Malaysian Journal of Tropical Geography, 2025, 51(1): 15-30

LOCAL ATMOSPHERIC OZONE VARIABILITY AND CHANGE AS OBSERVED AT KUALA LUMPUR (2.73^{O}N, 101.7^{O}E), MALAYSIA

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ABSTRACT

We present the first comprehensive analysis of attributing large-scale influence on the local changes in atmospheric ozone over Kuala Lumpur (KL). KL is located near the western fringe of the equatorial South China Sea. We focus on radio- and ozone- sonde data available from the Southern Hemisphere ADditional OZonesondes (SHADOZ) network and investigate the variability and trends observed from 1998 to 2016. The most important drivers of variability over KL are the Quasi-biennial oscillation (QBO) and the El Niño Southern Oscillation (ENSO). QBO signatures are evident in both the stratospheric ozone and temperature anomalies (including the 2016 disruption) while ENSO plays a small role in impacting tropospheric ozone and temperature variabilities. Over KL chemical depletion of stratospheric ozone is small and occurs in conjunction with decreasing temperature trend. However, tropospheric ozone and temperature show increasing trends. Apart from attributing observed local ozone and temperature changes to the most important drivers of year-to-year variability, trends obtained are regional indicators of a changing climate.

Keywords: *Stratospheric and tropospheric ozone, variabilities, trends, QBO and ENSO.*

INTRODUCTION

Local, regional and global climate change are linked in many ways. How large-scale atmospheric circulation changes are affecting local variability and long-term trends is increasingly important to judge manifestations of climate change. Here, we will focus on ozone- and temperature-sonde data from Kuala Lumpur (KL) from 1998 to 2016. We will attribute leading modes of variability (namely QBO and ENSO) and discuss the long-term trends. Temperature is an obvious choice in such an assessment, because it is well observed and directly related to climate change. Ozone might be a less obvious choice, but it is driven by circulation and temperature changes and has a direct radiative impact on the thermal structure of the atmosphere

In the atmosphere, 90% of the ozone (O_3) is above the tropopause and the stratospheric region with the highest ozone concentration is known as the ozone layer. Stratospheric ozone is produced photo-chemically. It plays an important protective role against the incoming harmful solar ultraviolet radiation. Certain human activities that have released chlorine and bromine containing gases transported dynamically towards the stratosphere have led to significant stratospheric ozone depletion, thus increasing the surface dosage of natural ultraviolet radiation. Even though stratospheric ozone production may be balanced by its destruction in chemical reactions with natural and human-produced chemicals, its depletion poses adverse health, biological, environmental and climatic effects, particularly in the equatorial region whereby the ultraviolet radiation can increase significantly. As a result, the Montreal Protocol on Substances that Deplete the Ozone Layer (WMO et al., 2015) has been designed and ratified internationally since 1989 to protect the ozone layer by phasing out the production of numerous ozone depleting substances. The remaining ozone, about 10% of the total, is found in the troposphere. Increase in ozone concentration near the surface is a result of pollution from human activities.

Govindan et al (2011) used the Brewer Ozone Spectrophotometer data to investigate the characteristics and variability of total ozone concentration over Petaling Jaya, Malaysia. However, we provide the first comprehensive analysis utilizing the radio- and ozone-sonde data from Kuala Lumpur, Malaysia. After describing the data, methods and validation procedure in Section 2, we discuss the characteristic features including the variabilities and their long-term behaviour of temperature and ozone in Section 3. The unusual 2015-2016 QBO disruption is described in Section 4 and we summarize our findings in Section 5.

DATA, METHODS AND VALIDATION

Vertical profiles of ozone are measured using electrochemical sensors coupled with meteorological radiosondes flown on balloons. Malaysian Meteorological Department (MMD) started the ozonesonde observations in November 1991 in Petaling Jaya (3.10^{o}N, 101.65^{o}E, a suburban town) and the release site was moved to Kuala Lumpur International Airport at Sepang (2.73^{o}N, 101.70^{o}E) in January 1998. Since 1998, Kuala Lumpur station has joined the Southern Hemisphere Additional Ozonesondes (SHADOZ) project to ensure sufficient numbers of soundings in the Tropics available for detailed studies of, for example, the impact of widespread biomass burning in the Tropics (Thompson et al., 2004). The Kuala Lumpur observations are usually performed twice a month, i.e. mainly at the beginning and the middle of each month around 0200 ~ 0400 Z. The data period available in SHADOZ is from January 1998 to December 2016. Unfortunately, some gaps and irregularities exist in the data record. Some data in 1998 as well as in October – December 2004 and January 2005 are missing. In addition, the magnitudes of wind speeds for May-December 2010 and January-December 2011 have been reported in knots instead of meters per second. The corrected observed monthly mean data are shown in Figure 1.

The vertical profiles of ozone, temperature, relative humidity and winds are available at a vertical resolution of about 5 ~ 8 hPa. Therefore, the raw sonde data are not on regular pressure levels, and logarithmic interpolation is used to obtain data at regular 5 hPa intervals from 1015 hPa to 5 hPa in the vertical, preserving the chemical, thermodynamic and dynamic characteristics of each sounding. These interpolated data in each month are binned in time so that a validity for the 1st and 15th day of the month can be assumed to enable contiguous analysis. The average of these two days in the month is thus taken as the monthly mean. As the time-height section of monthly mean zonal wind in Figure 1(d) is found to be in good agreement with that derived from Singapore radiosondes (Figure 1 in Newman et al., 2016), we consider them to be representative of the monthly mean values for Kuala Lumpur.

We use monthly upper air reanalysis data of 0.75º × 0.75º resolution at 00 Z from the European Centre for Medium-Range Weather Forecast (ERA-Interim, see Dee et al., 2011) for the same period to validate against the analysed SHADOZ dataset. Such validation is an important prerequisite for testing and improving models, including reanalysis systems like ERA-Interim.

