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Temporal Distribution of Total Column Ozone over Cochin—A Study Based on *in Situ* Measurements and ECMWF Reanalysis

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Abstract

The variability of Atmospheric ozone is very important to understand the radiative balance of the earth-atmospheric system and climate change. In order to understand the temporal variability of total column ozone (TCO) over the coastal station Cochin (9.95˚N, 76.27˚E), we used the ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis TCO and ground based measurements using Microtop II Sun Photometer (Ozonometer). The trend, seasonal changes and diurnal variation of ozone concentration have been studied in detail for the period 1981-2014. Cochin is a tropical coastal station with tropical monsoon climate and hence we examined the variability of TCO during pre-monsoon (March-May), monsoon (June-September) and post monsoon (October-December) seasons. Significant variations are noted in the TCO for the different seasons during the period of study. Based on the measurements and analysis, it is observed that TCO is maximum during monsoon and minimum during pre- and post-monsoon. We computed the TCO climatology for pre-monsoon (262.0 DU), monsoon (275 DU) and post-monsoon (253 DU) seasons and found that TCO shows a decadal trend (solar cycle). During monsoon season TCO varies with an increase of approximately 14 DU from the pre-monsoon value and a decrease of 22 DU from the post-monsoon value. The increase in TCO concentration during monsoon may be attributed to the monsoonal wind circulations and organized convection. The validation of ECMWF TCO with *in situ* measurements using Microtop II Ozonometer has been carried out for the year 2015 and found that the values are positively correlated. The diurnal variability of TCO was examined for vernal and autumnal equinox days and noticed the change in variability.

Keywords

Total Column Ozone (TCO), Solar Cycle, Seasonal Variability, Quasi-Biennial Oscillation

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1. Introduction

The study of temporal distribution of ozone is very important for understanding the atmospheric chemistry and thereby its impact on environment, weather and climate. The whole stratospheric chemistry is controlled by the ozone layer and it plays a key role in maintaining the earth-atmosphere radiative equilibrium. The maximum concentration of ozone is found in the stratosphere (90%), and the remaining 10% in the troposphere. Stratospheric ozone is essential for sustaining life on earth, whereas tropospheric ozone is a greenhouse gas [1] [2]. The net ozone production in a pure oxygen atmosphere is determined by the Chapman cycle. Tropospheric ozone is mainly produced due to the chemical reactions of pollutants and it is harmful to health. Hence the ozone which is in the stratosphere is termed as good ozone and that in the troposphere is known as bad ozone. Total column ozone at any location on the globe is found by measuring all the ozone in the atmosphere directly above that location. Total ozone present in the stratosphere and troposphere is expressed in Dobson Unit (DU). Higher values (~300 DU - 500 DU) of ozone are present in the polar stratosphere and lower values (~250 DU - 280 DU) in the tropical stratosphere. Majority of the ozone molecules are produced in the tropical upper stratospheric region where the exposure of sunlight is high. It is widely appreciated that the dynamics of the stratosphere is interrelated to a good extent with that of the troposphere [3] [4]. Thus transport and wind motion in the stratosphere are interconnected with that of the troposphere and thus play crucial role in ozone distribution over the tropics. Even though ozone is produced in the tropical upper stratosphere, it is being transported to higher latitudes and poles by Brewer Dobson Circulation.

The spatial and temporal distributions of ozone are greatly controlled by atmospheric circulation and this interaction leads to the seasonal-to-inter annual variability of TCO. From previous studies it is found that many factors affect the variability of total column ozone. Inter-annual variability of TCO depends on the production, distribution and transportation of ozone from the place where it is produced. The Quasi-Biennial oscillation (QBO) is the phenomenon in which tropical winds in the lower stratosphere switch from easterly to westerly within a period of two years. Thus the QBO plays a dominant role in the inter-annual variability of tropical lower stratospheric temperature, which is directly linked with ozone concentration and distribution [5]-[8]. The distribution of tracer gas such as ozone [5], meteorological parameter such as rainfall amount [7] and frequency of tropical cyclones are also linked with the phases of Quasi-Biennial oscillations (QBO). The QBO in lower stratosphere causes 1% - 2% of variation in TCO over the tropics. The changes in solar ultraviolet spectral irradiance directly modify the production of ozone in the upper stratosphere [9] and hence it is reasonable to expect a solar cycle in total column ozone. Solar constant shows a small variation (0.1%), which is more significant in the ultraviolet spectrum than in the visible. Since ozone is created and destroyed by solar UV radiation, there is a correlation of ozone concentration with 11-year sunspot cycles. Studies also show that solar cycle is a factor influencing the amount of TCO in a region [9] and 2% - 4% of TCO variation is due to sunspot cycle [10]. Several studies revealed that natural oscillation of the tropical atmosphere also influences ozone in mid-latitudes [11]-[13] and leads to a differing quantity of transport of stratospheric ozone from the tropical source region to mid-latitudes. The global satellite ozone records since 1979 show evidence for decadal oscillations of total ozone with maximum amplitude (~2%) at low latitudes [14]. Many research reports are available on the studies of seasonal cycles [15], trends [16], inter-annual and intra-seasonal variability of tropical ozone [15] [17].

