, 1996 until November 22nd, 2007.

Long before the failure of Earth Probe, on July 15th, 2004, the Aura spacecraft was launched. Aura is part of the Earth Science Projects Division, a NASA program dedicated to the monitoring of complex interactions that affect the Earth. Aura was provided with the Ozone Monitoring Instrument (OMI) and started the global coverage of TCO on October 1st, 2004. Since that date and until November 2007, TOMS aboard Earth Probe and OMI aboard Aura carried out simultaneous measurements. In fact, in this investigation, both measurements were superimposed, exhibiting a surprising coincidence with differences between ±3 DU for the latitudinal mean values at all the selected latitudes.

In the three stages of TOMS, aboard Nimbus-7, Meteor-3 and Earth Probe, the data files have the same structure. The gridded files contain daily averages of the retrieved ozone in a 1-degree latitude by 1.25-degree longitude grid. Each daily global coverage contains 288 longitudinal measurements or bins from 179.375° W to 179.375° E (1.25° steps) and 180 meridional measurements from 89.5° S to 89.5° N (1.00° steps). Due to the low luminance of the poles during spring (March 20th-21st) and autumn (September 22nd-23rd) equinoxes, daily global coverage does not manage to cover 6° of latitude in the vicinity of the poles. Moreover, due to polar nights, daily global coverage does not manage to cover a significant region, which reaches a maximum 29° of latitude on the summer solstice (June 21st-22nd) in the Southern Hemisphere and during the winter solstice (December 21st-22nd) in the Northern Hemisphere.

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For the three stages of TOMS, in March and September, each TOMS daily file implies approximately 48600 TCO values, whereas in December it implies around 43200 values. In the actual OMI stage, two capture data ways are provided. The first one is similar to the three stages of TOMS, but the longitudinal steps have changed from 1.25° to 1.00°. This implies a file structure with 360 longitudinal, 1.00° wide measurements from 179.5° W and 179.5° E, instead of the 288 bins from Nimbus-7 till Earth Probe, whereas latitudinal steps remained identical (1.00° wide, centered on 89.5° S to 89.5° N). The second capture data way has a better resolution: each bin has steps of 0.25 longitude degrees by 0.25 latitude degrees. In this study, for OMI measurements we are using the first capture data way (the 1.00° by 1.00° bins), which is similar to the TOMS file structure.

Satellite measurements have been validated against ground-based measurements [18-22]. TOMS data have become a standard long-record reference in many studies [23-26]. However, many authors and the WMO seem not to trust the TOMS data. The majority of global ozone study trends are simulations based on ground-based measurements and on zonal mean over large latitude bands. The change in the extra-tropical total ozone has been reported using total ozone average between 20° N and the polar night terminator [27]. A monthly total ozone mean has been used to study the ozone anomalies in the Northern Hemisphere [28]. Decadal trend changes in ozone are modeled by using satellite monthly mean of ozone data [29, 30].

Zonal means over large latitude bands have been used in different studies [31, 32]. In an accumulative study, Knudsen and Andersen highlighted a longitudinal dependence of TCO, finding in Siberia, in the Northern Hemisphere, the area that has accumulated the lowest levels [33].

The inter-annual variability of TCO has received less attention. Rarely can ozone studies based on narrow latitude bands be found. Ziemke *et al.* have exceptionally used a TOMS 25-year record to estimate the seasonal cycle, latitude dependence and long-term trends in ozone average over the Pacific region (120° W to 120° E) for six 5° latitude bands extending from 15° S to 15° N [34].

The goal of this study is to take advantage of the enormous amount of data provided by TOMS in order to study the inter-annual variability of the TCO as a function of latitude, using discrete 1º-wide latitude bands. To this end, we selected five latitudes over each hemisphere plus the Equator (a total of eleven) to analyze differences and similarities in the inter-annual ozone variations.

This article aims to emphasize the importance of the latitudinal behavior and to promote the TCO in narrow latitude bands as an analysis tool that enables the visualization of certain behavior peculiarities. The latitudinal behavior can contribute to acquire a greater comprehension of the dynamics of the TCO. An additional interest in presenting the behavior of the TCO in discrete 1º-wide latitude bands resides in its usefulness in didactics.

## 1. TOTAL COLUMN OZONE AT REPRESENTATIVE 1º-LATITUDE BANDS

### 1.1. Latitude Selection

In order to analyze the hemispheric asymmetry, we made an arbitrary selection from equivalent latitudes on both hemispheres. To represent the polar circles, 89.5° and 74.5° N and S latitudes were selected. For middle latitudes, 59.5° and 44.5° N and S latitudes were used. The tropics were represented by 23.5° N and S, and finally, the Equator as 0.5° N and 0.5° S latitudes.

TOMS and OMI Version 8 data, from November 1978 to December 2011, were used to obtain the mean, the minimum and the maximum ozone value at the selected latitudes. The distance between largest and smallest values -or range- has been taken as a dispersion measurement associated to the daily mean of latitudinal values of TCO. In fact, the range comprises the largest statistical dispersion measurements.

Graphical representation of the long-term generated data is presented. No data are given between November 25$^{th}$, 1994 and July 24$^{th}$, 1997, because of the well-known TOMS instrument failure. In addition, due to polar nights, the data latitudes 89.5° S, 89.5° N, 74.5° S and 74.5° N present annual discontinuities.

It must be noted that this study only takes into account the available data. In Polar Regions, instruments cannot measure ozone during polar nights. At 89.5º S, measurements begin on October 5$^{th}$ and end on March 8$^{th}$, covering only five months of the year. At 74.5º S, measurements begin on August 27$^{th}$ and end on April 15$^{th}$, covering almost eight months. At 89.5º N, measurements begin on April 2$^{nd}$ and end on September 10$^{th}$. At 74.5º N measurements began on February 22$^{nd}$, after the polar night and ended on October 20$^{th}$.

### 1.2. Range of the Column Ozone Values

The aim of the range assessment was to evaluate the dispersion maximum of the TCO measurements for the selected 1º-wide latitude bands.

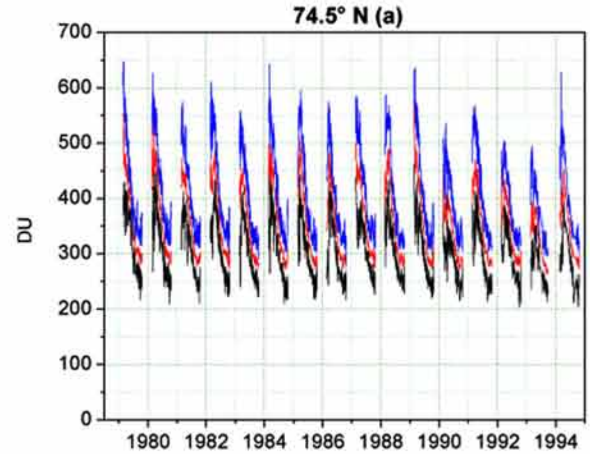
Fig. (**1**) shows the latitudinal daily behavior of the largest (blue) mean (red) and smallest (black) measurements of the TCO at nine selected 1º-latitude bands. The interval between largest and smallest values is just the statistical range. The corresponding graphics at the South and North Poles (89.5° S and 89.5° N) have not been presented for they show a feeble dispersion, like it can be seen in Table **1**.

It can be observed that for all graphics in Fig. (**1**), the range behavior is surprisingly systematic.

The range depends on the latitude and is greater at middle latitudes and in the Northern Hemisphere. This means that the TCO values have grater dispersions on high latitudes, but the dispersion is extraordinarily systematic.

In Fig. (**1**), three stages in the TCO behavior can be observed, especially in the Southern Hemisphere: the first corresponds to severe ozone depletion, occurring between 1978 and 1987; the second corresponds to a slowdown in ozone depletion occurring between 1987 and 1995, while the third corresponds to the current period and is characterized by an apparent stabilization.

However, the literature only mentions two stages. Newchurch *et al.*, amongst others, have reported a significant slowdown in stratospheric ozone losses since 1997 [35]. The inflection point in the trends of the TCO behavior could be placed in 1997. Nevertheless, since TOMS

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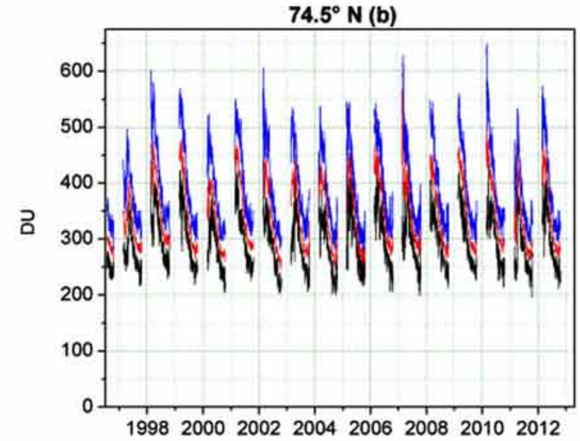


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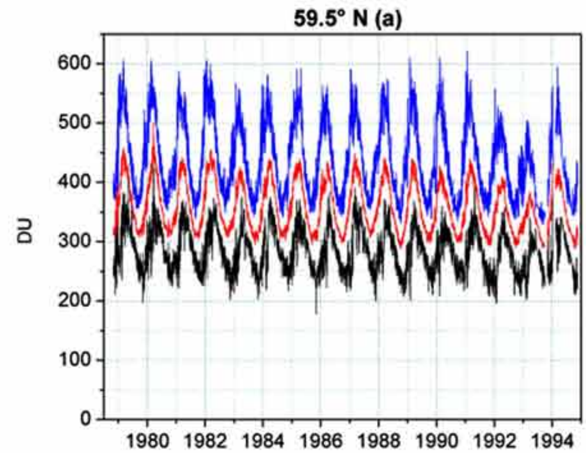


