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OZONE VARIABILITY AND OZONE DEPLETING SUBSTANCES (ODS) IN INDONESIA BASED ON MLS-AURA DATA

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Abstract. Research and characterizing the ozone profiles and Ozone Depleting Substances (ODS) in Indonesia is a satellite data-based research activities. The aim of the study was to obtain the characteristics of ozone in Indonesia as well as the contribution of ODS to the variability of ozone. By performing a data inventory based on satellite data, analyze the pattern of annual, seasonal and perform linkage analysis of the contribution of ODS changes to the conditions of ozone. Daily data of vertical profiles of ozone and in the form of volume mixing ratio (vmr) with format HDF (Hierarchical Data Format) is extracted to the territory of Indonesia to take parameters as latitude, longitude, and concentration. Then converted to Excel format with the help of data processing software of MATLAB. Results obtained in the form of ozone characteristics in Indonesia, the percentage of contribution to the variability of ozone also contribution to the variability of ozone in Indonesia in several levels of height. By using Microwave Limb Sounders (MLS) AURA satellite data in the period of 2005 to 2013 characteristics of monthly vertical profiles of ozone in Indonesia has been obtained. The ODS studied were ClO and BrO. Peak of vertical profiles of ozone occurs at a pressure of 10 hPa or altitude of 25.9 km. ClO peak occurs at a pressure of 2.1 hPa or altitude of 30.6 km and BrO reached the peak at 14 hPa or altitude of 24.5 km. When ClO and BrO reach a maximum concentration at stratosphere then ozone molecules is potentially damaging or decrease in the stratosphere. Temporal variations of ozone showed decrease when ODS concentrations increased (particularly ClO and BrO). Linear regression of ozone with ozone showed a negative correlation coefficient which indicates there is a strong relationship between ozone concentrations decline in pressure of 14 hPa when BrO reach the maximum. Likewise for ClO which also showed a negative correlation with the decrease in ozone concentration. ClO contribution to the decreasing of ozone in Indonesia was marked by every addition of 0.01 ppb ClO will reduce ozone of 0.00583 ppm (5.83 ppb). While any increase of 0.01 ppb of BrO will decrease 0.03 ppb of ozone.

Keywords: *BrO, ClO, MLS-AURA, ozone*

1 INTRODUCTION

Ozone in the stratosphere has globally decreased since about 25 years ago. For middle-latitude region, the characteristics of ozone vertically, latitudinal, and seasonal has indicated the change in accordance with the knowledge that the halogen is the main cause of this phenomenon. The process of ozone decomposition in the lower stratosphere is catalyzed by reaction with BrO, ClO, H_2O, and N_2O (Vogel *et al.*, 2005).

CFC and other ODS are released into the air, it continues to rise until it reaches the stratosphere and then decomposed by UV light which are then produces chlorine and bromine atoms that destroy ozone. In winter the temperature in Antarctica is very low causing the formation of polar clouds that contain ozone depleting substances. It is accumulated continuously because of the lack of sunlight, it makes difficult to unravel. In the early of spring, the existence of sunlight makes ODS decomposed largely

and produce Cl and Br atom in a large number. It causes the number of ozone molecules decomposed many times larger than formation of ozone molecules, further, it will creates the ozone hole. Based on the experts studies, we know that one of Cl atom can decompose up to 100,000 ozone and last up to 50 years in the atmosphere. The decomposition reaction of ozone molecules by chlorine can be seen in the following formula (Dyominov and Zadorozhny, 2005; Ambarsari et al., 2010).

$$Cl + O_3 \rightarrow ClO + O_2$$
$$ClO + O \rightarrow Cl + O_2 \quad (1\text{-}1)$$
$$ClO + ClO \xrightarrow{h\nu} O_2 + 2\,Cl \quad (1\text{-}2)$$

Chlorine monoxide (ClO) is a general form of reactive chlorine compounds in the stratosphere, this compound is the main agent in the decomposition reaction of ozone in the stratosphere with chlorine catalyst. The main source of chlorine in the stratosphere is CFC (Chloro Fluoro Carbon), it is a chemical compound composed of chlorine, fluorine, and carbon emitted by human activities on the earth's surface. After reaching the upper stratosphere (mainly due to the rising air in the tropics), CFC is decomposed by UV radiation with high energy to produce chlorine. Chlorine monoxide, ClO, plays a unique role in the formation of the Antarctic ozone hole, from observations ClO mixing ratio is detected up to 2.2 ppb (Connors *et al.,* 2007).

