Seasonal Variability Of Ozone Vertical Profiles in Indonesia Based on AQUA-AIRS Data

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Abstract. We examined the seasonal vertical profiles of ozone mixing ratios in Indonesia based on ozone monthly data of AQUA-AIRS from 2002 to 2016, analysed and discussed the characteristic of its seasonal profiles of ozone mixing ratios. The method used is by processing the ozone monthly data to be the seasonal profiles for December, January, February (DJF), March, April and May (MAM), June, July and August (JJA) and September, October and September (SON) from the surface to upper stratosphere (1000 hPa to 1 hPa) and comparing the time series, average and deviation of each ozone seasonal profile. The results indicate good agreement in shape of ozone seasonal profiles but the bias shows in the peak of ozone which was found at 10 hPa. The peak of ozone ranged between 8.58 ppm to 9.56 ppm in DJF, and 8.98 ppm to 9.87 ppm in MAM. In JJA, ozone peak ranged between 8.55 ppm to 9.44 ppm and the peak of ozone in SON showed 8.29 ppm to 9.48 ppm.

1. Introduction

The amount of ozone in the atmosphere can be measured by instruments on the ground level (sparsely distributed measurement sites). These instruments are thereafter set aloft on balloons, aircrafts, and/or satellites. Through ground and aircraft measurements, observations are only limited to the surface. As such, measurements are more sensitive to sources and sinks. However, these same instruments are unable to make evaluations based on daily global variations. The satellite remote sensing has very good global coverage to increase our capability to access the influence of human activities on the chemical composition of the atmosphere and on the climate changes [1]. The satellite also can provide the quantitatively data with high spatial or temporal resolution. In addition, the free download satellite data are provided by infrared measurements from the Atmospheric Infra Red Sounder (AIRS) on the NASA AQUA satellite to establish and produce the high quality spectrally resolved radiance climatologic for observing and detecting climate change, to understand the distribution of trace gases, sources and sinks, and to validate weather and climate models [2].

Atmospheric ozone is one of the highly variable trace gas constituents of the atmosphere. The concentration of ozone can vary in short to long-term scales which can profoundly influence the vertical thermal structure of the atmosphere [3]. Deviation in ozone concentration can change the radiative properties of the atmosphere inflicting a negative radiative forcing due to the absorption of shortwave radiation and a positive radiative forcing in the troposphere due to the absorption of long wave radiation. The change in ozone amount over a region can be due to natural and anthropogenic factors. Human activities can influence the ozone amounts in the atmosphere through the emission of
certain harmful substances that can destroy the ozone layer and also by the release of certain chemicals that can cause the production of ozone in the troposphere [4].

Although chemically identical, ozone in different layers in the atmosphere exerts different influences on the well-being of Man. In the stratosphere, where approximately 90% of the atmosphere’s ozone is found, ozone resides in the so-called ozone layer and prevents the sun’s ultraviolet radiation from reaching the surface of the Earth. In the troposphere, ozone is a direct greenhouse gas. In the boundary layer, ozone is a pollutant which harms the health of both Man and his crops [5].

Launched on board NASA’s Aqua satellite on 4 May 2002, Aqua’s cross-track scanning Advanced Microwave Sounding Unit (AMSU) with AIRS cross-track scanning grating spectrometer coupled, provides vertical profiles of the atmosphere with a nadir 45 km field-of-regard (FOR) across a 1650 km swath. AIRS broad spectral coverage (3.7 to 16 µm with 2378 channels) includes spectral features of CH₄, CO, O₃, and CO₂. The objectives of the AIRS is to determine the factors that control the global energy and water cycles, investigate the atmosphere-surface interactions, improve numerical weather prediction, assess climate variations and feedbacks and detect the effects of increased carbon dioxide, methane, ozone, and other greenhouse gases. The term “sounder” in the instrument’s name refers to the fact that water vapour and temperature are measured as functions of height. AIRS measures CO total column by (36) channels with uncertainty estimate 15-20% at 500mb, vertical coverage 1000 - 1 mb, global non-polar, mid-tropospheric total, (7 - 9) layers. Troposphere carbon monoxide (CO) abundance is retrieved in the 4.58-4.50 µm (2180-2220 cm⁻¹) region from the AIRS measured radiances of the IR spectrum. AIRS radiance data in the 9.6-µm band are used to retrieve column ozone and ozone profiles for both day and night [6-8].

A study by Bian et al., [9] has compared the AIRS ozone profiles with ozonesonde data from Beijing using a new type of ozonesonde called the Global Positioning System Ozone sensor (GPSO3). The ability to measure ozone variability has widespread application [10] and it also has used AIRS to show how transient convective events, associated with the Asian summer monsoon, lead to vertical transport of low ozone and high-water vapor into the UTLS region. AIRS-retrieved ozone has been evaluated against several datasets. Initial validation studies have shown that IR-retrieved ozone profiles using AIRS measurements capture the variability in the extra tropical upper troposphere and lower stratosphere (Ex UTLS) region observed in the ozonesonde data [9, 11].