The total column amount of ozone in Dobson unit is computed out of a vertical profile (between level 0 and N) as given by the formula below:

$$Column = 10\left(\frac{RT_0}{gp_0}\right)\sum_{i=1}^{N-1} 0.5\left(VMR(i) + VMR(i+1)\right)(p_i - p_{i+1})$$

where R is the specific gas constant for air;
T_o, the temperature (in Kelvin) at p_o (1000 hPa in our study);
g, the global average of gravity at mean sea level;
VMR, the volume mixing ration in ppm, and
p, the pressure in hPa.

Following LeBlanc and McDermid (2001), the long-term monthly mean for each month is calculated by averaging all the individual monthly means of the month for the 19-year (1998-2016) period. These long-term monthly means are then subtracted from the individual monthly means to obtain the required "deseasonalized" zonal wind, ozone and temperature profiles so as to assess the possible signatures of the QBO and any other interannual variations.

Principal sources of ozone variability are known to be the QBO and ENSO which are represented in the analysis by predifined indices. QBO shear index is calculated from the difference in the zonal wind at 60 hPa and 20 hPa while the Oceanic Nino or ENSO Index is obtained from http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml. A 13-month running mean is performed to assess the variability. A linear trend is calculated from each of the consecutive QBO and ENSO simple linear regressions.

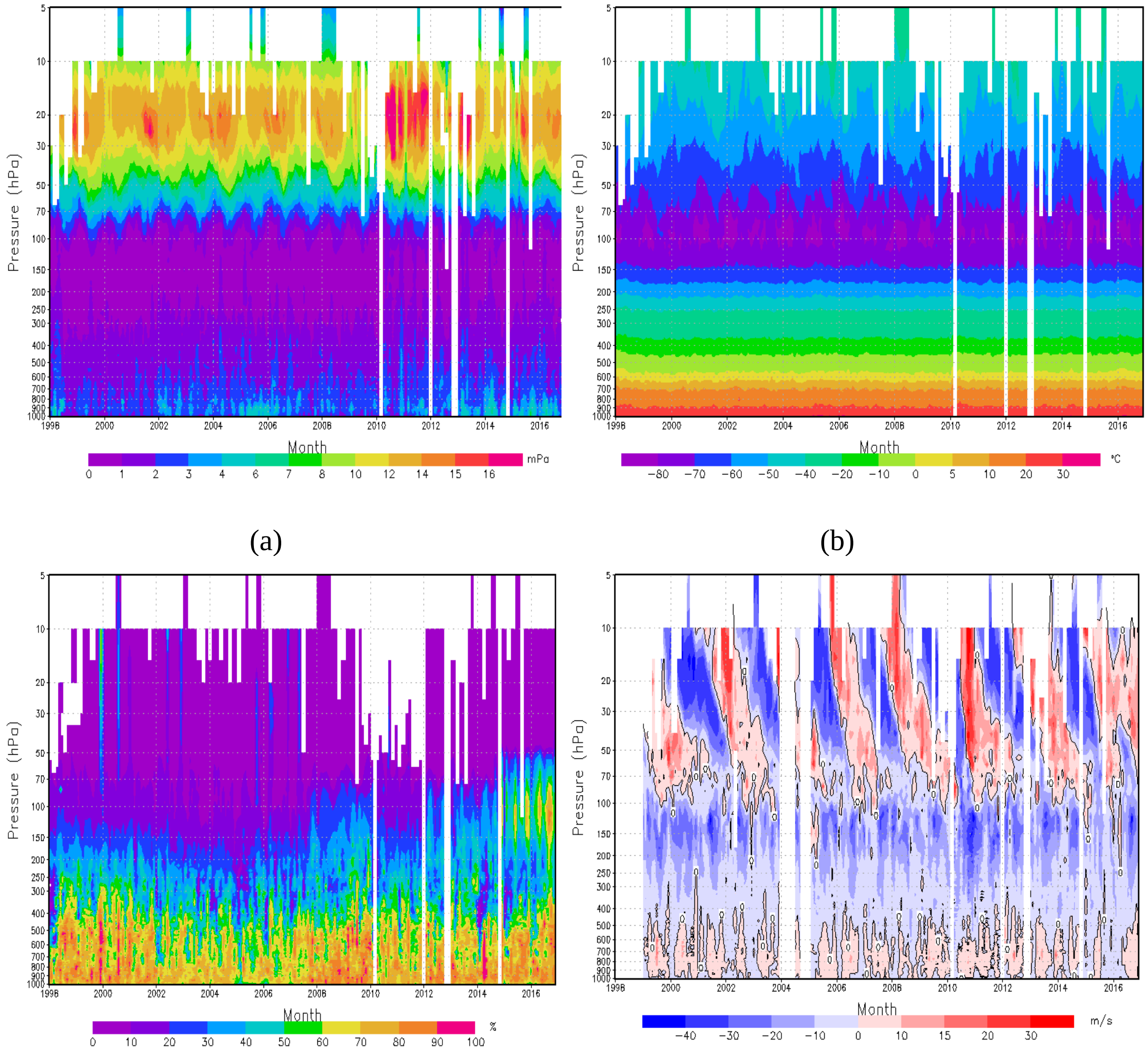
ANALYSIS AND DISCUSSION

Basic features and variability

From the 19-year measurement record at KL, Figure 1 shows the monthly mean profiles as a function of time for ozone (partial pressure), temperature (º C), relative humidity (%) and zonal wind component (m/s).

The ozone in Figure 1(a) shows its strongest vertical gradient in the lower troposphere and the weakest gradient (1 ~ 2 mPa) in the upper troposphere. Surface ozone enhancements are commonly measured and can be due to the influences of biomass burning, meteorological transport and regional pollution (Chan et al., 2003). In the stratosphere, ozone increases rapidly to values of around 15 mPa near 20 hPa before decreasing steadily in the upper stratosphere. We note that there was exceptionally high stratospheric ozone observed between 2010 and 2012.