Other reactions involve radicals HO_x (=H + OH + HO_2 + …), NO_x (=NO + NO_2), ClO_x (=Cl + ClO + OClO + HOCl + BrCl) and BrO_x (= Br + BrO + BrCl + HOBr), it also affects the amount of ozone. All of these radicals are derived from other compounds which are come from natural or man-made which have a long life time, so it can move from the troposphere to the stratosphere, such as CFCs. HOx is derived from chemicals photo process that breaks the H_2O molecules through the process of photolysis, or by reaction with highly reactive oxygen atoms (O) (Mc. Conell., 2008).

Bromine monoxide (BrO) plays an important role in the chemical reactions of ozone, because it is a substance that accelerates the destruction of ozone in the atmosphere according to the following reaction (Theys., 2004):

$$Br + O_3 \rightarrow BrO + O_2 \quad (1\text{-}3)$$
$$BrO + O \rightarrow Br + O_2 \quad (1\text{-}4)$$

BrO concentration in the atmosphere is dominated by anthropogenic emissions (especially Halon which has a long life time in the atmosphere to be transported to the stratosphere). Although, concentration of Bromine compounds in the atmosphere tends to be slightly compared with chlorine compounds, but Bromine compounds have an efficiency of ozone destruction in the stratosphere that makes Bromine contribute for 25% of the ozone depletion in the middle latitudes and 50% of the ozone depletion in the Arctic (Theys., 2009). The main source of bromine monoxide and other bromine compounds in the atmosphere comes from natural or anthropogenic. The largest contribution to the number of bromine compounds in the stratosphere is organic compounds containing bromine gas which experienced transport from Earth's surface up into the stratosphere (Theys., 2009).

Matveev, *et al.*, (2001) and Tas, *et al.*, (2006) found that the increased concentrations of BrO in the atmosphere up to 100 pptv will cause a decrease in ozone concentrations from around 50-80 ppbv in normal conditions into 10-30 ppbv. Berg in Martinez et al (1999) reported that total average mixing ratio of bromine in the atmosphere during the peak period in the Arctic from mid-February to mid-May for a few years of observation is increase around 130 ppt. For information, in a normal level, BrO in the atmosphere is 15 ppt.

Temperature is a key factor in radiative equilibrium in the atmosphere. The temperature at a certain pressure determines the density and dynamics across scales, it also determines the speed of chemical reactions and radiative transfer processes in the atmosphere. Vertical profile of temperature in the earth's atmosphere is globally associated with radiation, convection, and the dynamic heating process between the earth's surface and atmospheric system (Ramaswamy *et al.,* 2006).

Ambarsari *et al.*, (2010), has conducted ODS data inventory and other chemical compounds that could potentially damage the Indonesia's ozone layer as results of AURA and UARS satellite observations. In addition to human activity, natural phenomenon also affects the decrease of ozone layer such as volcanic eruptions. Komala *et al.*, (2013), measured the percentage effect of SO_2 (from volcanic eruptions = non ODS) to the changes in the chemical composition of atmospheric-ozone reduced ~ 20 DU (~ 8%) and CO_2 increase around 2 ppm ~ (~ 0.54%). The relationship between ozone and SO_2 is the decrease of ozone after 2-3 months of volcanic eruptions occur.

AURA satellite observations to detect ozone, other chemicals in the upper atmosphere and temperature can be done by the Microwave Limb instrument Sounders (MLS). Microwave Limb Sounder (MLS) is part of the Earth Observing System (EOS) conducted by NASA and installed on the AURA satellite. EOS MLS measure thermal emissions from a broad spectrum centered at 118, 190, 240, 640 and 2250 GHz, which is measured continuously (24 hours a day) with 7 micro-wave receiver. MLS is more accurate in measuring vertical profiles of ozone and other atmospheric components until the lower stratosphere. MLS-AURA has a vertical resolution approaching 3 km in the stratosphere with 200 km horizontal resolution (http://mls.jpl. nasa. gov/eos/instrument.php). This horizontal provides observation area coverage MLS around 82 degrees South and 82 degrees North latitude. MLS measures vertical profiles at 3500 locations around the world in every 24 hours (Ahmad *et al.*, 2006).