While providing the near-real-time AIRS-retrieved ozone at several pressure levels in the Upper troposphere and Lower Stratosphere (UTLS) during the 2005 and 2008 Stratosphere–Troposphere Analyses of Regional Transport Experiments (START05 and START08), significant agreement between the AIRS-retrieved ozone near the tropopause and aircraft ozone measurements was also found [12]. A detailed description of the AIRS retrieval method is presented in [13]. AIRS also provides information on several greenhouse gases, CO₂, CH₄, CO and O₃ [14].

2. Materials and methods

AIRS ozone profiles are available from 1000 hPa to 1 hPa. This study used the version 006 Level 3 ozone profile data which are available from the Goddard Earth Sciences Distributed Archive Center (http://disc.sci.gsfc. nasa.gov/data/dataset/AIRS/). The analysis of ozone volume mixing ratio was investigated for the period 2002-2016 in Indonesia (12N-12S, 94E-146 E) using the retrieved AIRS monthly product (AIRX3STM) Version 006 data. The ozone mixing ratios from 1000 hpa to 1 hPa Satellite data were evaluated over Indonesia in 14 years study period. The ozone mixing ratios data were gridded monthly at 1°x1° spatial resolution (latitude x longitude).

3. Results and Discussions

Figure 1 shows the results of the retrieved monthly analysis (AIRX3STM). The Atmosphere infrared sounder (AIRS) data were utilized to analyze vertical profile of ozone mixing ratio in Indonesia for the period 2002-2016. The analysis of monthly ozone profile for Indonesia region shows that maximum values occur in 2004, 2006, and 2008, with minima in 2005, 2007 and 2010. Ozone
concentration at 10 hPa (~ 26 km) or in the stratosphere was between 8.3 ppm and 10.39 ppm and it seemed high in January-May. However, it decreased during June-July and increased again from August to December. This condition relates to the cycles of the sun's movement which is away from the equator during June-July. The previous study using data derived from AURA-MLS [15] shows that the peak of ozone mixing ratio profile occurred at a pressure of 10 hPa with a concentration ranged from 9.04 to 10.24 ppm. Ozone from surface to 100 hPa was 0.021 ppm to 0.010 ppm, and the stratospheric ozone average was 9.15 ppm with standard deviation of 0.44 ppm.

**Figure 1.** The time series of monthly vertical profile of ozone in Indonesia from 1000 hPa to 1 hPa from 2002 to 2016.

**Figure 2** shows the time series of seasonal vertical profile of ozone in Indonesia from 1000 hPa to 1 hPa for 2002 to 2016. The seasonal profile of DJF shows that the O$_3$ mixing ratios in the stratosphere were higher in 2005, 2007 and 2011 and lower in 2012, 2015 and 2010. The seasonal profile of MAM shows that the O$_3$ mixing ratios in the stratosphere were higher in 2004, 2008 and lower in 2010. The JJA profile shows that the O$_3$ mixing ratios in the stratosphere were higher in 2008, 2006 and 2011 and lower in 2005, 2007 and 2010, while the SON profile shows that the mixing ratios of ozone were higher in 2015, 2006 and 2004, and lower in 2005, 2007, 2009 and 2012. In the lower troposphere, the mixing ratios of O$_3$ were 0.02 ppm to 0.05 ppm. While the mixing ratios of ozone in tropopause (100 hPa) shows 0.100 ppm to 0.150 ppm, and the peak of ozone in 10 hPa (~ 26 km) ranged between 8.3 ppm to 9.87 ppm.
Figure 2. The time series of seasonal vertical profile of ozone in Indonesia from 1000 hPa to 1 hPa from 2002 to 2016.

Figure 3 describes the ozone average profile of DJF and its deviation. It shows that the ozone mixing ratios in the stratosphere were higher in 2005, 2007 and 2011 and lower in 2012, 2015 and 2010. The deviation of stratospheric ozone was between -600 ppb to 600 ppb. The average profile of MAM shows that the O$_3$ mixing ratios were higher in 2004, 2008 and lower in 2010. The deviation also shows -600 ppb to 600 ppb with the highest minus deviation of ozone in 2010.

Figure 3. The average ozone profile from 2002 to 2016 for DJF and MAM and its deviation.

Figure 4 describes the ozone average profile of JJA and its deviation. The ozone mixing ratios in the stratosphere were higher in 2008, 2006 and 2011 and lower in 2005, 2007 and 2010. The deviation of stratospheric ozone was between -600 ppb to 600 ppb and the highest minimum deviation was in
2010. The average profile of SON shows that the $O_3$ mixing ratios in the stratosphere were higher in 2015, 2006 and 2004, lower in 2005, 2007, 2009 and 2012. The deviation also shows -600 ppb to 600 ppb with the highest minus deviation in 2005.

Figure 4. The average ozone profile from 2002 to 2016 for JJA and SON and its deviation.