The monthly mean temperatue in Figure 1(b) shows a layered structure. From individual profile analysis, thermal tropopause levels vary between 115 hPa and 85 hPa. In this analysis, we assume the thermal tropopause to be located around 100 hPa level. As regards the relative humidity in Figure 1(c), the depth of the wet layer (relative humidity around 40%) is increasing towards the upper troposphere and lower stratosphere since 2008. This can be attributed to more vigorous convective activities as a result of increasing tropospheric aerosols originated locally or transported regionally in this increasingly "urbanized" environment.



(c) (d)

Figure 1: Time-height sections of the monthly mean (a) ozone (mPa), (b) temperature (°C), (c) relative humidity (%) and (d) zonal wind component (ms^{-1}) from January 1998 to December 2016 for Kuala Lumpur. [Source: SHADOZ]

The Quasi-Biennial Oscillation (QBO) signature is clearly evident in the monthly mean zonal winds above the tropopause (Figure 1 (d)). The westerly and easterly wind phases propagate down from above 5 hPa (top of our measurement) to 100 hPa as time progresses with considerable variability in period and amplitude (Kwan et al., 2003 and Baldwin et al., 2001).

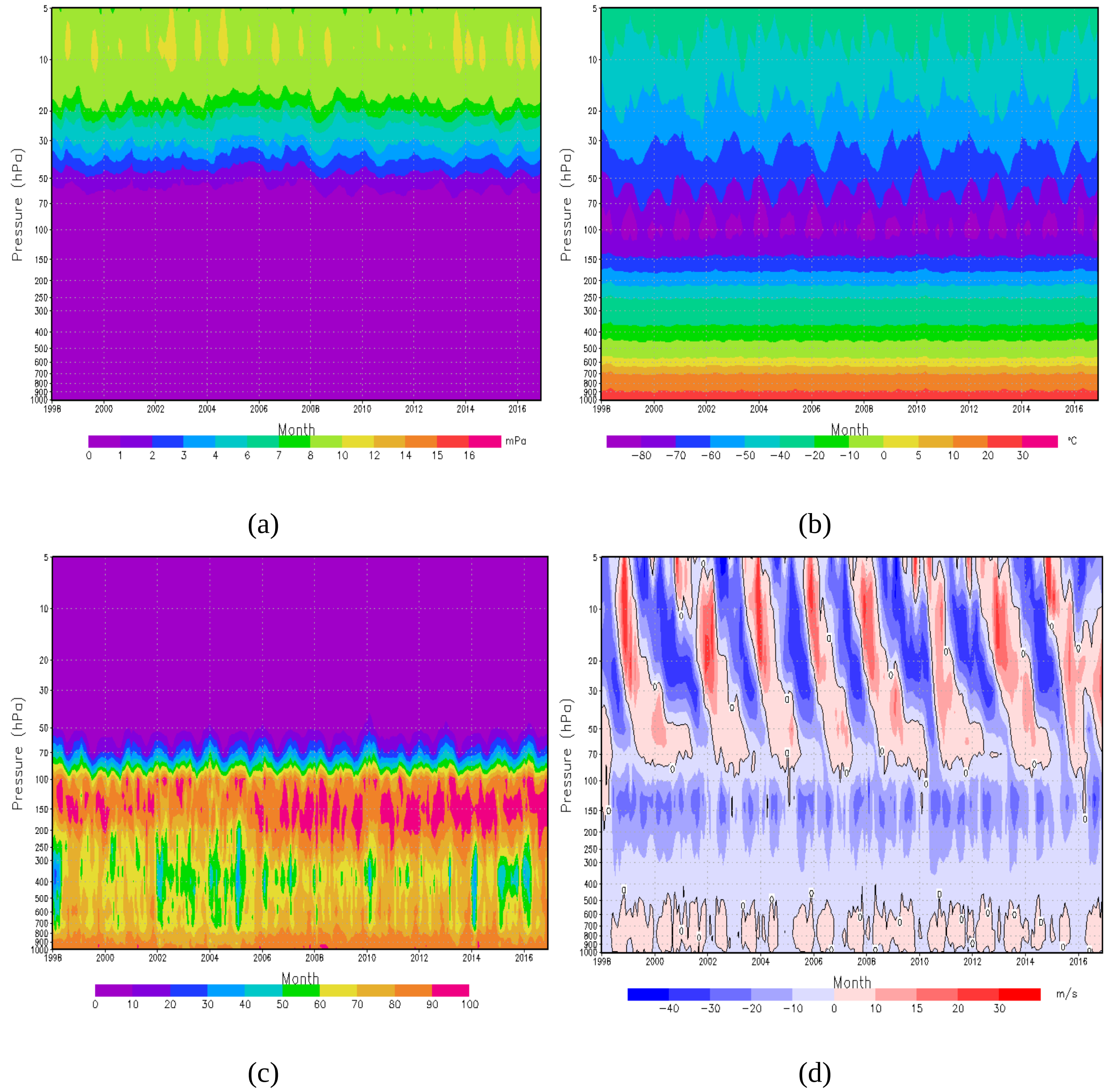
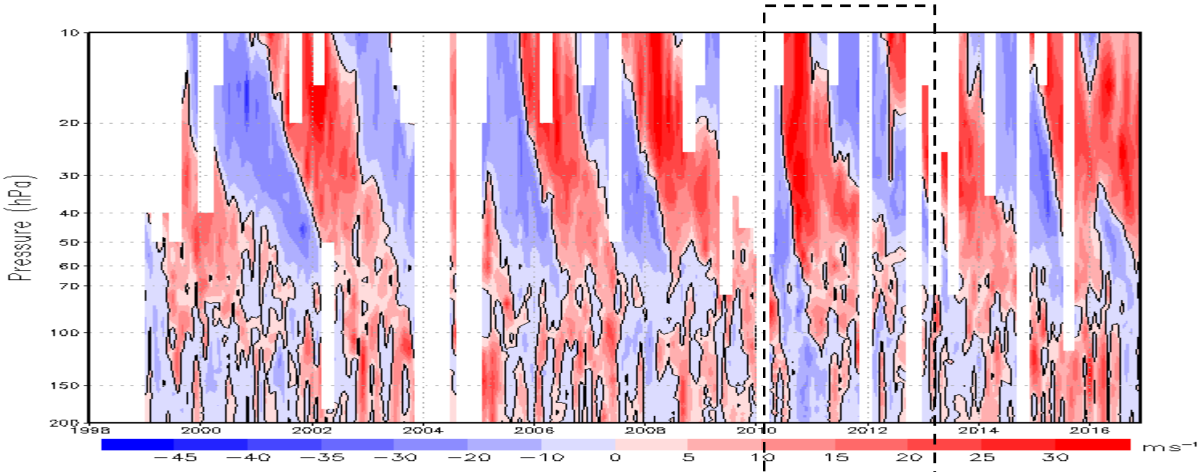