Although several studies have been carried out on the tropical ozone distribution and variation [13] [18] [19], more detailed study is required to understand the ozone climate interactions over the tropics. *In-situ* ozone data can resolve features in tropical ozone variability related to climate and dynamics, e.g. the Quasi-Biennial Oscillation (QBO) and El Ninõ-Southern Oscillation (ENSO). After the discovery of ozone hole over Antarctic, several studies have been carried out to find the long-term trend of ozone in different places. Most of the studies were based on mid and high latitude regions. Long-term variability of atmospheric ozone and regional variation of tropical total column ozone over Indian stations are reported by many authors [5] [20]-[26]. From 1970, observations show that the amount of total ozone on earth's atmosphere is decreasing due to the catalytic destruction of ozone by atomic halogens. Reduction of ozone depleting substances in the atmosphere was done through Montreal protocol in 1987. Few recent studies show that currently ozone in the atmosphere is in recovering stage. Using the state-of-the-art chemistry-climate models, it is predicted that the annual mean extra-tropical total ozone column will recover to pre-industrial period (1980) values by the end of 21st century [27] [28]. In the tropics, however, the models show no return of the ozone column value to levels existed before 1980 [29]. This different evolution is due to a significant decrease of the partial ozone column in the lower stratosphere [27], which is explained by an increase in tropical upwelling related to increasing concentrations of long-lived GHGs and a concomitant increase in the sea surface temperatures [30]. In the context of climate change and seal level rise, the present observational study of total column ozone is quite relevant to understand the tropical ozone variability with different seasons and its trend over this region. Modeling study of ozone-climate interaction with suitable chemistry climate models (CCM) will give a better understanding of regional climate change and extreme weather events.

2. Materials and Methods

In this study we used the total column ozone from ECMWF reanalysis and *in situ* measurements using a hand held Microtop II Ozonometer instrument (sun photometer) designed and manufactured by Solar Light Co, Inc., USA.

2.1. About the Location

Cochin is a major port city on the south west coast of Arabian Sea and is part of Ernakulam district in the state of Kerala. Cochin is the second largest city on the western coast of India (after Mumbai), with a total metropolitan population of 2.1 million. Most areas of Cochin lie at sea level, with a coastline of 48 km. Under the Köppen climate classification, Cochin features a tropical monsoon climate (Am). Cochin's proximity to the equator along with its coastal location results in little seasonal temperature variation, with moderate to high levels of humidity. Annual temperature ranges between 23˚C and 31˚C with the record high being 36.5˚C, and record low 16.3˚C. From June to September, the south-west monsoon brings in heavy rains as Cochin lies on the windward side of the Western Ghats. From October to December, Cochin receives lighter (yet significant) rain from the northeast monsoon, as it lies on the leeward side. Average annual rainfall is 2978.0 mm with an annual average of 125 rainy days. The station has distinct weather conditions during various seasons of the year like pre-monsoon (March-May), monsoon (June-August) post-monsoon (September-November) and winter (December-February), with an annual maximum solar radiation received during pre-monsoon followed by post-monsoon and winter. Cochin is home for many industries like FACT (Fertilizers And Chemicals Travancore), Refineries etc. which highly pollute the environment.