Figure 5 shows the 1000 to 100 hPa profile of DJF. In the troposphere, the $O_3$ mixing ratios were higher in 2011, 2014 and 2016 and 20111 and lower in 2003, 2006 and 2008. The deviation of tropospheric ozone between in DJF ranged between -10 ppb to 10 ppb. While the average profile of MAM shows that the $O_3$ mixing ratios were higher in 2015, and lower in 2011. The deviation also shows -10 ppb to 10 ppb with the highest minus deviation in 2010.
Figure 5. The average ozone profile from 2002 to 2016 in 1000 hPa to 100 hPa for DJF and MAM and its deviation.

In Figure 6, the 1000 hPa to 100 hPa ozone profile of JJA shows that in the troposphere the O\textsubscript{3} mixing ratios were higher in 2008 and 2013, and lower in 2005, 2007 and 2010. The ozone deviation of tropospheric ozone is between -10 ppb to 10 ppb. While average profile of SON shows that the O\textsubscript{3} mixing ratios were higher in 2004, 2006, 2010 and 2015, and lower in 2005, 2007 and 2012. The ozone deviation also shows -10 ppb to 10 ppb with the highest minus deviation of ozone in 2005.

Figure 6. The average ozone profile from 2002 to 2016 in 1000 hPa to 100 hPa for JJA and SON and its deviation.
Measurements of the vertical profile of ozone have been carried out over the last few decades by a large number of instruments, operating in situ or from remote vantage points on the ground and in space [16]. These indisputably show globally declining ozone levels during the 1980s and a large part of the 1990s in the lower and upper stratosphere (∼5% – 7% decade$^{-1}$), and to a lesser extent also in the middle stratosphere (1% – 2 % decade$^{-1}$) [17, 18].

For many decades, it has been known that the stratospheric ozone layer shields the Earth’s surface from harmful solar ultraviolet radiation (UV), thus enabling life on Earth and protecting humans and the biosphere against adverse effects. This protective layer could be depleted by anthropogenic emission of chlorofluorocarbons (CFCs) to the atmosphere. The photodecomposition of CFCs and other long-lived organic molecules in the stratosphere releases chlorine (Cl) and bromine (Br) atoms that destroy ozone molecules in catalytic cycles. In the last Scientific Assessment of Ozone Depletion: 2014 of the World Meteorological Organization [17], it is stated that global ozone levels decreased through the 1980s and early 1990s while stratospheric abundances of ozone-depleting substances (ODSs) were increasing.

The presence of declining ozone in the stratosphere and the increasing of tropospheric ozone occurrence in Indonesia were analyzed by investigating the long-term variation of ozone in the stratosphere (at ozone peak level ~ 26km) and ozone in the lower troposphere (at 700 hPa ~ 3 km). In Figure 7, the time series monthly ozone peak at 10 hPa (~26 km) in Indonesia show almost constant trend. It can explain that the declining of stratospheric ozone in Indonesia does not occur. In seasonal variation of ozone peak, the trend of each season shows a small negative variation. In DJF season trend of ozone peak show coefficient of determination of 0.113, in MAM 0.016, in JJA 0.028 and in SON 0.005.

![temporal variation of ozone peak](chart1.png)

**Figure 7.** The long term variation of ozone at stratosphere (at peak level) in Indonesia.

**Figure 8** presents the time series of monthly ozone at 700 hPa (~3 km) in Indonesia. The trend of tropospheric ozone in Indonesia shows little increasing, with coefficient of determination 0.007. Lower tropospheric ozone shows coefficient of determination 0.367 in seasonal DJF, 0.225 in MAM , 0.058 in JJA and 0.115 in SON .

The increasing of lower tropospheric ozone in Indonesia especially in SON (end of dry season) is affected by anthropogenic activities. Ozone levels will also be affected by the expected anthropogenic increases in abundances of other ozone-relevant gases (carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (N$_2$O) as well as by the natural influences of volcanic eruptions, solar activity, and the natural variability in the Earth’s climate [17].
Figure 8. The long term variation of ozone at lower troposphere (~3km) in Indonesia.

4. Conclusion

The seasonal profile of ozone mixing ratio in Indonesia based on AQUA-AIRS data for the period of 2002 to 2016 indicates good agreement in shape of ozone seasonal profiles and the bias shows in peak of ozone at 10 hPa. The peak of ozone in DJF ranged between 8.58 ppm to 9.56 ppm, the MAM ozone peak showed 8.98 ppm to 9.87 ppm. The JJA ozone peak ranged between 8.55 ppm to 9.44 ppm and the peak of ozone in SON showed 8.29 ppm to 9.48 ppm.

Time series of monthly ozone peak at 10 hPa (~26 km) in Indonesia are almost constant. It can explain that the declining of stratospheric ozone in Indonesia does not occur. In seasonal variation of ozone peak, the trend of each season shows a small negative variation (negative trend). The time series of monthly ozone at 700 hPa (~3 km) in Indonesia trend of tropospheric ozone in Indonesia show a little increased. The increasing of lower tropospheric ozone in Indonesia especially in SON (end of dry season) is affected by anthropogenic activities.

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