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Vertical Wave Number Spectra of Ozone and Temperature Fluctuations in the Troposphere and Lower Stratosphere over Costa Rica (10° N, 83.4°W) a Tropical Station

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Abstract: We examined the characteristics of ozone and temperature data over the tropical station Costa Rica during the period of 2012 – 2017, downloaded from Southern Hemisphere ADditional OZonsondes (SHADOZ) site. Our analysis reveals important variations of ozone and temperature structures in troposphere and stratosphere. An interannual variability of ozone fluctuations was observed in the measured wave activity and seasonal variation has also been observed with higher value in Summer Season (June July August). Vertical profiles of ozone and temperature have been used to examine the characteristics of wave number spectra of their fluctuations thereby assess the possible roles of gravity wave activity and to determine dominant vertical wavelengths of ozone spectra. Average slopes of wave number spectra are found to be –2.76 (–2.46) in the troposphere and –2.53 (–2.61) in the lower stratosphere for ozone (temperature) in summer. The corresponding values for winter are found to be –2.6 (–2.61) and –2.61 (–2.62) in the troposphere and stratosphere. Results indicate that there is consistency of the observed spectral slopes in the power law region which seems to be dominated by gravity wave activity. The energy density of ozone and temperature seems to be more in stratosphere when compared with troposphere. Mean vertical wave number spectra reveal dominant vertical wavelength 3.3 km in both troposphere and stratosphere.

Keywords: Gravity Waves, Ozonesonde, Wave Number Spectra, Stratosphere, Troposphere

I. INTRODUCTION

Ozone observations in troposphere and lower stratosphere over tropics show variability on a range of time scales, including an annual cycle and interannual variations. Mesoscale wind, temperature, and density fluctuations are conveniently described in terms of their power spectra versus frequency and horizontal, vertical wave number. In the early 1980s, [1] showed the power spectra of wind fluctuations from the inertial period to the Brunt – Väisalä period (5 to 10 minutes in the troposphere and lower stratosphere) and also reported that the corresponding ranges of horizontal and vertical wavelengths can be described in terms of universal spectrum of internal gravity waves. The frequency and wave number spectra are supposed to have almost constant shape throughout the lower and middle atmosphere with logarithmic slopes of ~ –5/3 and ~ –3 respectively. Subsequently, various gravity wave saturation models have been developed ([2], [3]–[5]).

Number of authors has examined the character of the atmospheric spectra using a variety of data. Vertical wavenumber spectra of wind, temperature, and density fluctuations were obtained from MST radar observation [6], lidar measurement [7], and rocket [8]. These observational studies generally appeared to be consistent with the saturation model.

Gravity waves generated in the Earth's lower atmosphere grow in amplitude with height, become convectively and/or dynamically unstable, break in the stratosphere and mesosphere. Under such conditions the amplitude growth stops and the waves are considered "saturated" [9]. Theory predicts that the superposition of saturated gravity waves over a broad – spectrum result in the vertical wave number spectrum of gravity wave energy.

A key finding of many experimental studies on wave number and frequency power spectra of atmospheric gravity wave motions was that, their spectral characteristics are widely uniform in frequency and wave number, despite different generation sources, meteorological conditions, and locations of observations.

On the other hand, Ozone is an important trace gas in both the stratosphere and troposphere. In the former region it filters harmful solar UV rays, while in the latter region it serves as a cleaning agent. It adds to the greenhouse effect in the troposphere and contributes to global warming [10]. Reference [11] showed that the ozone also contributes to the warming of the atmosphere. Ozone in the troposphere has severe effects on the human health, plants and marine lives. Vertical distribution of ozone provides information regarding the chemistry and dynamics with its distribution. Observations show that ozone variation has strong dependence on location. In recent decades, increasing ozone mixing ratios have been observed both in high and low latitudes ([12], [13]).

The Costa Rica is unique for unpredictable climate. The weather is tropical, as it is very close to equator. In the above site, the climate is characterized by long winters and short, cool to mild summers and it can be considered as boreal in northern hemisphere. Based on this climate is divided two seasons: winter (November – March) and summer (June – July – August) [14].