2.2. About Data and Microtop II Ozonometer

In the present study we tried to examine the inter-annual, seasonal and diurnal variability of TCO over Cochin with ground observations and ECMWF reanalysis. Microtops II Ozonometer is capable of measuring the total ozone column and optionally the water vapor column as well as aerosol optical thickness. The photometer measures the direct solar radiation at five wavelengths *viz* 300, 305.5, 312.5, 940 and 1020 nm using narrow band interference filters. A self-contained microcomputer automatically calculates the solar zenith angle, total column ozone, water vapor and aerosol optical depth. The total column ozone is automatically calculated based on measurements at wavelengths 300, 305.5, 312.5 nm, at the site's latitude and longitude, universal time, altitude and pressure. The measurements at 940 and 1020 nm are used for the calculation of water vapor column and aerosol optical depth. The field of view of each of the optical channels is 2.5˚. The instrument stores 800 scans of all 5 channels, the time and date, the geographic coordinates, the temperature inside the instrument and the barometric pressure. The basic operating principle of the Microtops II Ozonometer is derived from the fact that ozone absorbs shorter wavelengths more effectively than longer wavelengths. The ratio of the intensity of direct sunlight at two wavelengths within the range of 300 - 320 nm is related to the total abundance of ozone in a column through the atmosphere. The amount of ozone between the observer and the sun is proportional to the ratio of two wavelengths of the sun's ultraviolet radiation. The complete description of the instrument and measurement technique can be found elsewhere [31].

Daily total column ozone from the ERA-Interim global atmospheric reanalysis from 1981 to 2014 [http://www.ecmwf.int/en/research/climate-reanalysis/era-interim] and Microtops II Ozonometer measurements for the year 2015 were used to calculate the trend, seasonal and diurnal variation at Cochin (9.95˚N 76.27˚E). In order to calculate seasonal anomaly, TCO for pre monsoon, monsoon and post monsoon period has been averaged separately for 34 years (1981-2014). An hourly measurement of TCO during the equinoxes days in March and September, 2015 (Vernal and Autumnal equinox days) were used to study the diurnal variation. Since the Microtops II Ozonometer is a sun targeted instrument, the measurements were done from 08.30 to 16.30 hours.

Cochin is a tropical coastal station under the threat of sea level rise, global warming and climate change. Moreover this region is convectively very active, most of the time the location is cloudy in the afternoon hours, which does not permit the observations using Microtops II Ozonometer. Pertaining to limited observational sites in the west-coast of southern India, the present study of total column ozone at Cochin is vital in generating useful information on a regional basis for the development of an overall database.

3. Results and Discussions

Present study discusses the temporal variability of ozone over the tropical coastal station Cochin, using *in situ* measurements. Even though such works have already been reported from northern parts of India, this is the first report of this kind from southern part of India. As mentioned earlier, the study location is meteorologically very important with its proximity to the equator and different weather conditions during different seasons. Cochin is also considered as the gate way of Indian summer monsoon (June-September). Recently there observed considerable variations in the extreme conditions of rainfall and the date of onset from the long term average. This clearly indicates the regional climate change. Moreover for the last few years many sunburn cases were reported from different pockets of Cochin, indicating the increase in UVB radiation reaching the surface of the earth during March-April month. This happened because of the low ozone concentration over this location. Hence the present study contributes more to the proper understanding of the atmospheric ozone variability and associated climate change.

3.1. Climatology and Trend of TCO

Figure 1 shows the climatological value of total column ozone over Cochin for the period 1981-2014. Total column ozone varies with seasons in this particular location with high concentration during the monsoon period (June-September). The annual average of TCO at Cochin is 261 DU with a variation of 36 DU between the maximum and minimum. During monsoon season TCO vary with an increase of approximately 14 DU from the pre monsoon value and a decrease of 22 DU from the post monsoon value. The lowest value of 241.77 DU is observed in the months of December-January and the highest values are observed in the monsoon period (June, July and August) with an approximate value of 277 DU. The climatology of TCO for pre-monsoon (262.22 DU), monsoon (275.75 DU) and post monsoon (253.39 DU) were also calculated.