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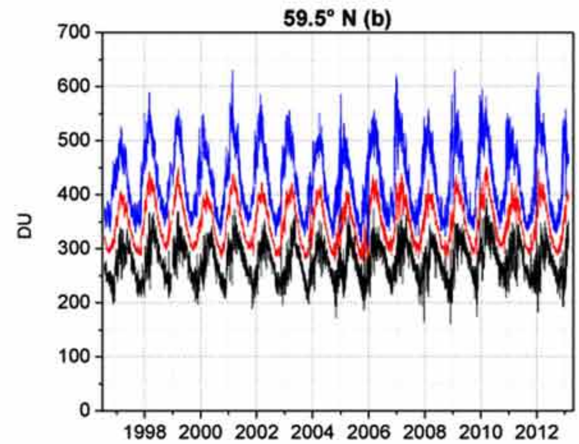


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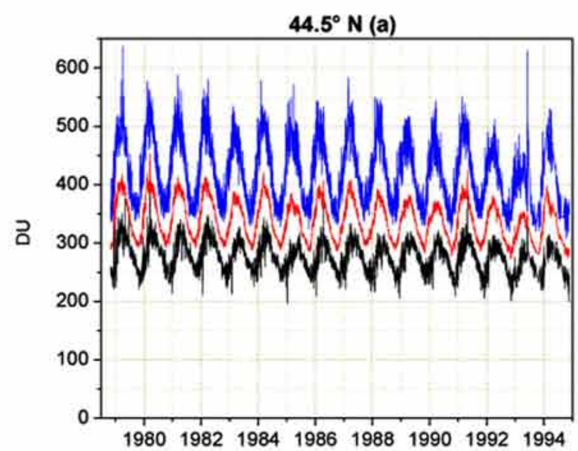


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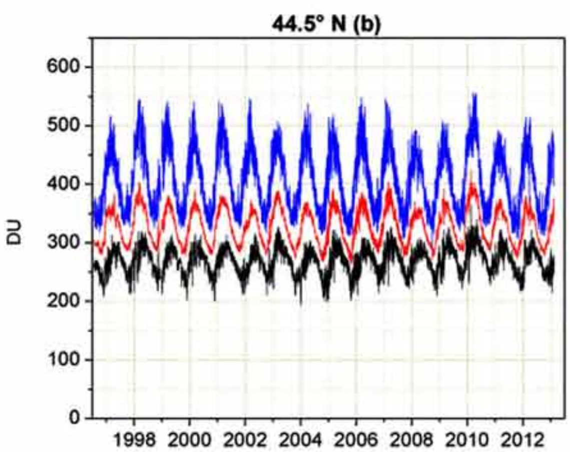


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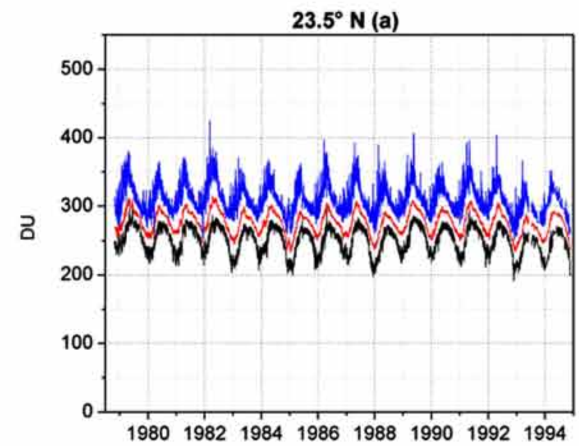


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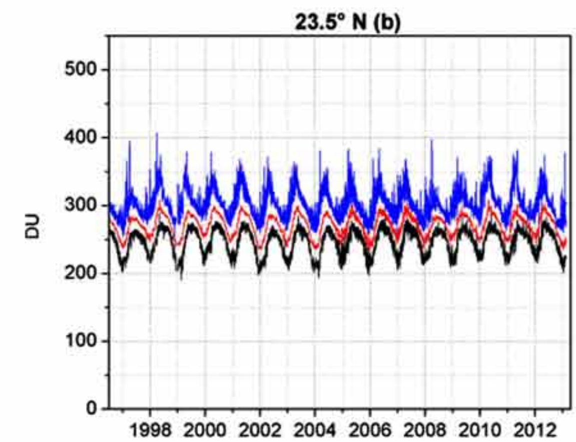


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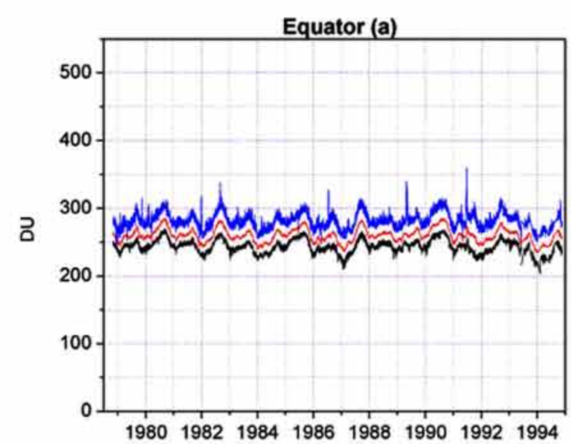


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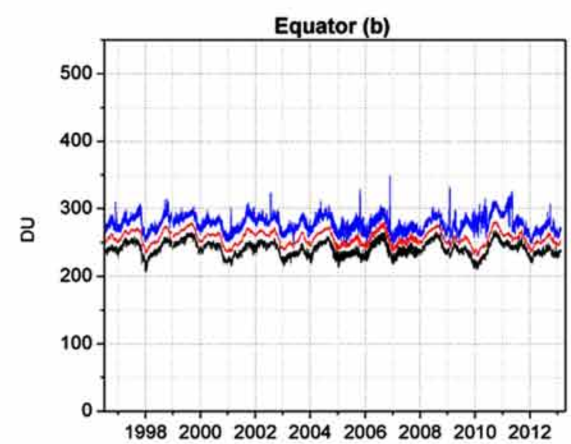


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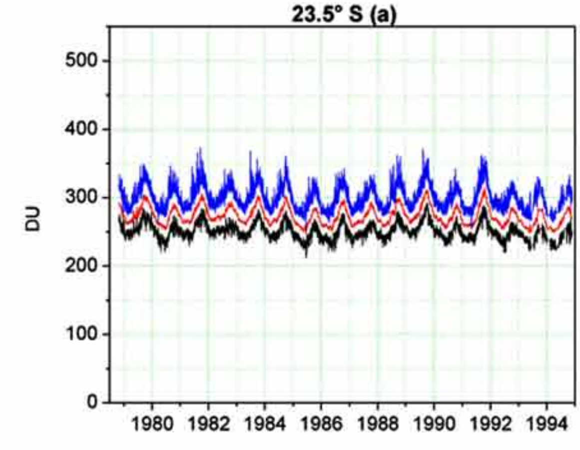


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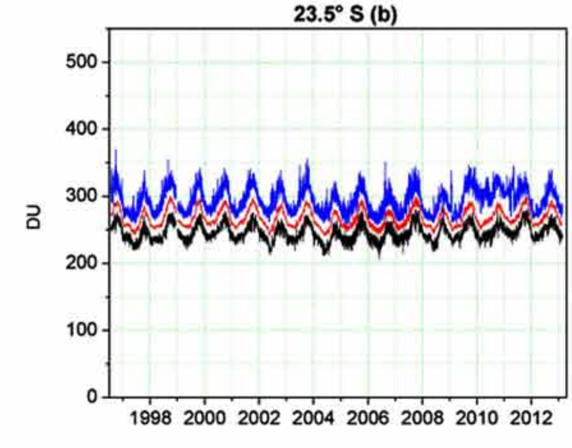


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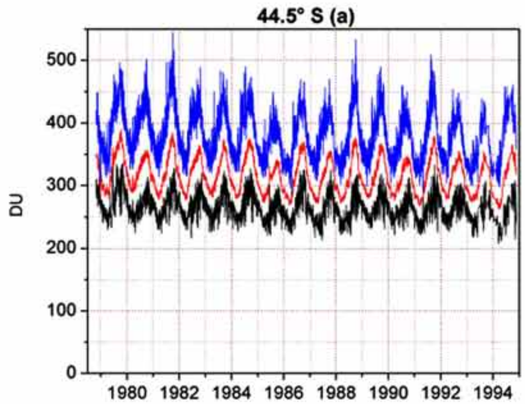


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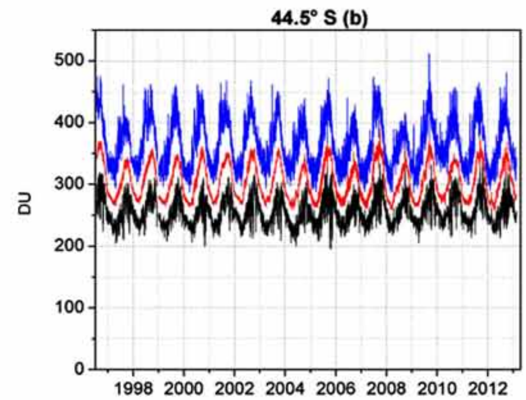