Figure 2: Time-height sections of the monthly mean (a) ozone (mPa), (b) temperature (^{o}C), (c) relative humidity (%) and (d) zonal wind component (ms^{-1}) from January 1998 to December 2016 for the grid point closest to Kuala Lumpur. [Source: ERAI]

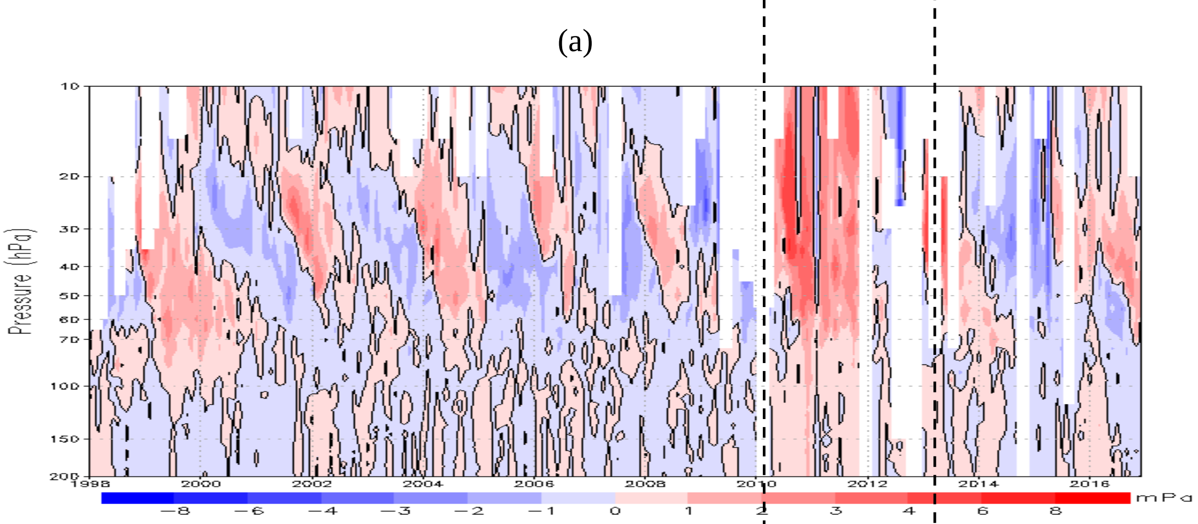
These stratospheric zonal winds weaken on reaching the tropopause and seldom propagate further downwards. In other words, their magnitudes with maximum around 20 hPa decrease as the height decreases and the conspicuous signature level is in the range 70-10 hPa. In view of the variation in the length of QBO cycles, the easterly to westerly transition phase is said to occur at 40 hPa while the transition from westerly to easterly phases is at 10 hPa for each regular QBO cycle so as to enable direct comparison (Newman et al., 2016). There is a total of around seven complete QBO cycles of easterly and westerly winds from 1998 to 2015. The period of the oscillation is around 24 months. Easterlies are generally stronger than westerlies while westerlies move down faster than the easterlies as indicated by the steepness of the zero line. This is well in-line with the Baldwin et al. (2001) overview. There is an unusual QBO disruption from late 2015 to 2016, which we describe in a separate section

Figure 2 shows corresponding data to Figure 1 but from the ERA-Interim Reanalysis for the grid point closest to KL. Ozone (Figure 2(a)) shows smaller extremes and the strongest gradient occurs at higher altitudes. In addition, the lower tropospheric ozone variations as observed in the SHADOZ are not visible here (the product is not designed to capture them). Temperatures (Figure 2(b)) are in good agreement but relative humidity (Figure 2(c)) is vastly different particularly in the troposphere. Zonal wind (Figure 2(d)) variations agree well with that from SHADOZ and are smoother as they reflect the true monthly mean.

Figure 3 shows “deseasonalized” zonal wind, ozone and temperature profiles from the SHADOZ data for the stratosphere and upper troposphere. A clear QBO signature can be identified in all data above the thermal tropopause (100 hPa). It is important to note that both, the ozone and temperature anomalies (Figures 3(b) and 3(c) respectively), are closely in-phase while the zonal wind anomaly (Figure 3(a)) lags slightly behind. In Figure 3, variations of the temperature anomalies around the thermal tropopause are rather complex. However, the ozone anomalies are very small.