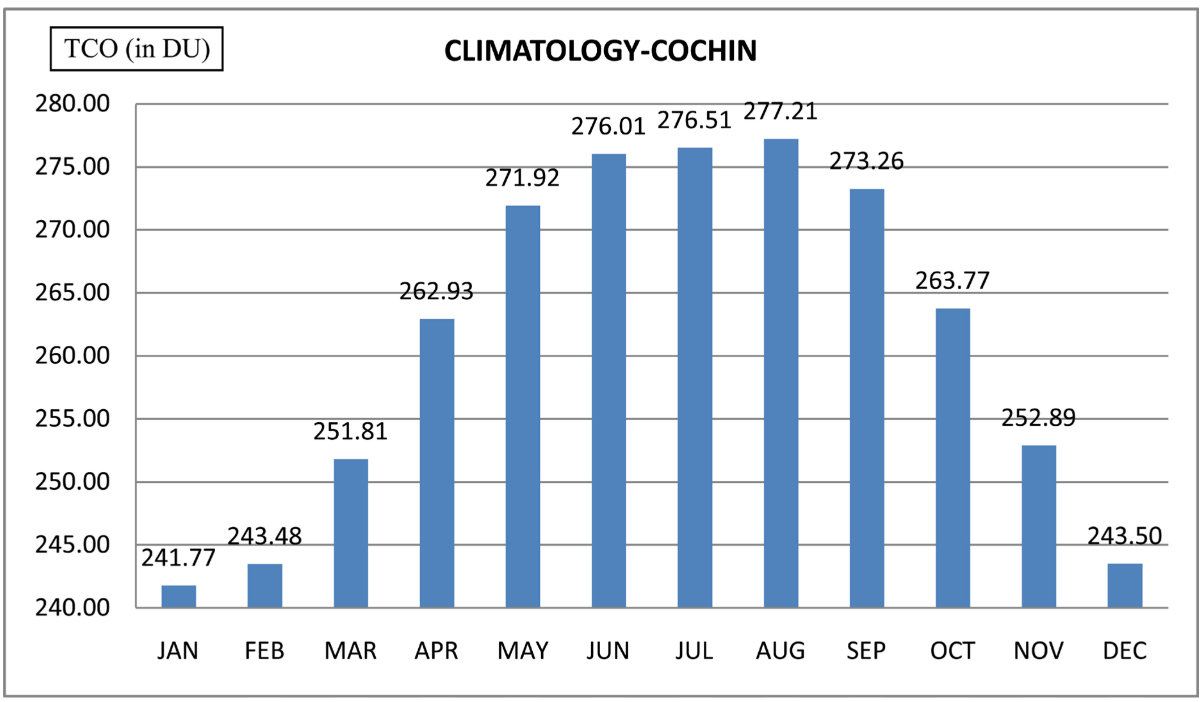

Figure 1. Climatology of TCO (in Dobson unit) over Cochin (1981-2014).

Figure 2 shows the trend of TCO over the tropical station Cochin for the period 1981-2014. It is very evident that there is a positive trend in TCO with a standard deviation of 5.07 DU and for higher latitude it is quite high. During the period of study TCO values fluctuates between 271.44 DU (1999) and 251.3 DU (2005) with a difference of 20 DU. For tropics ozone variability is low compared to poles and ozone trend is maximum over the pole compared to tropical latitudes. During every spring there occurs drastic reduction in ozone over the poles and next year it recovers. This phenomenon as we call ozone hole, occur due to the catalytic destruction of ozone over the poles because of the peculiar weather conditions prevailed during the winter stratosphere. The trends in ground level ozone in the urban and rural areas of industrialized regions are strongly linked to the changes in anthropogenic emissions of ozone precursors [32]. Hence to calculate the trend of TCO variability we have to consider the ozone destruction and production due to anthropogenic emissions. So an integrated approach is required to calculate the trend of column ozone which is beyond the scope of this study.

3.2. Seasonal Variation of TCO with Solar Cycle

Figure 3 shows the total ozone anomaly for pre monsoon (March-May), monsoon (June-September) and post monsoon (October-December) period along with sunspot number (sunspot activity). We computed the seasonal anomaly of TCO by subtracting the climatology (34 years) from the seasonal average of the individual years for the period. The global satellite ozone records since 1979 show evidence for decadal oscillations of total ozone with maximum amplitude (~2%) at low latitudes [14]. Many researchers have studied the seasonal cycles [15], trends [16] and inter-annual variability of tropical ozone [15]. Most of the year's TCO varies in a similar fashion for all the three seasons but few exceptions are noted. Calculation of standard deviation of TCO variability for all months separately and found that during monsoon season standard deviation is little higher than pre and post monsoon season. A decadal type of variability is observed and the anomaly values of ozone are well correlated with sunspot maxima and minima during the period. It shows that ozone concentration and its variability are linked with the solar maximum and minimum. The concentration of ozone is high during the maximum sunspot years and low during the minimum sunspot years of the solar cycle.