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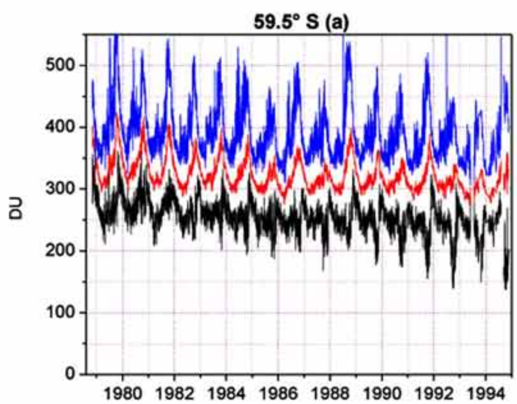


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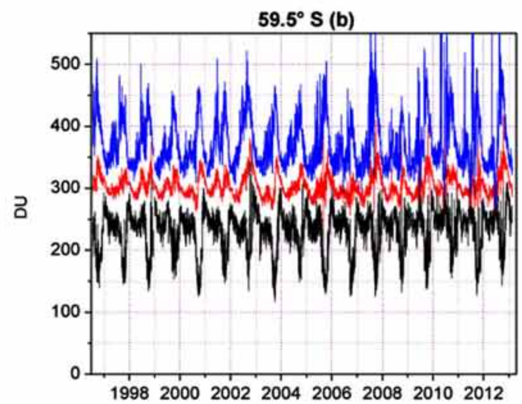


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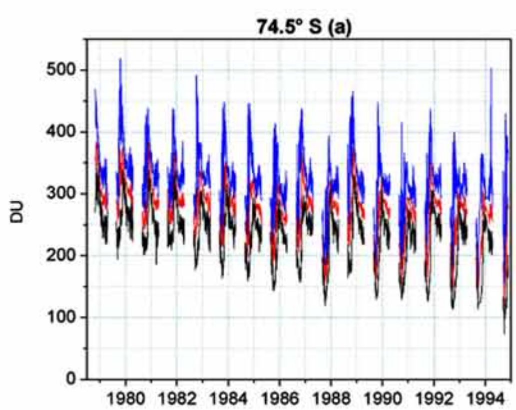


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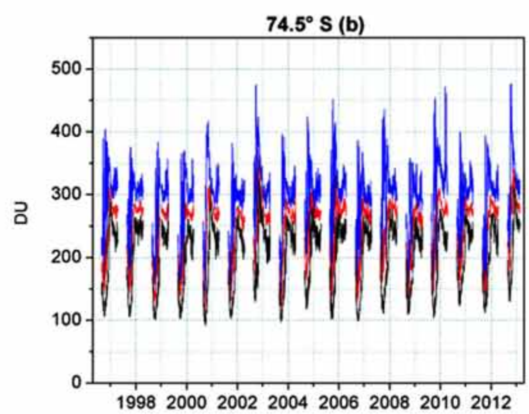


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**Fig. (1).** Latitudinal daily behavior of the largest (blue) mean (red) and smallest (black) measurements of the TCO at nine selected 1º-latitude bands.

**Table 1. Average Total Column Ozone, Mean and Range, for the Periods 1978-1994 and 1996-2013**

| | Period 1978-1994 | | | | Period 1996-2013 | | | |
|---|---|---|---|---|---|---|---|---|
| | Total Column Ozone | | Range | | Total Column Ozone | | Range | |
| Latitude | Mean (DU) | Standard Deviation (DU) | Mean (DU) | Standard Deviation (DU) | Mean (DU) | Standard Deviation | Mean (DU) | Standard Deviation (DU) |
| 89.5° N | 345.9 | 60 | 24.9 | 13.4 | 336.5 | 57.3 | 21.4 | 13.0 |
| 74.5° N | 355.6 | 65 | 104.9 | 45.6 | 342.5 | 57.7 | 100.9 | 45.3 |
| 59.5° N | 358.2 | 41.9 | 156.4 | 56.6 | 348.8 | 39.9 | 151.6 | 58.1 |
| 44.5° N | 338.0 | 33.4 | 146.1 | 45.6 | 327.8 | 30.6 | 139.2 | 47.6 |
| 23.5° N | 276.2 | 16.2 | 59.3 | 19.8 | 270.5 | 15.5 | 55.5 | 19.7 |
| Equator | 260.2 | 9.8 | 37.9 | 7.6 | 256.2 | 9.9 | 36.7 | 8.9 |
| 23.5° S | 273.4 | 12.8 | 48.9 | 11.4 | 267.2 | 13 | 47.4 | 12.3 |
| 44.5° S | 316.0 | 27.4 | 116.5 | 32.9 | 304.5 | 28.5 | 109.8 | 32.3 |
| 59.5° S | 323.0 | 24.5 | 138.4 | 54.9 | 303.6 | 17.8 | 143.1 | 70.2 |
| 74.5° S | 274.8 | 43.4 | 94.4 | 52.1 | 245.3 | 47.2 | 99.9 | 59.8 |
| 89.5° S | 262.1 | 56.2 | 19.1 | 9.9 | 232.1 | 56.7 | 14.3 | 10.7 |

measurements campaign was interrupted in November 25th, 1994 due to the failure of Meteor-3, data is unavailable between this date and July 24th, 1997.

In this study, the trends are analyzed at two periods: the first period, marked by the severe ozone depletion, is adjusted to the available measurements from the beginning of the TOMS campaign (November 1st, 1978) until the interruption of Meteor-3 (November 25th, 1994). The second period, characterized by a slowdown comprises the period from July 24th, 1997 until February 2013.

Fig. (**2**), presents the average TCO values, and its statistical range for the two already mentioned periods that correspond to the selected 1° latitude bands.

North and South average TCO values show important differences. In the Northern Hemisphere the levels of the ozone column are systematically higher than those of the Southern Hemisphere.

Table **1**, presents the average values of TCO, the mean and range for the two before mentioned periods. It can be observed that the TOC mean values show an important decrease, from the first to second period, for all the select latitude bands; whereas the mean ranges and their standard deviation are on the same order.

Previously, Price and Vaughan [36], and Salby and Callaghan [37] reported that ozone column changes locally and daily by as much as 100% at the same latitude. In this work we were able to analyze the dispersion orders by using the statistical range.

Additionally, the largest and the smallest TCO values follow similar trends or their inter-annual variations have

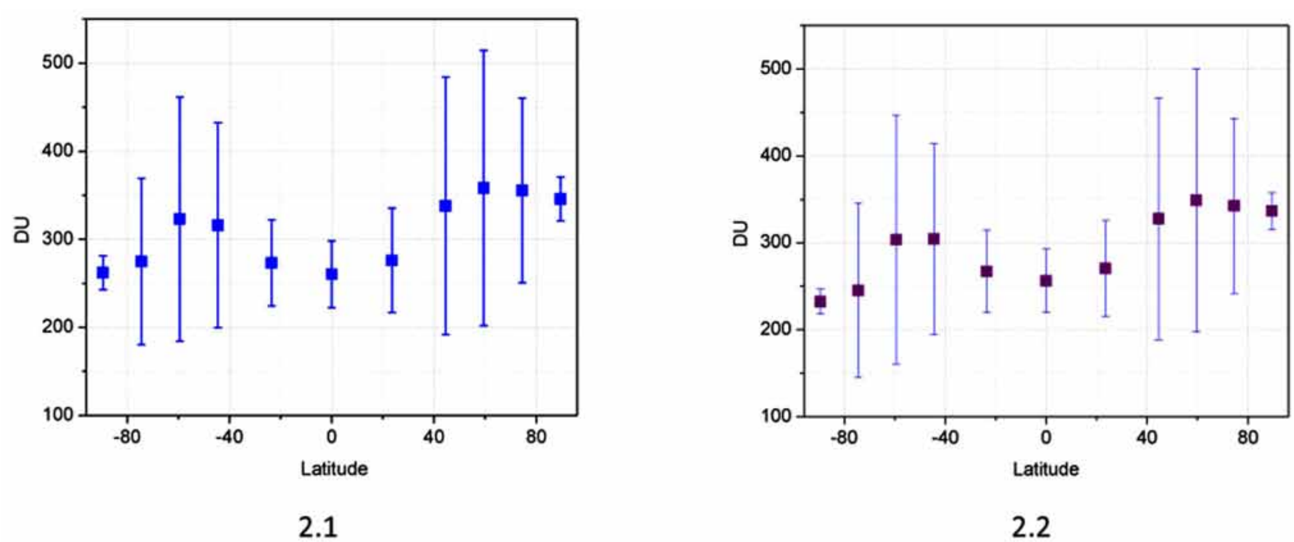



**Fig. (2).** Total column ozone average, mean and range, for the 1978-1994 (2.1) and 1996-2013 (2.2) periods, at the selected 1° latitude bands.

similar phases. However, shifts can be observed, particularly in the cases of the Equator and 59.5º S.

Remarkably, the range allows the finding of distortion or perturbation in the periodicity. In Fig. (**3**) –which is an expanded plot of Graphic 1.8–, Graphic 3.1 shows details of the perturbation observed at 59.5º S. The perturbation appears like a shift of the minima of the smallest values of the ozone column. To emphasize this shift, Fig. (**4**) –which is an expanded plot of Graphic 1.2– shows the range at 59.5º N, in which an evident regularity can be seen; i.e. the largest and smallest values have a similar phase. Assuming equivalent atmosphere dynamics, at 59.5º S, this regularity should be observed.

The apparent regularity shown in Graphic **3.1** may indicate that up to the seventies this was the case. However, this graphic shows the appearance of a sort of repetition of the minima for the smallest values by 1982, which turns into a shift by 1984. The minima of the smallest values shift from April to September.