(a)



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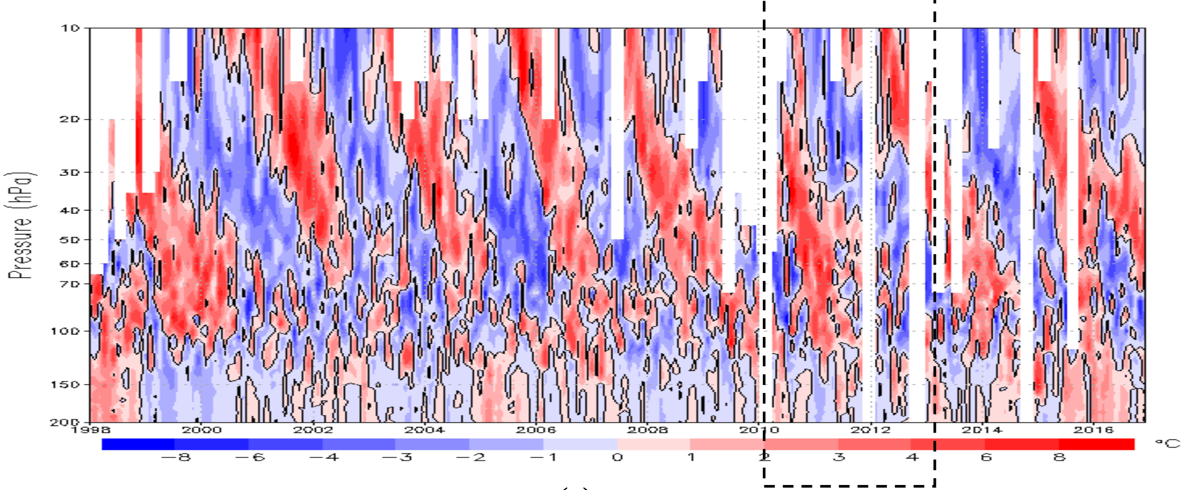


(c)

Figure 3: Time-height sections of the deseasonalized (a) zonal wind component (ms^{-1}) , (b) ozone (mPa), and (c) temperature (^{o}C) in the stratosphere and upper troposphere. [Dashed box delineates the period 2010-2012]

Earlier, we mentioned about the exceptionally high stratospheric ozone between 2010 and 2012. Such sudden surge of ozone abundance since 2010 is also noticeable in Figure 2(a) of Oman et. al (2013) and Figure 2(c) and (d) of Neu et. al (2014). The agreement implies that the spike is not an artefact of changing instrumentation but could have been caused by a sudden change in the atmosphere. In November 2010, Mt. Merapi volcano (Java, Indonesia) erupted (Zuev et. al, 2017). Its impact should have increased the reactive halogen radicals, leading to regional ozone destruction. In addition, its plume carrying the aerosols that could affect the regional heating rates was reported to drift east south of the equator instead. Hence, the eruption effect of aerosol heating and ozone depletion in the lower stratosphere over KL could not be detected (see the period within the dashed box of Figure 3). Plausibly, the prolonged high positive ozone anomaly within the period could be due to the strong easterly anomalies before and after the strong westerly anomaly which might further advect ozone eastwards from the neighbourhood. In addition, as noted by Ooi et al (2011), deep convection over land is a possible fast-transport route for tropospheric air containing trace gases and aerosols from the surface to enter into the upper troposphere and lower stratosphere. However, ozone amount from such tropospheric-stratospheric exchange is insignificant.

Variability and Change

A long time series with continuous data is essential to assess correctly the trend and influences of different drivers on ozone variability. Maximum ozone abundance occurs at 925 hPa and 20 hPa (Figure 1(a)). There are also few missing data in these two levels and the gaps have been filled by linear interpolation. We hence select them as representative levels for the troposphere and stratosphere respectively. The period selected is from 1999 to 2016 as there is no wind data in 1998. We also look into the controlling factors that cause the inter-annual variations of the associated temperature fluctuations and calculate linear trends for both pressure levels.

Figure 4(a) shows the time series of the ENSO index and a QBO shear index (derived from the KL station data). It shows that ENSO and the QBO are mostly not in phase, indicating clearly that both modulate the variability independently.

The 13-month moving average (black solid line) of ozone at 20 hPa (Figure 4(b)) reveals the strong influence of the QBO modulation. A very small positive trend (red solid line) is detectable. As reported in WMO (2015), stratospheric ozone depletion in the tropics is very small. In terms of temperature (Figure 4(c)), QBO influence is very strong and there is a very small decreasing trend. By comparing with Figure 4(a), increasing stratospheric ozone and temperature coincide closely with the maximum of the westerly vertical shear. The westerlies aloft and easterlies below of this shear leads to downward, adiabatically heated anomalies. Similarly, decreasing ozone and temperature coincide with the maximum easterly vertical shear. In contrast, this easterly shear consisting of easterlies aloft and westerlies below produces an upward, adiabatically cooled anomalies.

Surprisingly, even though the 13-month moving average of both ozone and temperature at 925 hPa (Figures 4(d) and 4(e) respectively) follows closely that of that ENSO index variation (Figure 4(a)), the impact of ENSO is not pronounced except the increasing ozone in the El Niño years of 2007 and 2015 and the decreasing ozone in the La Niña years of 2000 and 2008. This is understandable as the impact of ENSO lessens significantly westwards from Sabah (close to sphere of influence from the Pacific) towards Peninsular Malaysia. In other words, lower troposphere over KL is impacted mostly by above-normal ENSO.

(a)

(b)

(c)

(d)

(e)