In this paper, we investigated the characteristics of ozone and temperature using high resolution ozonesonde data for a tropical site San José, Costa Rica. Section II of this paper gives the details of related work on the present study. Section III describes the data details briefly and discusses the methodology. Results are discussed in section IV and finally conclusions are presented in section V.

II. RELATED WORK

A variety of techniques includes balloon, aircraft, lidar, rocket and satellite observations ([15]–[17]) are used to get large quantity of atmospheric ozone data due to the importance of it in terrestrial climate and ecosystem. The distribution of ozone in the tropics is inhomogeneous with latitude and longitudinal gradients. Seasonal variations of ozone have been observed ([18], [19]) and its inter–annual variability (IAV) in stratospheric region is reported to impact the IAV of upper troposphere [20]. The atmospheric ozone data provide another potentially important source of information about power spectra. Reference [21] studied the characteristics of vertical wave number spectra of ozone fluctuations and stated that they are primarily due to atmospheric gravity waves.

In lines of above research work, we examined the characteristics of ozone and temperature by studying the inter–annual variation of their fluctuations. Further, the seasonal variation of ozone mixing ratio and their fluctuations are also studied. We also reported vertical wave number spectra of ozone and temperature in the troposphere and stratosphere in two different seasons (winter and summer) to assess the possible role of gravity waves in ozone and temperature fluctuations and determined the dominant vertical wavelengths of corresponding spectra in both troposphere and stratosphere.

III. METHODOLOGY

Open source ozone data from Southern Hemisphere ADditional OZonsondes (SHADOZ) was used in the present study. The SHADOZ Network was initiated in 1998 as an international partnership with both technological and scientific goals related to the collection of ozone profiles in the troposphere up to the mid – stratosphere [22]. Ozonesondes have been launched at numerous sites around the world for many decades. The measurements in this network are made by electrochemical concentration cell sondes that are calibrated before launch and subject to consistent procedures. More than 5000 sets of ozone and pressure–temperature–humidity profiles are available at above site. Balloon – borne ozonesondes are launched regularly (once a week) from the stations in SHADOZ network. The high resolution (in height) data can be archived from the website http://tropo.gsfe.nasa.gov/shadoz/archive. html.

Ozone Mixing Ratio (OMR) and temperature data, from year 2012 to 2017 over a tropical station Costa Rica (10° N, 83.4° W) have been downloaded from the above site. Data gaps were filled with cubic spline interpolation which has rendered continuous data with time to carry out for further studies. Lot of efforts from many scientists and technicians have resulted in developing standard methods to measure ozone concentration which are employed in SHADOZ stations and the report is available at http://www.wmo.int/pages/prog/arep/gaw/documents/(GAW_201.pdf).

Initially, weekly ozone and temperature profiles are averaged month–wise for the above mentioned station and period. The resulting monthly profiles are further averaged over two seasons: Winter (November – March) and Summer (June, July and August) to study the seasonal variations of ozone and temperature in upper troposphere and lower stratosphere (UT/LS) region and also to examine the characteristics of wave number spectra of ozone and temperature fluctuations thereby assess the possible roles of gravity wave field in fluctuations, and to determine dominant vertical wavelengths of ozone spectra. To increase the sample size, we extended the winter domain to include measurements made in November and March [14]. We have chosen the data of Costa Rica in our studies, since the data gaps are less in number during the period of observation (2012 – 2017).

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IV. RESULTS AND DISCUSSION

The high resolution (~4 to 10 m) data of ozone and temperature, arranged in ascending order and linearly interpolated to obtain the height profiles with uniform vertical resolution of 100m, is used to observe the variations of ozone and temperature in UT/LS region from the data set of Costa Rica for two seasons' winter and summer. Fig. 1 shows mean profiles of temperature and ozone mixing ratio for the two seasons, along with corresponding standard error. The Profiles in above figure were produced by averaging the available data over the period of six years from 2012 to 2017. Cold point tropopause (CPT) and ozone tropopause (O_3T) as defined [O_3] = 90ppbv [23] are denoted by red square and red diamond on temperature and ozone profiles respectively.