MLS provides data measurement results in daytime and nighttime globally for vertical profiles for some chemical components of the atmosphere (O_3, HCl, ClO, HOCl, BrO, OH, H_2O, HO_2, HNO_3, N_2O, CO, HCN, CH_3CN, volcanic SO_2), ice cloud, and atmospheric temperature. MLS EOS AURA are the development of UARS MLS with a better spatial resolution and wider coverage, including the measurement of vertical profiles and the ability to detect chemical compounds which has not been detected by any instruments before (OH, HO_2, and BrO) (Ahmad *et al.,* 2006).

This research aims to study the variability of ozone and ODS in Indonesia as well as the percentage contribution to the reduction of ozone concentration based on MLS-AURA satellite observation data.

2 MATERIALS AND METHODOLOGY

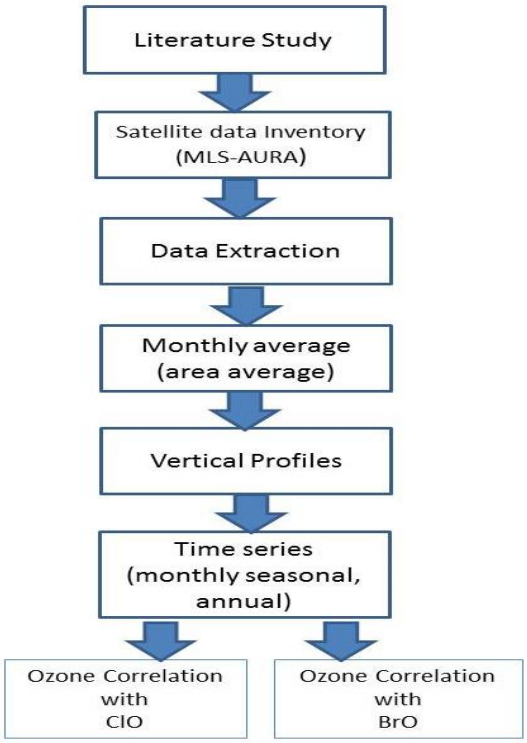


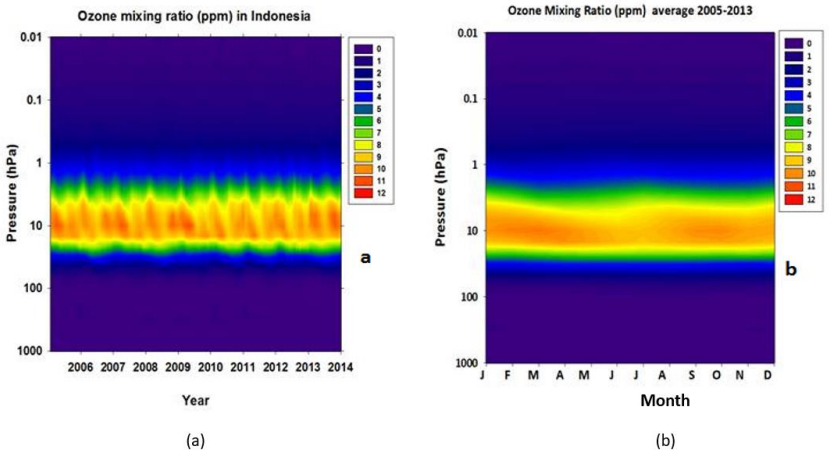
Figure 2-1: Research flow chart

The data used in this research are ozone and Ozone Depleting Substance (ODS) of MLS/AURA period 2005 to 2013. Data measurement instrument results obtained from the MLS-AURA NASA website, the data provider is MIRADOR (http://mirador.gsfc.nasa.gov/). In this study the ODS data in the inventory is ClO and BrO. Daily data of vertical profiles of ozone and ODS in the form of volume mixing ratio (vmr) with format HDF (Hierarchical Data Format) is extracted for the territory of Indonesia to take parameters as latitude, longitude, and concentration. These data are then converted to Excel format with the help of data processing software MATLAB. Extraction of satellite data for ozone and ODS parameters of HDF shape file for Indonesia region are converted to excel with data processing software MATLAB. Then we conducted vertical profile ozone and ODS data processing for the average region of Indonesia (10 LU-10 LS and 94 BT-141BT) by using Sigma plot software. These processes should include vertical profile ozone data processing and ODS with analysis of time series (monthly, seasonal, annual) and consider its peak. After that, graphed simple linear regression correlation between ozone with ODS in Indonesia. Vertical profile of ozone is then compared to ODS vertical profiles to see which might be the dominant influence on a certain pressure level. In this case the correlation is focused on pressure/altitude at the time of ODS reaches its maximum. Flowchart of the study can be seen in Figure 2-1.