This perturbation can be considered as the result of two opposite ozone transport mechanisms. In fact, in Fig. (**3**) (Graphics 3.2, 3.3 and 3.4) the perturbation manifests itself as a collapse of the range located around February, followed by an expansion located around early September. During the collapse, the range is reduced until around 80 DU and during the expansion the range can reach 300 DU. At this stage, the smallest values can drop under 150 DU and the largest values can reach the 450 DU. The 59.5° S perturbation can be a layer-like effect due to the circulation of the polar vortex, which seems to be stronger since the early eighties in comparison with the ozone transport from low latitudes into high latitudes.

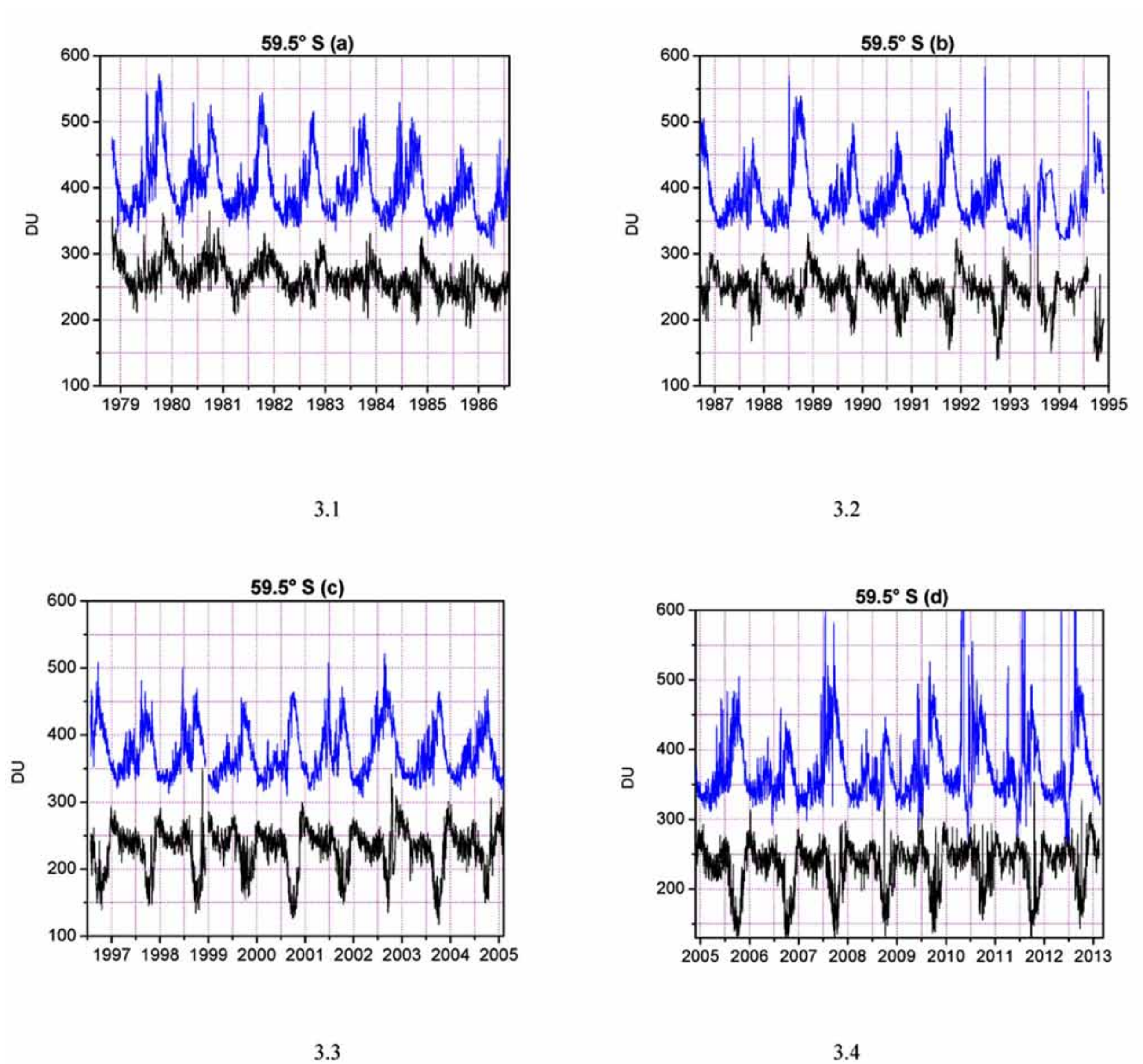



**Fig. (3).** Range of daily column ozone values at the 59.5 ° S latitude band.

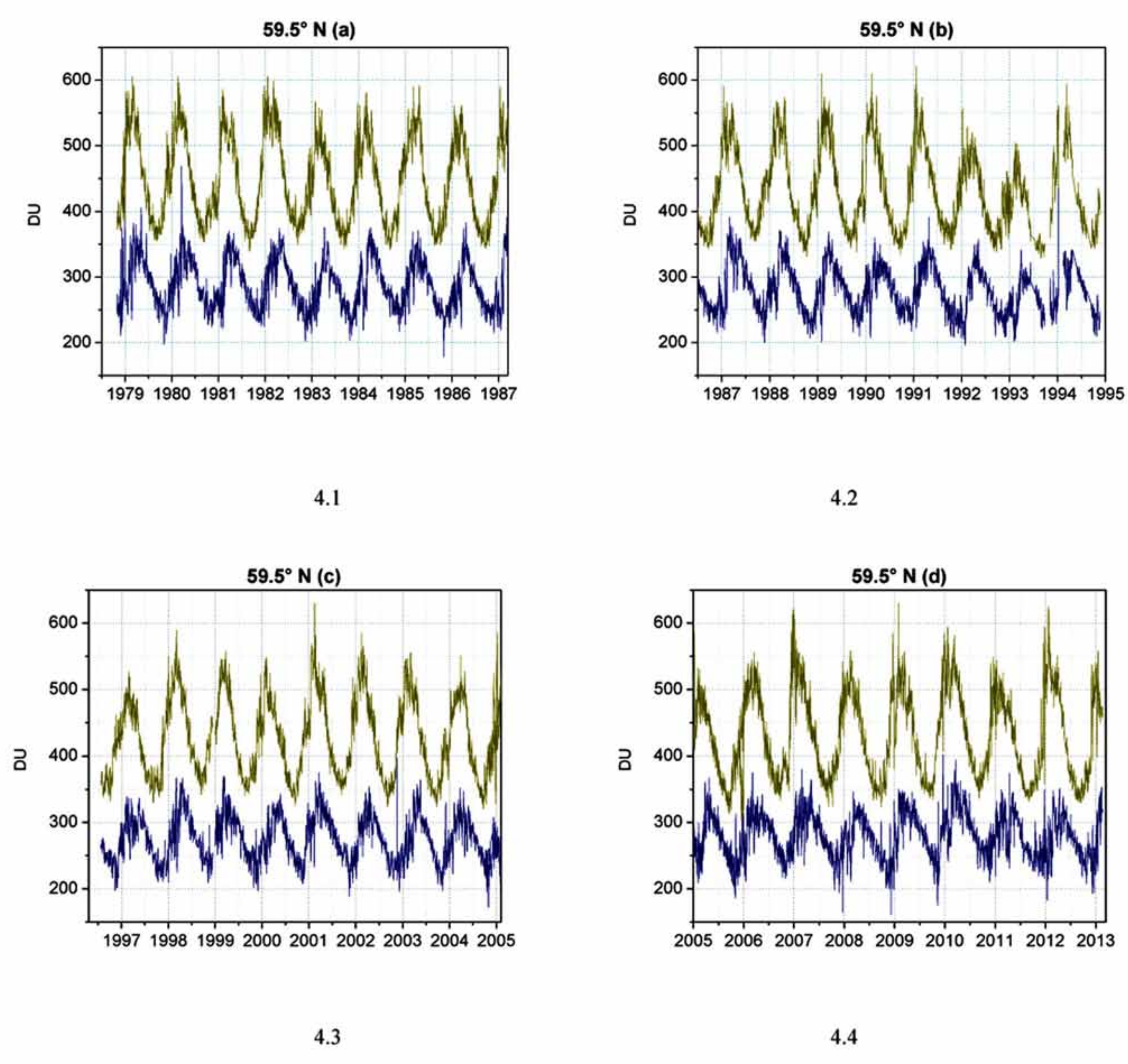



**Fig. (4).** Range of daily column ozone values at the 59.5° N latitude band.

## 2. DAILY MEAN OF THE OZONE COLUMN AT REPRESENTATIVE 1º-LATITUDE BANDS

The daily mean of the stratospheric ozone column for the selected eleven latitudes are presented in Fig. (**5**). The set of plots shows general seasonal variations and trends.

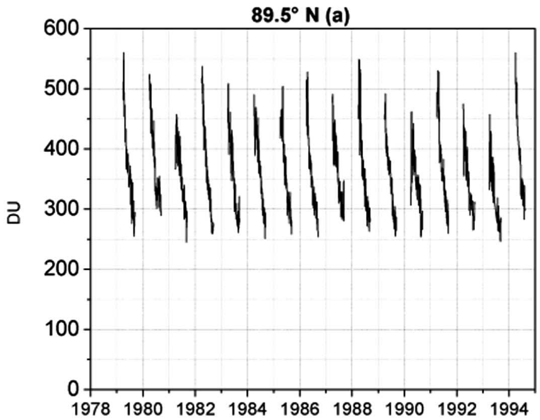
North and South inter-annual variations show important differences. In the Northern Hemisphere, the levels of the daily TCO mean are systematically higher than those of the Southern Hemisphere. The amplitude of inter-annual variations is wider in the Northern Hemisphere, especially at high and middle latitudes. In addition, while in the Northern Hemisphere the higher ozone column values occur at the beginning of the polar day, in the Southern Hemisphere the values are low early in the polar day and decrease until middle October.