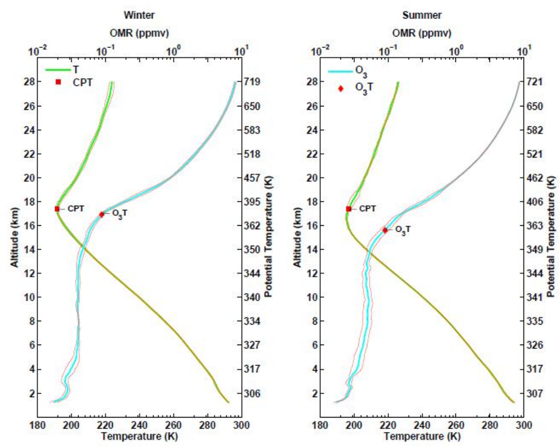

Fig. 1 Height profiles of mean temperature and ozone along with standard error (red) for winter (left panel) and summer (right panel) seasons.Filled square and diamond indicates Cold point tropopause and ozone tropopause, respectively.

Table 1 summarizes the mean height of cold point tropopause and ozone tropopause in winter and summer seasons. Temperature, potential temperature and ozone values corresponding to CPT and ozone tropopause are also shown in the table.

TABLE I
MEAN HEIGHT OF COLD POINT TROPOPAUSE AND OZONE TROPOPAUSE IN WINTER AND SUMMER SEASONS

Parameter	Seasons	CPT	O_3T
Altitude (km)	Winter	17.4	16.9
	Summer	16.6	15.6
Temperature (K)	Winter	191.6	192.3
	Summer	195.5	197.6
Potential Temperature (K)	Winter	379.8	371.7
	Summer	372.9	358.4
Ozone (ppmv)	Winter	118.7	–
	Summer	131.3	–

Fig. 1 reveals various observations in the structure of the UT/LS region for both the seasons. Firstly, the temperature range is relatively constant at higher heights in both seasons. To a very good approximation, the cold point tropopause (CPT) in both seasons was located at same height (~ 17 km). These values are well within the standard deviation of the global average values in the tropical tropopause climatology [24]. Another striking feature of the temperature is the sharp increase of temperature variability above the 355 K potential temperature level in summer, shown in Fig. 1.This rapid increase in variance is substantially larger than the growth rate $e^{Z/2H}$ due to decreasing density [25] and is consistent with upward propagation of wave energy from the troposphere and into the lower stratosphere [26].

The mean profile of ozone in the troposphere is almost remains constant with altitude having values between 0.05 ppmv to 0.055 ppmv. In UT/LS region, the ozone mixed ratio is found to be higher in summer than winter. In addition to variability due to adiabatic motion, it is possible that horizontal transport from middle latitudes may be contributing to the increased ozone variance as well affecting the steepness of vertical gradient mean ozone profile ([27], [26]).

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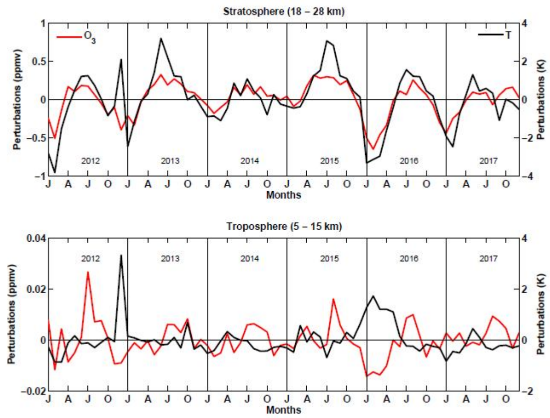
Another noticeable difference between summer and winter mean profile is in ozone tropopause. It is found to be higher in winter than in summer and strong vertical ozone gradient is observed in winter particularly below tropopause. Similar results have been reported from the same site earlier [14]. The analysis submits that ozone variability in the UT/LS is coupled to temperature variability above the 350 – 355 K potential temperature level and the vertical motions driving the latter.