3.3. Validation of ECMWF TCO with Microtop II Ozonometer Measurements

Figure 4 shows the comparison of real time TCO measurements using Microtop II Ozonometer for the year 2015 with the ECMWF reanalysis climatology. The ECMWF reanalysis follow the similar trend of variability in TCO with Microtops measurements, but higher values are observed for the *in situ* measurements. In January and February, when the sun is in the southern hemisphere the TCO measured *in situ* is found to be less compared to other months. The effective solar radiation reaching the northern hemisphere is less during the southern summer,

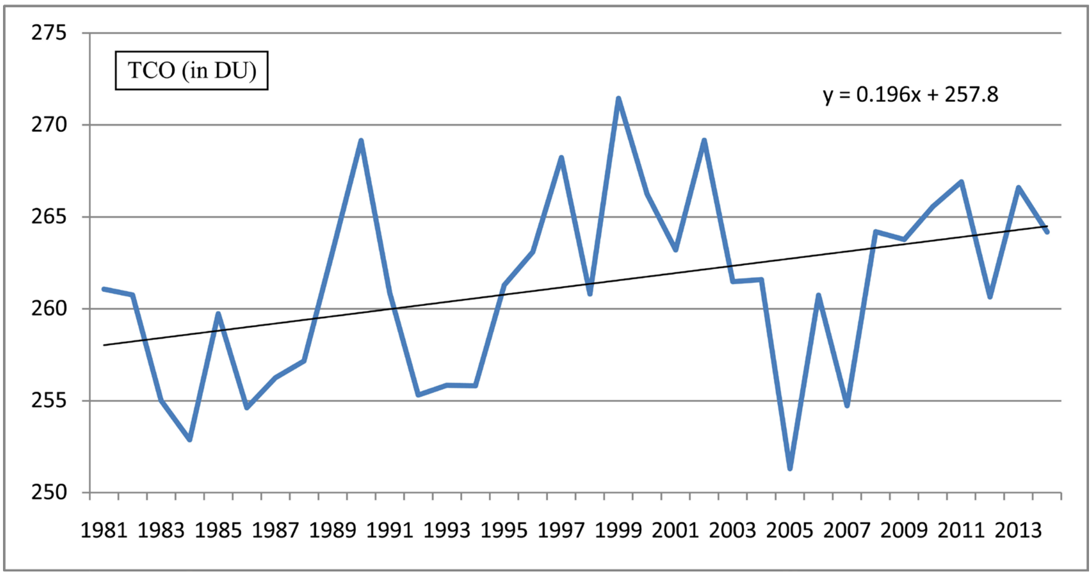

Figure 2. TCO (in DU) trend over Cochin during the period 1981 to 2014.