The inter-annual variations only have a quasi-regular periodic shape between 23.5° and 59.5°. In the Polar Regions, seasonal changes are abrupt, whereas at the Equator, the inter-annual variations present unsystematic perturbations (Graphic 5.6).

### 2.1. The Ozone Depletion

The trends in the selected 1º-wide latitude bands show ozone depletion occurring in both hemispheres and practically at all latitudes.

In this study, the trends are analyzed at two periods: the first period, marked by the severe ozone depletion, is adjusted to the available measurements between the

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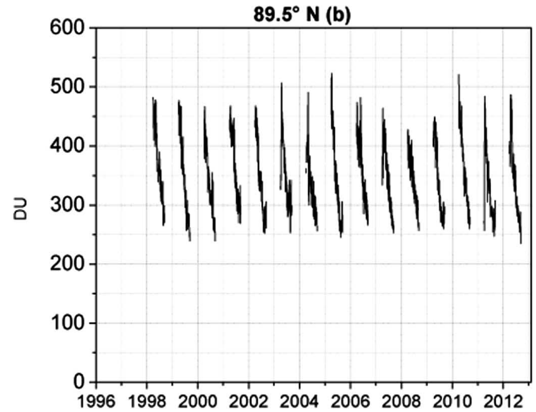


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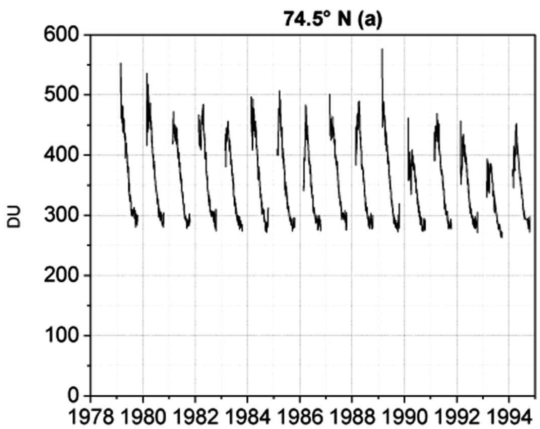


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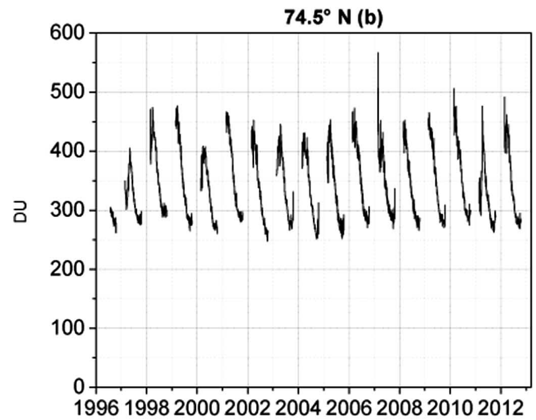


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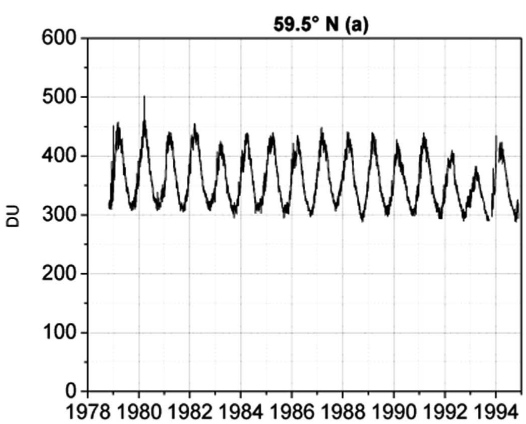


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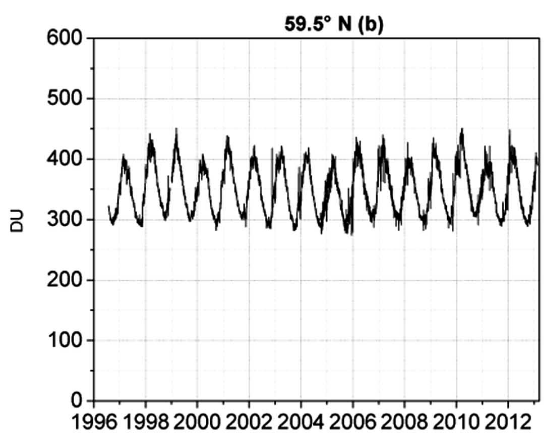


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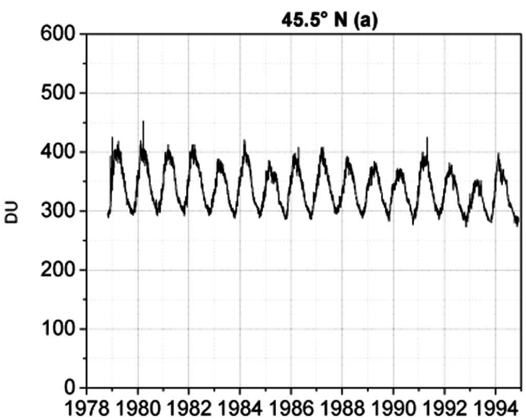


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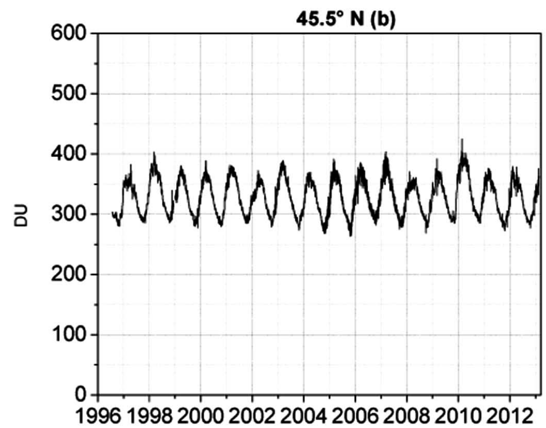


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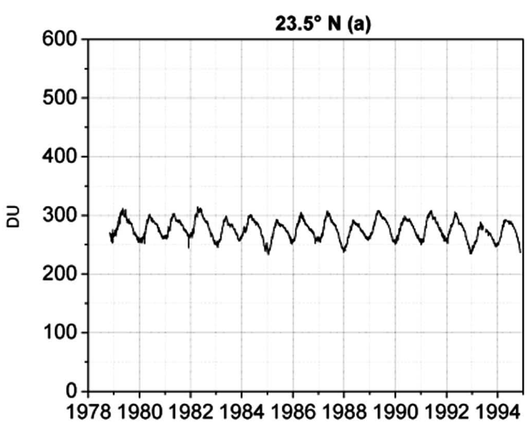


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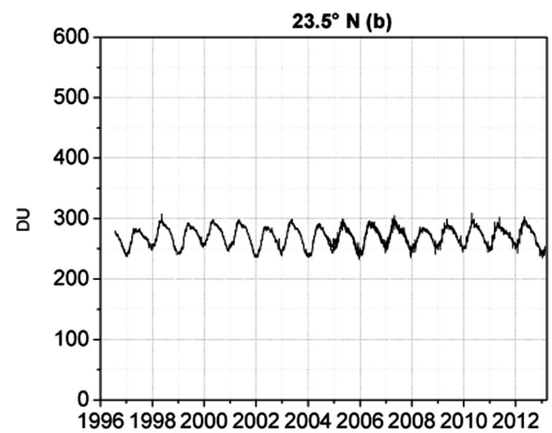


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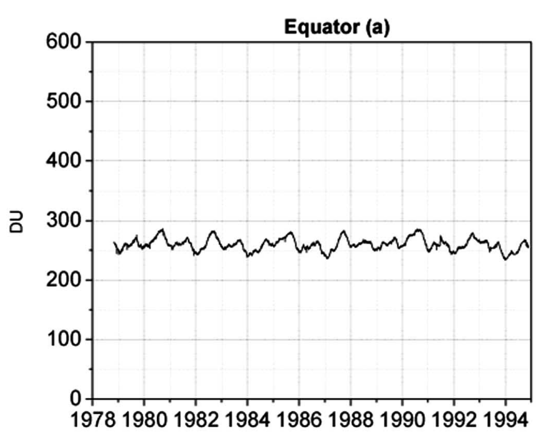