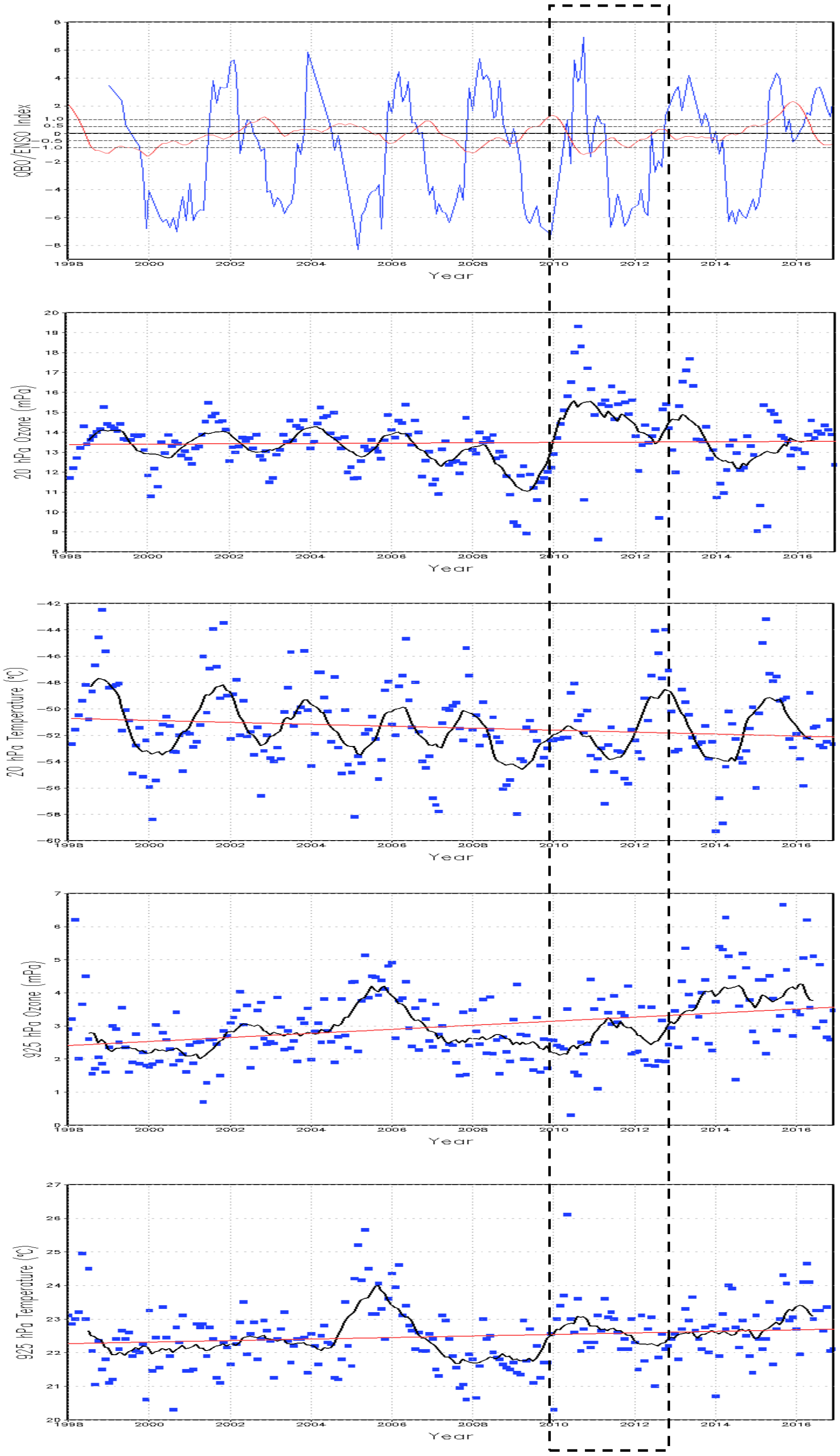
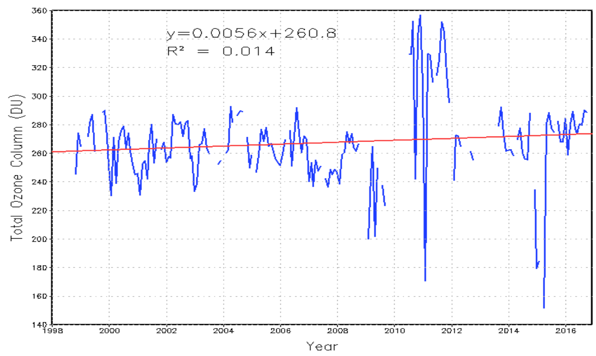


Figure 4: (a) Time series of ENSO Index (red solid line with +/- 0.5 as normal) and QBO shear index(solid blue line). (b) Time series of ozone at 20 hPa (blue dots) with 13 month running mean (black wavy line) and the linear trend (red solid line). Same as (b) except for (c) temperature at 20 hPa, (d) ozone at 925 hPa and (e) temperature at 925 hPa. [Dashed box delineates the period 2010-2012]

(a)



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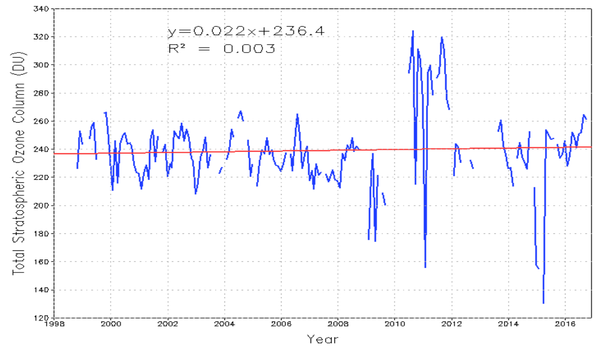

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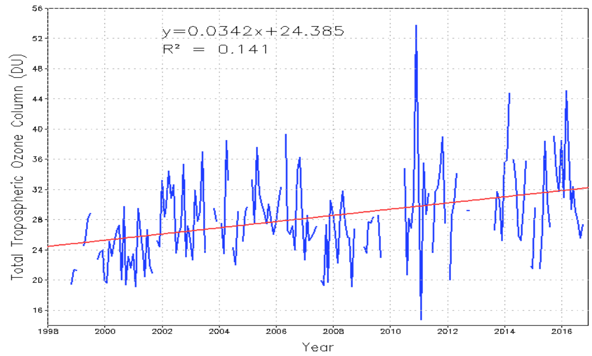

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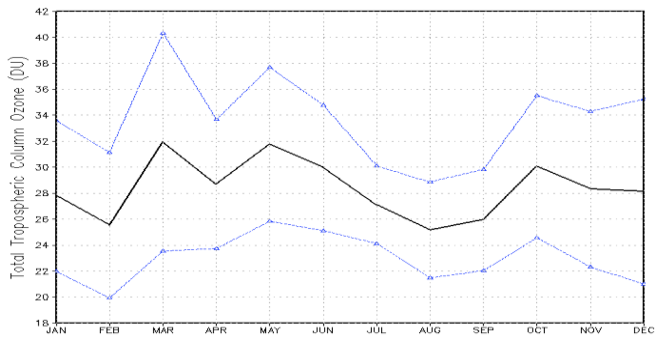

Figure 5: Time series of (a) total column ozone (in Dobson units, DU, as blue solid line), (b) total stratospheric column ozone, and (c) total tropospheric column ozone with their associated linear trend lines (solid red lines). (d) Long term (1998-2016) monthly variation of total tropospheric column ozone. The dashed lines with diamond markers are the standard deviations.