The influence of atmospheric oscillations on ozone and temperature are investigated by detrending (mean removed) the time series of monthly means in the two regions: troposphere (5 – 15 km) and stratosphere (18 – 28 km) as illustrated in Fig. 2.



Fig, 2 Time series of monthly mean ozone and temperature fluctuations in troposphere (5 – 15 km) and stratosphere (18 – 28 km)

The Ozone and temperature fluctuations show a clear annual variation in stratosphere. But in troposphere, a mixed of annual and semi-annual variation was observed. A good correlation of 0.82 was noticed in the variation of ozone with temperature in stratosphere and it is anti – correlated (–0.36) in troposphere. Comparatively ozone fluctuations are twenty five times higher in stratosphere when compared with tropospheric fluctuations. The fluctuations of ozone (temperature) range between ± 0.02 ppmv (±2 K) in troposphere and ± 0.5 ppmv (± 3 K) in stratosphere.

To study the climatology, the ozone data of corresponding months of all the years from 2012 to 2017 are averaged. Seasonal variation of ozone mixing ratio averaged in the altitude ranges of 9 – 12 km; 12 – 15 km; 18 – 21 km and 21 – 24 km are depicted in Fig. 3 (left panel). The mean tropopause height over Costa Rica is found around 17 km and hence the region between 15 and 18 km has been excluded from the study. Magnitude of ozone mixing ratio in all height blocks tends to show strong peaks in summer months. The corresponding ozone fluctuations are shown in Fig. 3 (right panel) also shows similar variations.

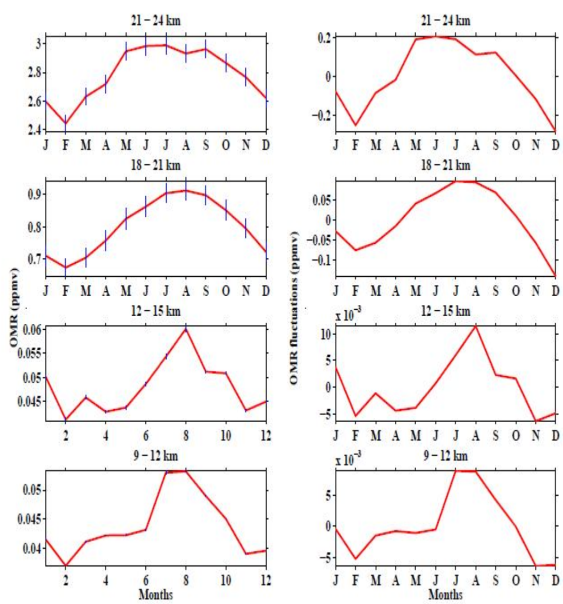


Fig. 3 Seasonal variation of Ozone mixing ratio (OMR) with standard errors (left panel) and its fluctuations (right panel) average over different height blocks

The weekly profiles of ozone and temperature from SHADOZ over Costa Rica were used to produce meaningful vertical wave number spectra. The fluctuations have been obtained by removing quadratic fit from the profiles and the corresponding height profiles have been subjected to 5 km high pass filter. Then a Power Spectral Density analyses were carried out to form their respective wave number spectra. We examined the character of each spectra observed during 2012 – 2017. These individual spectra are averaged monthly to increase confidence level in the spectral power. In order to exclude the effect of the tropopause and Brunt Väisalä frequency squared on vertical wavenumber spectra, we first examined the tropopause height and it was found to be at ~17 km. Then the region between 15 and 18 km was taken as transition region between purely tropospheric behaviour below 15 km and purely stratospheric behaviour above 18 km. Now the complete altitude region has been divided into two regions Troposphere (5 – 15 km) and stratosphere (18 – 28 km). Table 2 shows the monthly and yearly mean spectral slopes of ozone and temperature in the wave number range of 4.69×10^{-4} – 2.50×10^{-3} cycle/m separately in troposphere (5 – 15 km) and stratosphere range (18 – 28 km).A considerable variability in the spectral slope of individual monthly ozone and temperature spectra was observed, which is consistent with the predictions of various gravity wave saturation models. Such variability in both slopes is also observed by other workers using Lidar and rocket measurements ([7], [8], [21]).This variability may be attributed to several factors that include intermittent sources in time and propagation through and interaction with a complex environment [9]. Reference [21] reported clear variation of monthly spectral slopes of ozone spectra with steepest slope of –4.10 and the shallowest is –2.44.