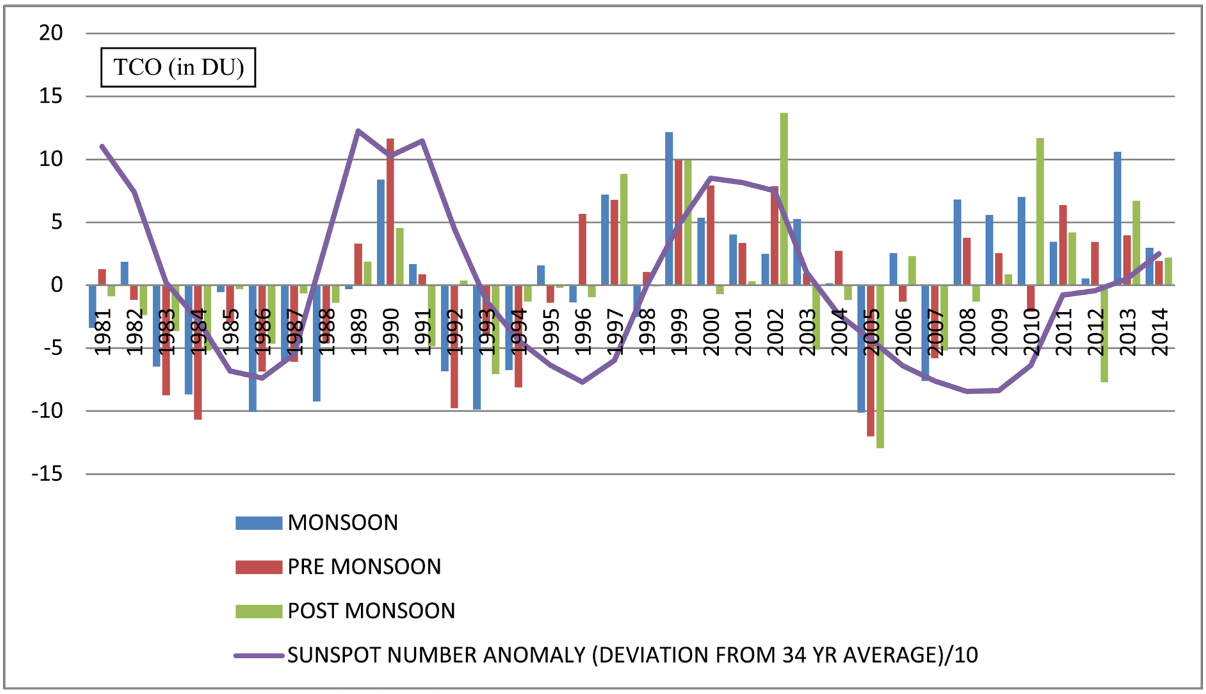

Figure 3. Total column ozone anomaly (in DU) for the monsoon, pre and post monsoon seasons over Cochin for the period 1981-2014.

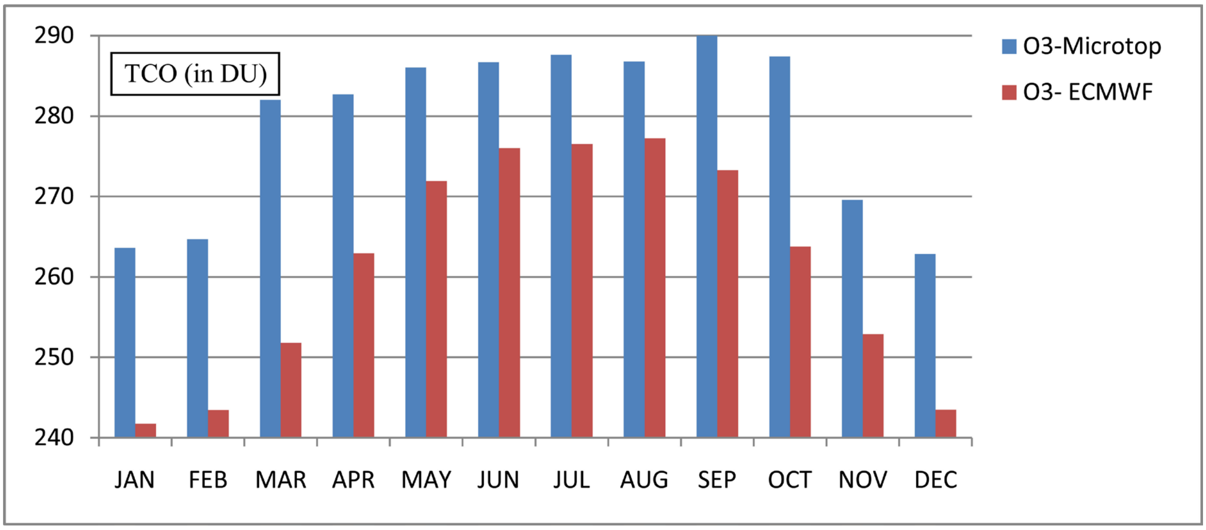

Figure 4. Comparison of TCO (in DU units) measured over Cochin using Microtop II Ozonometer for the year 2015 with ECMWF reanalysis.