In addition, the lower tropospheric ozone exhibits a significant increasing trend (Figure 4(d)). It is known that tropospheric ozone is produced through photo-chemical reactions among nitrogen oxides, carbon monoxide and hydrocarbons whereby their concentrations have increased due to industrial combustion and biomass burning on the ground surface and lightning and exhaust from aircraft engines in the upper troposphere. As tropospheric ozone traps the Earth's thermal radiation, it produces a greenhouse effect and its increasing trend may impact global warming.On exploring the large-scale features of ozone transport associated with ENSO, Zeng and Pyle (2005) noted that there is a large increase of stratosphere-troposphere exchange (STE) following a typical El Niño year, leading to an increase of ozone in the troposphere. The opposite occurs during La Niña. Nevertheless, such STE is not conspicuous in KL as seen from Figure 3(b). In fact, Figure 1 of Neu et al (2014) reveals clearly STE is only prominent in the middle and higher latitudes due to Brewer-Dobson circulation.

Total column ozone

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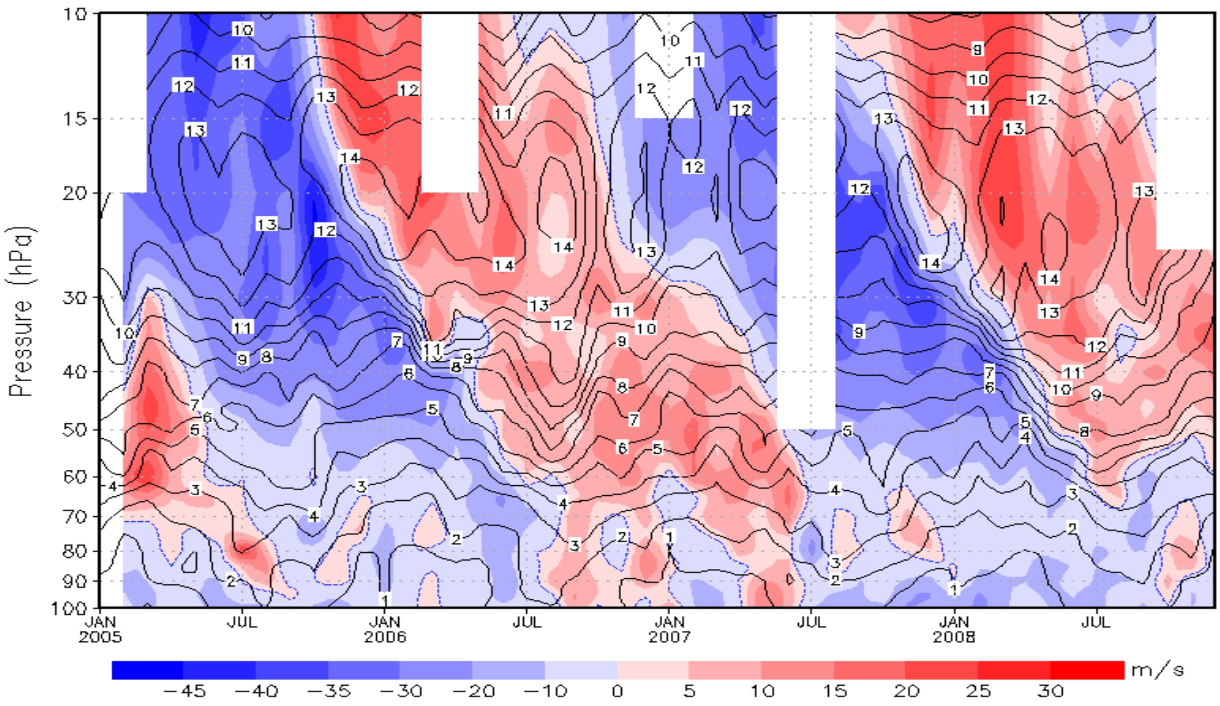
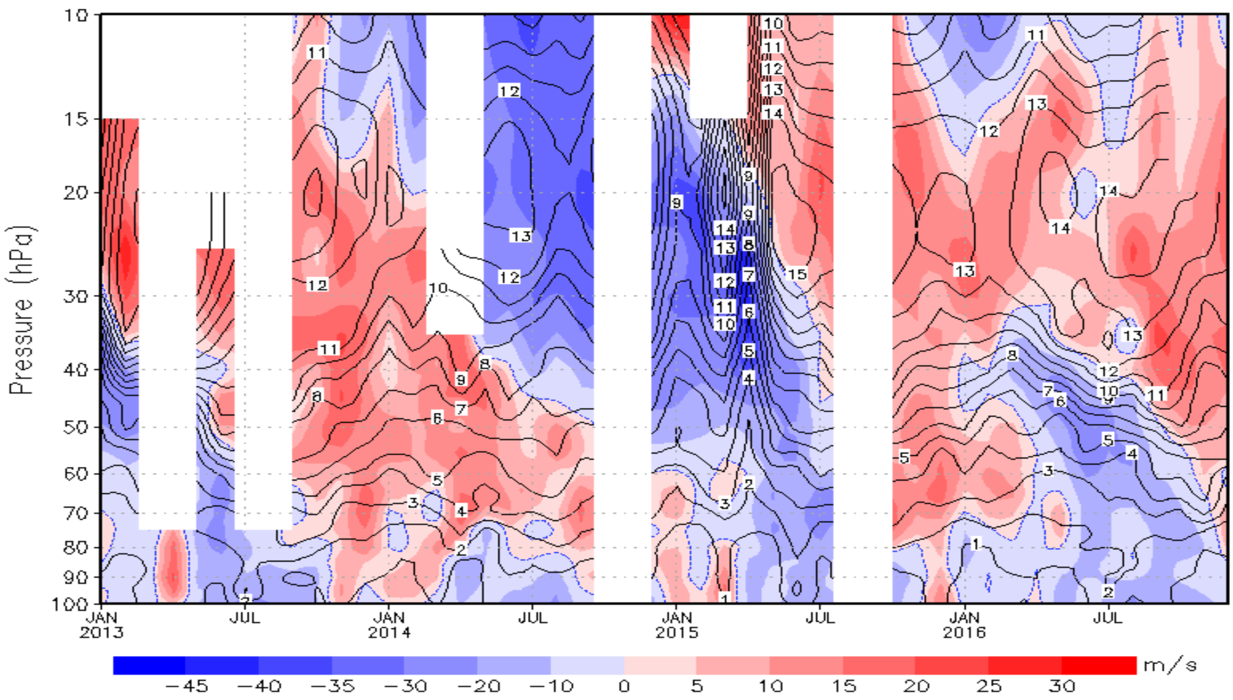
2015-2016 QBO Disruption