TABLE II
MONTHLY AND YEARLY MEAN SPECTRAL SLOPES OF OZONE AND TEMPERATURE

Month	Ozone		Temperature	
	Troposphere	Stratosphere	Troposphere	Stratosphere
Nov	–2.56	–2.64	–2.58	–2.47
Dec	–2.48	–2.53	–2.49	–2.54
Jan	–2.66	–2.36	–2.58	–2.78
Feb	–2.74	–2.74	–2.75	–2.73
Mar	–2.67	–2.81	–2.66	–2.57
Apr	–2.86	–2.16	–2.67	–2.43
May	–2.68	–2.50	–2.71	–2.56
Jun	–2.54	–2.46	–2.91	–2.25
Jul	–2.90	–2.56	–2.61	–2.64
Aug	–2.88	–2.54	–2.24	–2.70
Sep	–2.62	–2.38	–2.39	–1.70
Oct	–2.58	–2.48	–2.40	–1.91

An attempt has been made to investigate the seasonal variation of spectra. To do this, initially the ozone and temperature data of corresponding months of all the years from 2012 to 2017 are averaged and then subjected to Power Spectral Density analyses. Thereby spectral data of tropospheric and stratospheric segments has been divided into two seasons: winter (November to March) and summer (June to August). The average spectra with their slopes are plotted in Fig. 4. The spectral slopes of ozone and temperature in the troposphere are found to be –2.6; –2.61 and –2.76; –2.46 during winter and summer respectively. The corresponding slopes in stratosphere are –2.61, – 2.62 and–2.53, –2.61. This shows that the slope of ozone spectra in troposphere is higher than that of stratosphere [21].

Sample variability bars have been included for all spectra. They are ± two times the standard deviation divided by the square root of the number of spectral averages i.e., 95 % confidence limit for normal distribution. Our results show that the spectral slopes are in general close to the slope of –3 predicted by various gravity wave models ([28], [29], [30]). References ([31], [32]) reported clear seasonal variation of the spectra in the lower stratosphere from radiosonde observations over a mid – latitude and observed spectra had slope closer to the model in winter while the summer spectra had small amplitudes and less spectral slopes (~ –2.5). A clear enhancement was observed in ozone spectra from troposphere to stratosphere in both the seasons, more prominent in winter.

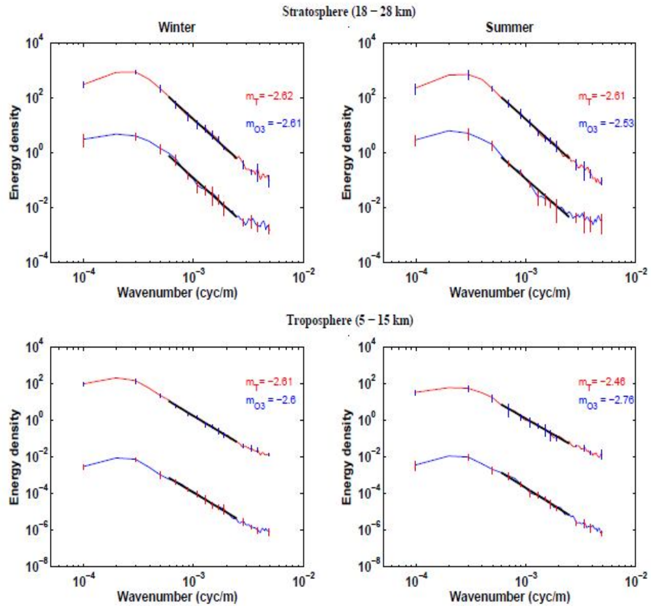


Fig. 4 Mean vertical wave number spectra of ozone and temperature fluctuations of 2012- 2017. Plots show the spectra for winter (left panel) and summer (right panel) in troposphere and stratosphere

The power spectra of ozone during winter and summer are found to overlap with each other in stratosphere with amplitudes of the order of 10–2 $ppmv^2$/(cycle/m) with slope of –2.6. The slope of ozone spectra during winter in troposphere is found to be steeper than in summer.