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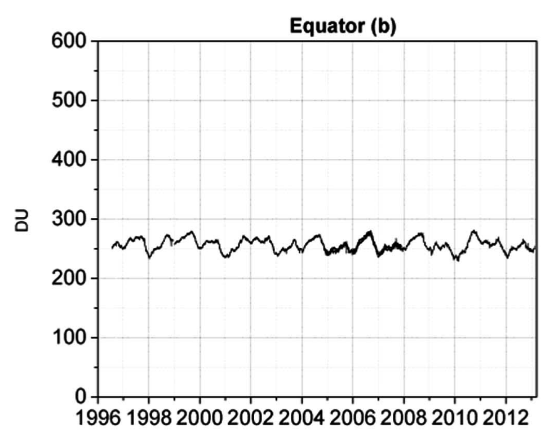
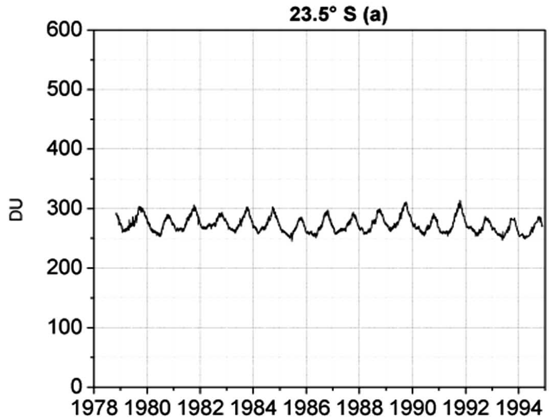
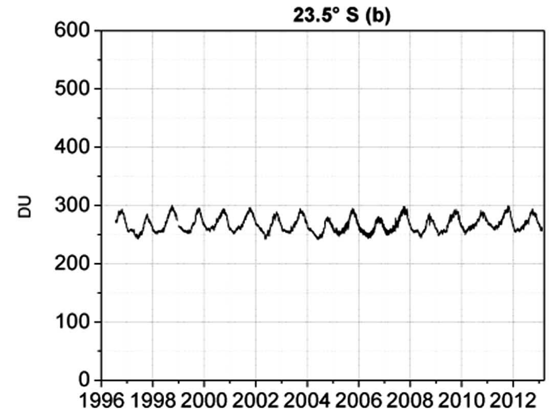



5.6 b

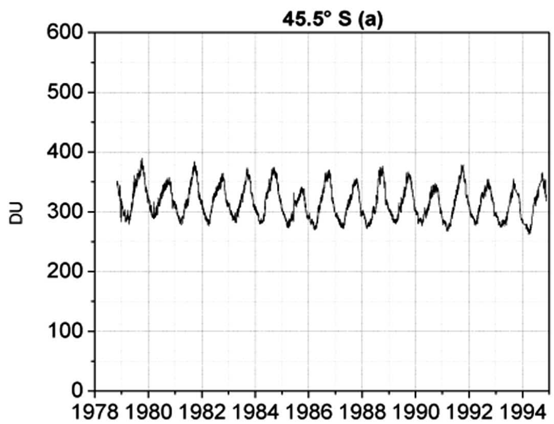
**(Fig. 5) contd…..**



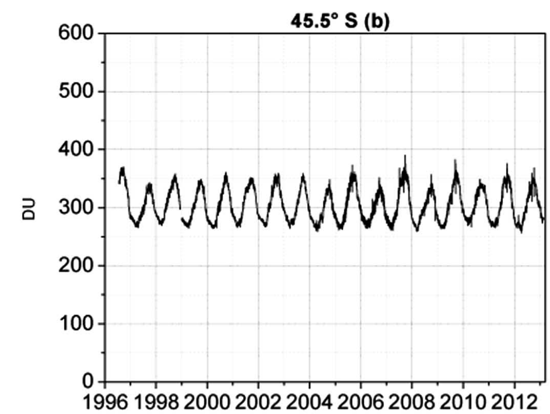

5.7 a



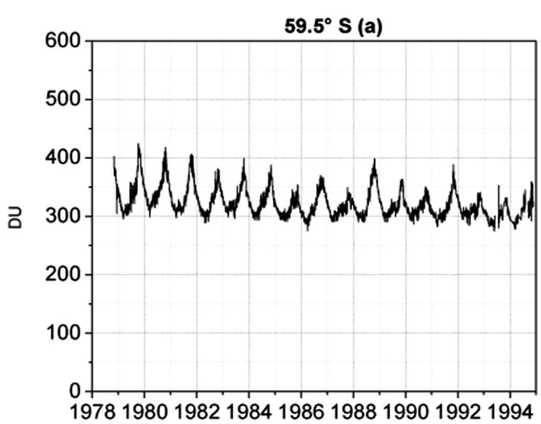

5.7 b




5.8 a




5.8 b

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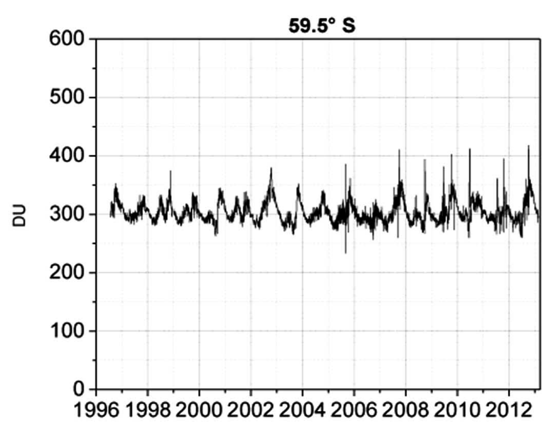
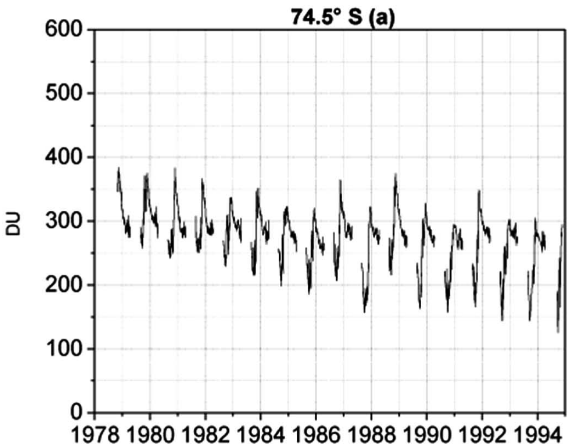
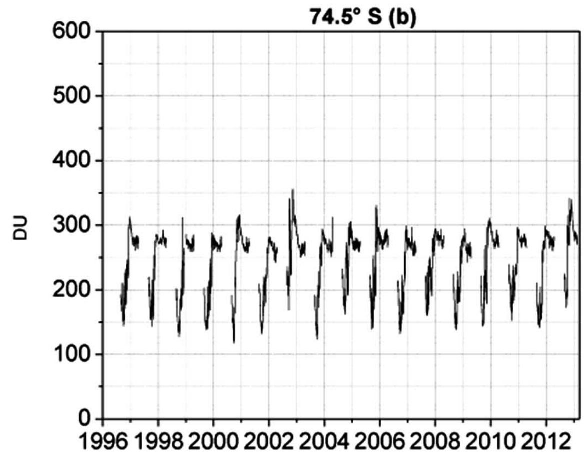



5.9 b

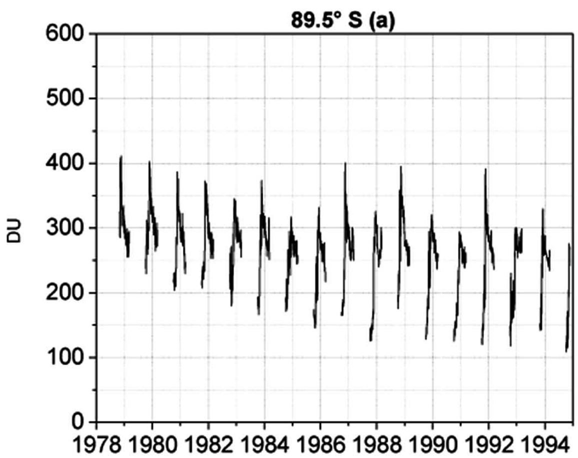
**(Fig. 5) contd…..**



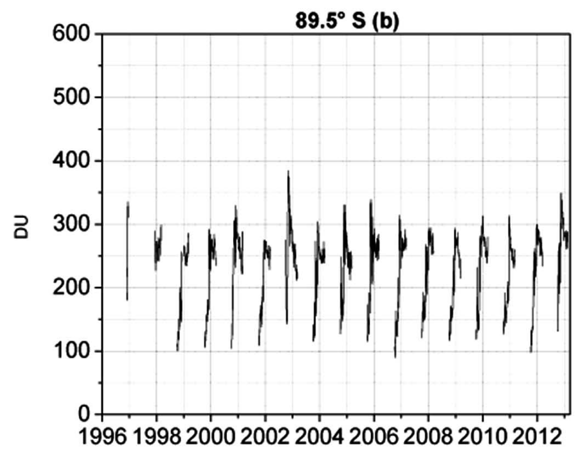

5.10 a




5.10 b




5.11 a




5.11 b

**Fig. (5).** Mean daily stratospheric column ozone for eleven 1° latitude bands.

beginnings of the TOMS campaign (November 1st, 1978) until the interruption of Meteor-3 (November 25th, 1994). The second period, characterized by a slowdown, comprises the period from July 24th, 1997 until February 2013.

Table **2** presents the trends in the TCO for the period, from 1978 to 1994, assuming a linear fitting.

Scientific Assessment of Ozone Depletion 2002, accounted a fall in the ozone levels of 4% per decade in the middle latitudes [29]. As can be seen from the last column of Table **1**, the estimated decade depletion is in good agreement with the WMO in the case of the Northern Hemisphere. In fact, decade depletion in the order of 4% characterizes almost all the Northern Hemisphere, with the exception of the Tropic of Cancer and the Equator, where the decreases were respectively of 1.5 and 0.5%. However, in the case of the Southern Hemisphere, the decade depletion was higher than 4% from 59.5° S and increased with the latitude. Although the average ozone depletion of the middle latitudes is indeed in the order of 4%, it is evident that the trends in the selected 1°-wide latitude bands offer a greater precision. The depletion of 13.3% at 74.5° S and 15.9% at 89.5° S per decade describes the degree of severity in the case of the South Pole.