Figure 6 shows the time evolution of the Kuala Lumpur stratospheric ozone profiles superimposed on the zonal winds for the two periods, viz. 2005-2008 and 2013-2016, in which the first period encompasses two complete QBO cycles. The figure emphasises that the QBO plays a dominant role in causing temporal variability of the ozone maximum between 15 and 30 hPa (Logan et al., 2003). Based on Figure 6(a), from 20 to 35 hPa, ozone concentrations are decreasing in late 2005 due to the relative upward motion of the easterly shear induced by the QBO. Subsequently, with the descent of the westerly shear zone down to about 60 hPa in the first half of 2006, ozone then increases rapidly as a consequence of the relative downward motion after the passage of the maximum easterly shear. Generally, the cyclical pattern repeats. However, the 2015-2016 QBO showed a very unusual behaviour. In late 2015, the QBO downward propagation of the westerly phase is clearly seen (Figure 6(b)), but by January 2016 there is an upward displacement of westerly winds around 20 hPa with an extended descending westerly wind layer until December 2016. This anomalous westerly phase appears to interrupt the easterly downward propagation that is apparent at 10 hPa in late 2015 and early 2016. The anomalous westerlies are accompanied by the development of easterlies in the 30-70 hPa layers in 2016 probably due to the further upward propagation of the equatorially trapped Kelvin waves. A further analysis from the 00 Z operational upperair ascents at KL (not shown) reveals that the normal downward propagation of the easterly phase above 10 hPa is only apparent in January 2017, signalling the return to a more typical QBO behaviour. This 2015-2016 QBO disruption is unprecedented since 1953 (Newman et. al., 2016). Causes and implications such as extreme weather risks of this rare disruption due to change of wind shear between the lower stratosphere and upper troposphere need to be investigated. Nevertheless, we note that such disruption gives rise to positive stratospheric ozone anomalies and rather complex temperature anomalies (Figures 3(b) and 3(c)). It also raises the positive trend slightly for both the stratospheric ozone and temperature.



(a)



(b)

Figure 6: Contour maps of monthly mean stratospheric ozone partial pressure (mPa) superimposed on the zonal wind component in shaded colour from (a) 2005 to 2008 and (b) 2013 to 2016.

CONCLUSIONS

QBO, being a dominant feature of the zonal wind circulation of the stratosphere in this equatorial South China Sea region, produces a clear signature in both temperature and ozone anomalies. It has a profound impact on the variability of the stratospheric ozone. Stratospheric ozone varies almost in phase with the QBO cycle (as defined by our proxy). The peak value of the stratospheric ozone is around 15 mPa at 20 hPa and is a consequence of the relative downward motion after the passage of the maximum easterly shear at 20 – 35 hPa level. Above this peak, ozone is photochemically controlled. A small long-term stratospheric ozone decrease is detectable in this region and occurs in conjunction with a small negative temperature trend. The evolution of the unusual 2015-2016 QBO disruption is clearly depicted.

Variability of tropospheric ozone and temperature are related to ENSO but the magnitude of ENSO induced changes are small. Generally, the main effect of El Niño is to increase the tropospheric ozone in the region of KL while the opposite occurs during La Niña. A significant positive trend of tropospheric ozone is clearly evident. This can partly be due to pollution from increasing human activities which are further enhanced during El Niño years.

The time series of tropospheric column ozone shows significant positive trend. The annual cycle shows higher maximum in March as well as May and lower maximum in October and minimum in both February and August. Our approach of analysing total tropospheric and stratospheric coloumn ozone separately instead of solely the whole atmospheric column ozone as done by Govindan et al (2011) leads to have different inference on the controlling drivers.

We have only 19 years of atmospheric measurements over KL from the SHADOZ dataset. In spite of this and the constraints due to data quality, our analysis represents an important contribution to investigate in greater detail not only the variabilities of stratospheric and tropospheric ozone and associated temperature but also the dominant dynamical controlling drivers like QBO and ENSO on the variations as well as the trends in the changing climate.

ACKNOWLEDGMENTS

The authors would like to acknowledge Fundamental Research Grant Scheme (FRGS) FP104- 2018A. This study was part of HiCOE project with a grant by the Malaysian Ministry of Higher Education (MoHE) Higher Education Center of Excellence fund (HICoE IOES-2014A and also part of Newton-Ungku Omar grant No. IF023-2017. This study is also a contribution to the Helmholtz Climate Initiative REKLIM, a joint research project of the Helmholtz Association of German Research Centres (HGF). Ozonesonde data were provided by the Malaysian Meteorological Department via SHADOZ. The data analysis of this Project was carried out using the Grid Analysis and Display System (GrADS) software from OpenGrADS.

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