Since the dominant vertical wavelengths are poorly represented in these power spectra diagrams, the vertical wave number of ozone spectra in flux content form for tropospheric and stratospheric segments during winter and summer seasons are depicted in Fig. 5, which clearly demonstrate the dominant vertical wavelength to be approximately 3.3 km both in troposphere and stratosphere. Reference [6] observed the wavelengths around 2.5 km for temperature data. Reference [21] reported the vertical wavelength ~2.6 km in the troposphere and ~2.7 km in the lower stratosphere.

As the mean spectral slopes are consistent with the value predicated by gravity wave saturation models one can suggest that the observed ozone fluctuations are due to atmospheric gravity waves.

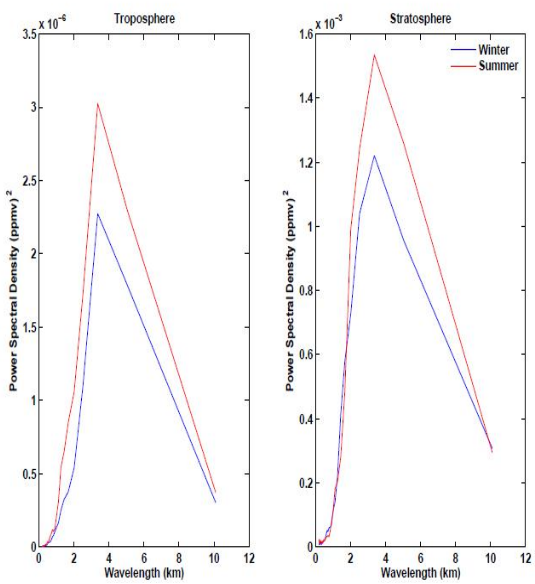


Fig. 5 Comparison of power spectral densities of ozone fluctuations in flux content form for two seasons in troposphere (left panel) and stratosphere (right panel)

V. CONCLUSIONS

This paper presents spectral analysis of ozone and temperature in troposphere and stratosphere over tropical station Costa Rica during the period 2012 – 2017. We assessed the possible role of gravity waves by characterizing and determining the vertical wavelengths from the wave number spectra of ozone and temperature fluctuations. The profiles of both ozone and temperature reveal similar characteristics of their vertical structure as presented by [14]. The ozone tropopause and cold point tropopause of mean ozone (temperature) profiles 16.9 km (17.4 km) for winter season and 15.1 km (16.6 km) for summer season. A clear annual variation in ozone and temperature fluctuations are observed in stratosphere, but a mixture of annual and semiannual variation was found in troposphere. A clear seasonal variation is observed with maxima in summer months at all heights.

Spectral properties of ozone and temperature fluctuations were characterized by forming their wave number spectra. The monthly spectral slopes of ozone and temperature spectra show considerable variability. But the mean values of spectral indices are found to be close to saturation model in both winter and summer seasons. The mean spectral slope of ozone spectra in troposphere is more than in stratosphere. Although various saturation models have been widely applied to predict the vertical wavenumber spectra of the wind, temperature and density fluctuations, in slope and amplitude, the theoretical predictions for the ozone spectrum are rudiment. Therefore, further theoretical studies are required in order to be able to explain well the observed ozone spectral slopes and amplitudes. The mean spectra show a dominant wavelength of 3.3 km in both troposphere and stratosphere. Indeed, the results presented in the paper appear to be the first comparative study of vertical wavenumber spectra of ozone and temperature fluctuations over tropical station.

VI. ACKNOWLEDGMENT

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