**Table 2. Depletion of Total Column Ozone, at 1°-Wide Latitude Bands, from 1978 to 1994**

| Latitude | TCO 1978 | Linear Fit | | TCO 1994 | Net Depletion | | Decade Depletion | |
|---|---|---|---|---|---|---|---|---|
| | DU | Slope | Standard Error | DU | DU | % | DU | % |
| 89.5° N | 352.4 | -1.8 | 0.2727 | 324.3 | 28.1 | 8.0 | 17.5 | 5.0 |
| 74.5° N | 367.6 | -2.4 | 0.2294 | 329.7 | 37.8 | 10.3 | 23.6 | 6.4 |
| 59.5° N | 364.7 | -1.8 | 0.1228 | 336.4 | 28.4 | 7.8 | 17.7 | 4.9 |
| 44.5° N | 345.9 | -1.7 | 0.0966 | 318.8 | 27.0 | 7.8 | 16.9 | 4.9 |
| 23.5° N | 283.2 | -0.4 | 0.0478 | 276.5 | 6.8 | 2.4 | 4.2 | 1.5 |
| Equator | 258.4 | -0.1 | 0.0292 | 256.4 | 2.1 | 0.8 | 1.3 | 0.5 |
| 23.5° S | 279.0 | -0.4 | 0.0378 | 272.2 | 6.9 | 2.5 | 4.3 | 1.5 |
| 44.5° S | 328.7 | -0.9 | 0.0808 | 313.8 | 14.9 | 4.5 | 9.3 | 2.8 |
| 59.5° S | 341.0 | -2.2 | 0.0673 | 305.8 | 35.2 | 10.3 | 22.0 | 6.5 |
| 74.5° S | 310.7 | -4.1 | 0.1458 | 245.4 | 65.3 | 21.0 | 40.8 | 13.1 |
| 89.5° S | 303.3 | -4.7 | 0.2367 | 227.3 | 75.9 | 25.0 | 47.5 | 15.6 |

Table **3** presents the changes in the TCO column for the slowdown period (1997–2013). Small decreases can be observed in seven of the twelve studied latitudes and particularly in all the Southern Hemisphere, with the exception of 74.5° S and 23.5 °S. Although it is clear that the changes are very small and therefore not very significant, this does not in any way indicate a complete stabilization, much less a recovery of the levels of the TCO. The most noticeable decreases in the TCO can be observed in both poles (at 89.5° N y S).

An apparently contradictory tendency appears in both polar regions: at 89.5° N, a decrease of 5.5 DU (1.7%) per decade is observed and in contrast, at 74.5° N, an increase of 5.5 DU (1.7%) is observed; similar to 89.5°, a decrease of 11.9 DU (4.1%) per decade is observed, whereas at 74.5° S, a 7.7 DU (3.1%) increase per decade is observed. Since this takes place in polar vortex regions, this could be related to a compensatory effect, given that the decrease at 89.5° N is almost of the same order of magnitude as the increase at 74.5° S. Regardless of any interpretation, it is interesting to observe that this double tendency appears in a systematic way, which points out that vortex dynamics follow specific mechanisms and have absorbed the changes of the past decades.

Another quality of Table **3** is the fact that it stresses the appearance of a decrease in the total column ozone at the Equator during the slowdown period. This decrease is more important than the one observed during the depletion period. During the depletion period (1987-1994), the decrease was only of 1.3 DU (0.5 %) per decade. In contrast, during the slowdown period (1997-2013) the decreases are of 3.5 DU (1.4%) per decade. That is to say that the depletion was multiplied by a 2.7 factor. This deserves special monitoring, for indeed a persistent decrease at the Equator should be taken seriously since it represents a large extension of the planet.

**Table 3. Changes of Total Column Ozone, at 1°-Wide Latitude Bands, from 1997 to 2013**

| Latitude | TCO 1996 | Linear Fit | | TCO 1994 | Net Depletion | | Decade Depletion | |
|---|---|---|---|---|---|---|---|---|
| | DU | Slope | Standard Error | DU | DU | % | DU | % |
| 89.5° N | 324.3 | -------- | -0.55433 | 314.9 | -9.4 | -2.9 | -5.5 | -1.7 |
| 74.5° N | 322.7 | 34.7 | 0.54974 | 332.1 | 9.3 | 2.9 | 5.5 | 1.7 |
| 59.5° N | 343.0 | 34.1 | 0.28869 | 347.9 | 4.9 | 1.4 | 2.9 | 0.8 |
| 44.5° N | 324.3 | 26.8 | 0.21162 | 327.9 | 3.6 | 1.1 | 2.1 | 0.7 |
| 23.5° N | 264.2 | 14.5 | 0.33759 | 269.9 | 5.7 | 2.2 | 3.4 | 1.3 |
| Equator | 259.6 | 5.6 | -0.35989 | 253.6 | -6.0 | -2.3 | -3.5 | -1.4 |
| 23.5° S | 265.3 | 15.2 | 0.05952 | 266.3 | 1.0 | 0.4 | 0.6 | 0.2 |
| 44.5° S | 307.1 | 33.7 | -0.24303 | 303.0 | -4.1 | -1.3 | -2.4 | -0.8 |
| 59.5° S | 307.1 | 14.1 | -0.24848 | 302.9 | -4.2 | -1.4 | -2.5 | -0.8 |
| 74.5° S | 244.3 | 49.0 | 0.4506 | 252.0 | 7.7 | 3.1 | 4.5 | 1.8 |
| 89.5° S | 263.2 | 60.5 | -0.6991 | 251.3 | -11.9 | -4.5 | -7.0 | -2.7 |

**Table 4. Dates of Occurrence of the Maxima and Minima of the Interannual Variations**

| Latitude | Maximum | Std. Dev. (Days) | Minimum | Std. Dev. (Days) | Semi-Periods |
|---|---|---|---|---|---|
| | Date | | Date | | Days |
| 74.5° N | March 19 | 22 | October 1 | 14 | - |
| 59.5° N | March 12 | 18 | October 13 | 23 | 215 |
| 44.5° N | March 15 | 20 | October 21 | 13 | 220 |
| 23.5° N | May 10 | 14 | December 16 | 68 | 220 |
| 0.5° N | September 2 | 37 | January 6 | 24 | 239 |
| 0.5° S | September 3 | 36 | January 7 | 27 | 239 |
| 23.5° S | October 10 | 11 | April 15 | 48 | 180 |
| 44.5° S | September 25 | 21 | March 31 | 18 | 178 |
| 59.5° S | October 21 | 33 | May 30 | 62 | 144 |
| 74.5° S | December 3 | 51 | September 28 | 6 | - |

## 3. INTER-ANNUAL VARIATIONS

### 3.1. Periodicity

Table **4** presents the dates of occurrence of the inter-annual maxima and minima TOC, the related standard deviation and the duration of these inter-annual periods or maxima-to-minima separation. In the Polar Regions, due to the polar night, neither the maxima nor the minima can be localized with precision. Therefore, the duration of these inter-annual periods has not been taken into account.

For the majority of the 1º-wide latitude bands studied, a standard deviation of the order of 20 days associated to the maxima is observed, which indicates a convenient regularity. However, in the cases of the Equator and of the Antarctic Polar vortex region, the standard deviation is greater than 30 days, which is interpreted as a reflection of fluctuations in the periodicity.

In the Northern Hemisphere the maxima appear in a simultaneous way at middle and high latitudes (between 45.5° and 74.5° N) in mid-March –by the vernal or spring equinox- with a standard deviation of the order of 20 days. In the Tropic of Cancer, the maxima appear on May 10$^{th}$, almost two months later, compared with 44.5° N. This highlights a 2-month delay with regard to middle and high latitudes.

Little is said in the literature regarding the position of the maxima.

According to Bojkov *et al.*, [9], Miller *et al.*, [38], and Jackman *et al.*, [39], the zonal mean ozone trend across the Northern Hemisphere reaches a maximum during February. Remarkably and in comparison to these authors, the selected 1º-wide latitude bands place the maxima one month later, and additionally show that there is a 2-month delay at 23.5° N, which should be the consequence of the competition between ozone transport mechanisms in the Northern Hemisphere.

The minima in the Northern Hemisphere appear in October, 7 months after the maxima, repeating a 2-month delay at 23.5° N, although with a standard deviation of 68 days. This indicates that low levels of the TCO are observed at this latitude during a period that extends from November to January, in which the minimum does not have a precise location.

On the other hand, in the Southern Hemisphere, maxima form first at 44.5° S in September –in the autumnal equinox- with a standard deviation of the order of 20 days. This is the latitude at which the most regular behavior seems to be observed. At 59.5° S the maxima appear a month later with a standard deviation of 33 days, forming slightly more than two months later at 74.5° S with a standard deviation of 51 days, whereas at 23.5° S the maximum appears almost two months later with a standard deviation of 11 days.

At 74.5° S, the great values of the standard deviations can be derived from the circulation effect of the Antarctic polar vortex, which avoids a latitudinal homogenization of the levels of the TCO.

The minima in the Southern Hemisphere occur with a delay that moves towards the South Pole at a rate of 31 days for each 10° of latitude. Additionally, at 23.5° S an important 48-day standard deviation is emphasized, which is certainly the result of the persistence of low levels of TCO.

In the case of the Southern Hemisphere, the duration of these inter-annual periods at 23.5° S and 44.5° S is precisely of 6 months, which represents a regular behavior. However, at 59.5° S it is slightly less than 5 months, which in conjunction with a standard deviation of the order of 60 days regarding the minima and of 33 days regarding the maxima, point out to an anomaly previously analyzed (§ 1.2).