which reduces the ozone production by the oxygen photolysis according to the Chapman reaction. Monthly average of TCO is calculated by considering the available days of *in situ* measurements for that month (~20 days) and the data gap is filled with linear interpolation technique. Monthly variations of TCO are well represented with ground measurements for the year 2015. During pre and post monsoon seasons a difference of 20 DU and in monsoon period a difference of 10 DU are observed in the total column ozone between Microtops measurements and ECMWF reanalysis. Seasonal variability of TCO from ECMWF reanalysis is verified with Microtops measurements. Even though there are minor variation in TCO between Microtops and ECMWF, the pattern of monthly variations is found to be the same. The ECMWF reanalysis is a simulated (Chemistry Climate Model output) value using data obtained from different measurements such satellite, balloon and ground based observations over the globe. However this data set well represents the tropical ozone variability. Hence the comparison of measured and reanalysis TCOs confirm that ECMWF reanalysis can be used effectively for understanding the temporal variability of tropical ozone and ozone-climate interactions.

3.4. Diurnal Variability of TCO during Vernal and Autumnal Equinoxes

The diurnal variability of TCO over Cochin during two equinoxes days were examined for the year 2015. To study the diurnal variation of TCO, measurements were taken from 8:30 am to 4:30 pm in both the days. The availability of solar radiation is very important for the production of ozone in the upper stratosphere by photolysis of oxygen molecules according to Chapman reaction. Photolysis rate depends on altitude, latitude, season and time of the day. Cochin is a coastal city in the tropical region and at noon hours, the sun is almost overhead enhancing the photochemical production of ozone. The changes in the position of sun with seasons affects the ozone production considerably. **Figure 5** & **Figure 6** show the TCO variability over Cochin during vernal

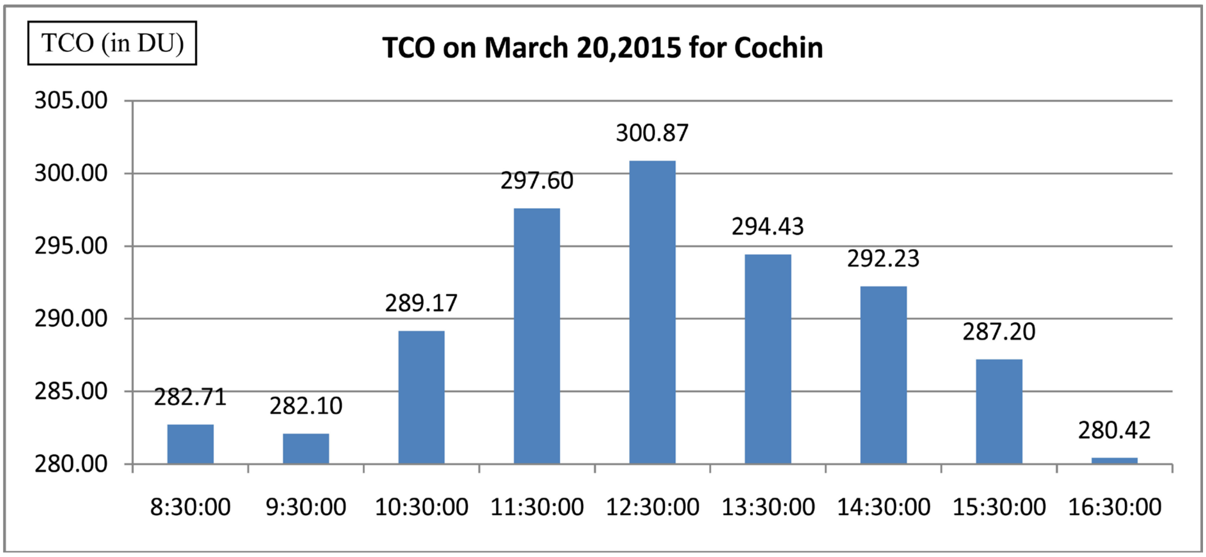

Figure 5. Microtop II Ozonometer measurements of TCO (in DU) for vernal equinox on 20/03/2015.

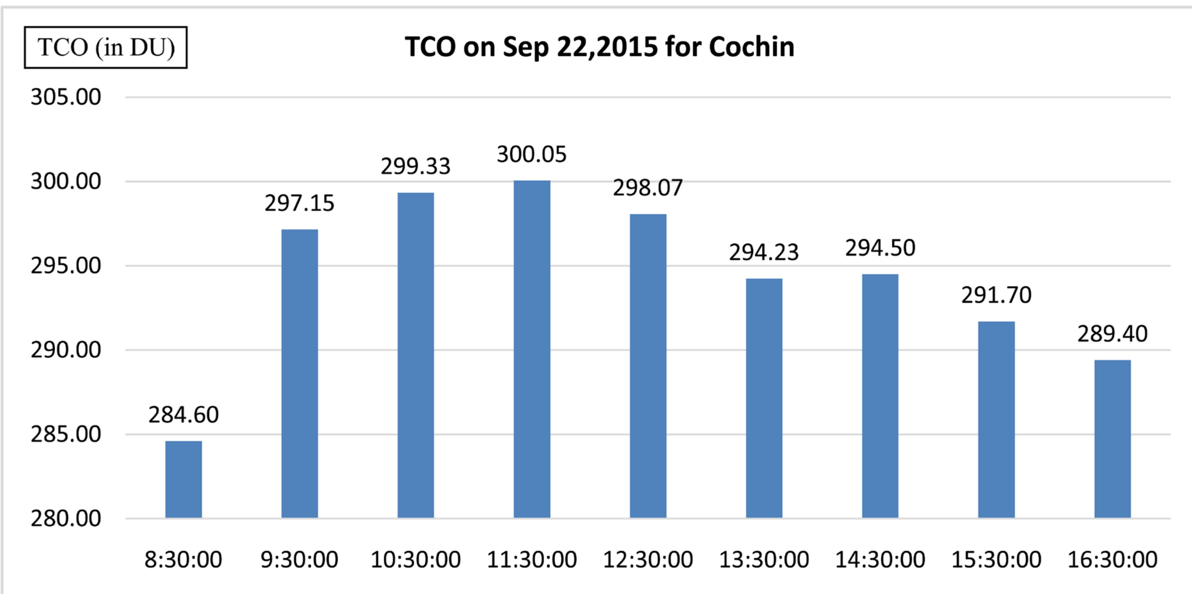

Figure 6. Microtop II Ozonometer measurements of TCO (in DU) for autumnal equinox on (22/09/2015).

equinox (March 20, 2015) and autumnal equinox (September 22, 2015) respectively. The difference in the patterns can be attributed to the difference in the intensity of solar radiation and hence the ozone production. It is noted that the vernal equinox diurnal pattern and the climatological pattern (**Figure 1**) of TCO variability are the same. During vernal equinox the diurnal range is about 20 DU (7% variation) and that during autumnal equinox is 16 DU (5.4% variation). Since the diurnal equinox patterns are measured only for the year 2015, a conclusion regarding the behavior of the pattern could not be explained, which is a limitation of the present study.

4. Conclusion

The temporal variability of total atmospheric column ozone over Cochin is well explored in this study. Total ozone concentration is maximum during the monsoon period and it can be attributed to the enhancement of photo chemical ozone production due to the availability of solar radiation over this region (Northern Summer). The ozone variability calculated using ECMWF reanalysis is in good agreement with Microtop II Ozonometer observations. For the 34-year climatology the annual average of TCO is 261 DU with an annual range of 36 DU between maximum and minimum. During monsoon season TCO varies with an increase of approximately 14 DU from the pre monsoon value and a decrease of 22 DU from the post monsoon value. Total column ozone shows the decadal variability in tune with the solar maximum (TCO maximum years) and minimum (TCO minimum years) cycles. The validation of ECMWF TCO with Microtop II Ozonometer measurements shows a good agreement in representing tropical ozone variability. Hence the ECMWF reanalysis TCO can be used for climate studies to understand the tropical ozone variability and associated changes in climate due to ozone forcing. The diurnal pattern of TCO variability over Cochin is different for the two equinoxes days and vernal equinox pattern is similar to that of climatology pattern. The difference in diurnal pattern of both equinoxes could not be explained due to the lack of measurements and it is a limitation of the present study on diurnal variability. Cochin is a coastal urban city in the west coast of southern India vulnerable to sea level rise and hazards of climate change. Hence this sort of study will enrich our knowledge about regional climate change and extreme weather events in the context of climate change due to atmospheric ozone forcing.

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