## 4. UNSYSTEMATIC INTER-ANNUAL VARIATIONS

### 4.1. Northern Hemisphere

At 89.5º N, measurements began on April 2$^{nd}$ and end on September 10$^{th}$; covering only five months of the year. At 74.5º N measurements begin on February 22$^{nd}$, after the polar night and ended on October 20$^{th}$, covering eight months of the year. The maximum values of the inter-annual variations of the TCO appear practically at the onset of the polar day or at the onset of measurements, for 89.5° as well as for 74.5° N.

Graphics 5.1 and 5.2, which respectively correspond to 89.5º and 74.5º N latitudes, indicate a progressive decrease in the amplitude of the inter-annual variations, that reflects the ozone depletion. At 89.5º N in 1978, the amplitude was of the order of 270 DU and in 1990 the amplitude dropped to 200 DU. In a similar way, at 74.5º N in 1979 the amplitude was of the order of 240 DU and dropped to 190 DU in 1990.

In the Northern Hemisphere, depressions in the maximum values of the inter-annual variations are systematically observed in 1981, 1993, 1997, 2002 and 2008. The 1993 depression was the most severe and generalized. The 1981 depression can be the consequence of the volcanic activity of Mount St. Helen in Washington State, which occurred from March to May 1980. The 1993 depression can be attributed to the activity of the Pinatubo volcano which took place in June 1991 in the Philippines. This reflects that the effects upon the TCO can persist for up to two years, like in the case of the Pinatubo, which generated a decrease of 70 DU at 74.5° N, 60 DU at 59.5° N and 30 DU at 23.5° N. The 1997 and 1998 depressions can be associated to the minima in the solar activity.

### 4.2. The Equator

Unlike the rest of the studied latitudes, an annual periodicity does not occur at the Equator, where apparently arbitrary distortions and perturbations in the inter-annual variations are exhibited (Graphics 5.6). At best, indications of a biannual periodicity appear; however, this takes place in a very irregular and alternate way. The maxima occur in the middle of the year: sometimes on even years (1980, 1982, 1990, 1992, 2004, 2006, 2008, and 2010) and in other times in odd years (1979, 1981, 1985, 1987, 1989, 1991, 1993, 1997, 1999, 2001, 2003, and 2007). Nevertheless, in even years, the maxima are clearly higher (of the order of 10 to 15 DU higher) than those of odd years. The minima are observed at the beginning of each year, sometimes in even years (1982, 1984, 1992, 1994, 1998, and 2010) and in other times in odd years (1987, 2001, 2003, 2005, and 2007). Intercalations of years and even periods for which coincidences in the maxima and minima cannot be localized are observed. These can be considered as periods in which the periodicity is inverted. By taking these observations as an indication, in a first approach we could interpret that the perturbations in the inter-annual variations at the Equator result from the quasi-biennial oscillation (QBO) effect upon ozone transport.

### 4.3. The Southern Hemisphere

Although apparently imperceptible, Graphics 5.10 and 5.11 show significant changes in the inter-annual behavior at 74.5º and 89.5º S respectively. At first, the maxima as well as the minima represent sharp peaks, which point out abrupt changes in the behavior. Since 1983, the maxima are clear peaks; however, from 1984, the maxima present a sort of a repetition or perturbation; the shape of the inter-annual behavior progressively resembles the shape of the Greek letter μ. This indicates a reflux-like effect, which given the fact that it is observed in the maximum, represents a kind of a gain or compensation.

Additionally, surprising variations of the position of the annual maximum ozone values are observed. Between 1978 and 1982, the maximum appears around November 20th; between 1990 and 1993 this was observed between the 4th and the 16th of December; between 2002 and 2007, the maximum was again observed in late November; and between 2009 and 2011, it was observed again on November 20th. This, in conjunction with the appearance of maxima repetitions, can result from the dynamics of the polar vortex. However, an interesting feature is that the perturbations are relatively systematic and persistent.

Moreover, in 1987, 1989, 1992 and 2003, four recovery episodes are highlighted on both latitudes. Although it is clear that they do not represent an important recovery, these episodes have led to stabilization.

At 59.5° S, Graphic 5.9a shows a progressive decrease in the amplitude of the TCO inter-annual variations, whereas Graphic 5.9b remarkably shows disturbances in the periodicity, shape and amplitude of the inter-annual variations. In 1979, the amplitude was around 120 DU; whereas in 1988 it was around 60 DU. The 59.5° S latitude band is characterized by amplitude values between 60 and 70 DU, with exception of the years 1989, 1991, 2002 and 2008, in which the amplitude was between 80 and 100 DU. However those years of apparent recovery were observed also at 74.5º S and 89.5º S, therefore they do not give account of a latitudinal recovery. The installation of disturbances, consequently point out an alteration on the TCO behavior at this latitude.

At 44.5° S, Graphic 5.8 shows the progressive decrease in the minima of the TCO and in the amplitude of the inter-annual values. However, since 1997 the amplitude returns to normal. Indeed, not only the 1989 and 1992 episodes are repeated, but also three other recovery episodes appear in 2006, 2008, and 2009, which are apparently characteristic of these latitudes.

At 23.5° S, Graphic 5.7, the periodicity seems to be regular, although the appearance of a depression of the maxima in 1985 may be significant. Indeed, this depression, which is observed from 23.5° to 59.5°, seems to govern the behavior since 1985. At this latitude, two recovery episodes appear in 1990 and 1992.

## DISCUSSION AND CONCLUSIONS

TOMS data Version 8, from November 1978 to February 2013, have been used to analyze inter-annual ozone variations over nine selected 1º-wide latitude bands, as presented in this article. The selected 1º-wide latitude bands point out certain features and interesting changes in the TCO behavior, some of which involve apparently irreversible modifications:

A depletion of 13.3% per decade at 74.5° S and 15.9% per decade at 89.5° S, between 1878 and 1994, highlights the degree of severity of the depletion in the case of the South Pole. One of the consequences of the severe Antarctic ozone depletion is that, whereas in the Northern Hemisphere the values of the TCO increase with latitude and the highest values are located at 89.5° N, in the Southern Hemisphere, since 1980, the highest values are observed at 59.5° and 45.5° S.

Between 1997 and 2011, decreases in the TCO levels are observed in 7 of the 12 studied latitudes. Although it is clear that they do not seem very significant, they do not indicate a complete stabilization, much less a recovery of the TCO.

On the other hand, the selected 1º-wide latitude bands offer certain precisions and show interesting observations:

Little is said in the literature regarding the localization of the maxima. The selected 1º- wide latitude bands show important differences between both hemispheres. In the Northern Hemisphere the maximum values are found in March, and not in February, as had been by other authors reported, using zonal measurements; and at 23.5°, the maxima appear with a two-month delay with respect to middle and high latitudes. In the Southern Hemisphere the maxima appear first at 44.5° S in September. One month later, they appear at 59.5° S and two months later at 74.5° S, whereas at 23.5 ° S the maximum appears almost two months later.

The localization of the inter-annual maxima and minima and the associated standard deviation indicate fluctuations in the periodicity, whose explanation may be the aim of future studies.

At 59.5° S several factors point out an apparent anomaly: the maxima have a standard deviation of 33 days, the minima have a standard deviation of 60 days and the duration of the semi inter-annual period is slightly shorter than 5 months. In addition, a progressive reduction in the amplitude of the inter-annual variations is observed. Remarkably, by analyzing the statistical range or difference between the largest and the smallest daily ozone column values, it was possible to visualize the features of such perturbation. Graphically, at this latitude a shifted phase of the smallest inter-annual ozone column values is observed. This behavior becomes systematic from 1987 on. In a first approach, it could be considered that this perturbation is a boundary-layer-like effect due to the polar vortex circulation, which points out the localization and the amplification of the edge of the Antarctic polar vortex. Anyway, the emergence of such perturbation does not indicate a recovery in the levels of the TCO. In such case, the range magnitude can be seen as an indicator of the dynamics of ozone transport.

At the Equator, between 1997 and 2011, the 1º-wide latitude bands demonstrate a decrease in the total column ozone of 3.7 DU (1.4%) per decade, which is significantly more important than the 1.3 DU (0.5%) decrease that occurred during the 1987-1994 period. Such variation deserves special monitoring: indeed, a systematic decrease at the Equator should be important, since it represents a large extension of the planet.

Additionally, at the Equator arbitrary distortions and perturbations in the inter-annual variations are clearly seen. An annual periodicity does not take place. In any case, indications of a biannual periodicity appear, nevertheless, in a very irregular and alternate way. In 8 of the studied years, the maxima occur in even years, 12 occur in odd years, although the values are on the order of 10 to 15 DU lower than that of even years. Years during which periodicity is inverted are interspersed. It could be interpreted that the perturbations or distortions in the inter-annual variations at the Equator result from the quasi-biennial oscillation (QBO) effect upon ozone transport.

An interesting phenomenon is that in both polar regions an apparently contradictory tendency appears: at 89.5° N, 7.8 DU (-2.3%) decreases per decade are observed and in contrast, at 74.5° N, 6.5 DU (1.9%) increases are observed; and in a similar way, at 89.5° S, a 7.1 DU (-3%) decrease per decade is observed while at 74.5° S, a 5.1 DU (2.2%) increase per decade is observed. This double tendency occurring in both polar regions points out that the dynamics of both vortexes follows specific mechanisms.

This interesting observation results from the impact of volcanic eruptions, which produce mainly a depression in the amplitude and the maxima of the inter-annual values of the TCO. This persists for two years and is more severe during the second year.

This study aims, on the one hand, to stress the importance of latitude-based analyses, and on the other hand to make an attempt of massive use of the valuable amount of data successfully obtained by TOMS.

Further investigations taking advantage of the voluminous narrow-band data available from TOMS and OMI is indicated for a greater understanding of transport phenomena.

## CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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Declared none.

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