3 RESULTS AND DISCUSSION

The time series of ozone profile mixing ratio to the altitude in Indonesia from the MLS-AURA in 2005 to 2013 shows that the ozone dominant distribution at pressure of 10 hPa with 10 ppm concentration (ppm = parts per million = 10^{-6}) (Figure 3-1a). Indonesia ozone concentration at 10 hPa or in the stratosphere seems high in January- May. However it decrease during June-July and increase again in August to December. It relates to the cycles of the sun's movement which is away from the equator during the June-July. It causes the reaction of inhibited ozone formation, so that the concentration of ozone decreased (Ambarsari *et al.*, 2013). The peak of ozone mixing ratio profile occurs at a pressure of 10 hPa with a concentration range of 9.04 to 10.24 ppm.

The monthly average of ozone concentration shows a maximum value in March 2005 to 2013 at a pressure of 10 hPa with a concentration of 10.24 ppm, whereas the concentration of ozone monthly average minimum in July 2005-2013 is at pressure of 215 hPa and the concentration is only 0.0213 ppm (Figure 3-1b).



(a) (b)

Figure 3-1: Graph of time series of Indonesia's ozone profile from MLS in 2005 to 2013 (a) and the pattern of average annual ozone profile (b)

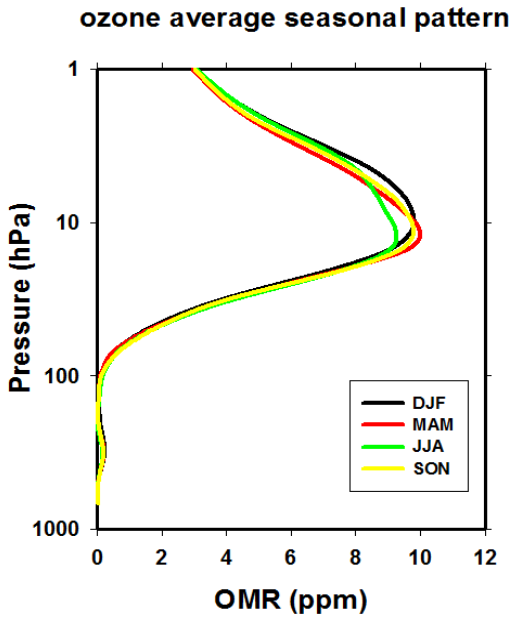


Figure 3-2: Graph of Indonesia's ozone profile average seasonal patterns

Indonesian's Ozone Profile Seasonal Variation (Figure 3-2) shows peak pressure ozone at 10 hPa in March-April-May (MAM) from 2005 to 2013 with a concentration of 9.87 ppm. The minimum stratospheric ozone peak occurred in June-July-August (JJA) from 2005 to 2013 at a concentration of 9.16 ppm.

The time series of Indonesia's average ClO vertical toward the heights in 2005-2013 (Figure 3-3a) shows that ClO peak profile occurred at 2 hPa with a concentration range of 0.21 to 0.31 ppb (part per billion or 10^{-9}). When we compared to the ozone concentration, the concentration of ClO was 1000 times smaller than the concentration of ozone. The highest peak concentrations occurred in July 2005 to 2013 at 2 hPa with 0.31 ppbv concentrations and the lowest peak was in February 2005 to 2013 with 0.21 ppb concentration.

The monthly average concentration of ClO shows maximum values during July at pressure of 2 hPa, while the concentration of ClO monthly average minimum time is in January (Figure 3-3b).

Indonesia Seasonal variations of ClO profile (Figure 3-3) shows that the CIO peak at 2 hPa maximum pressure is in June-July-August (JJA) from 2005 to 2013 at a concentration of 0.30 ppb. The minimum ClO peak occurred in December-January-February (DJF) from 2005 to 2013 with a concentration of 0.24 ppb.

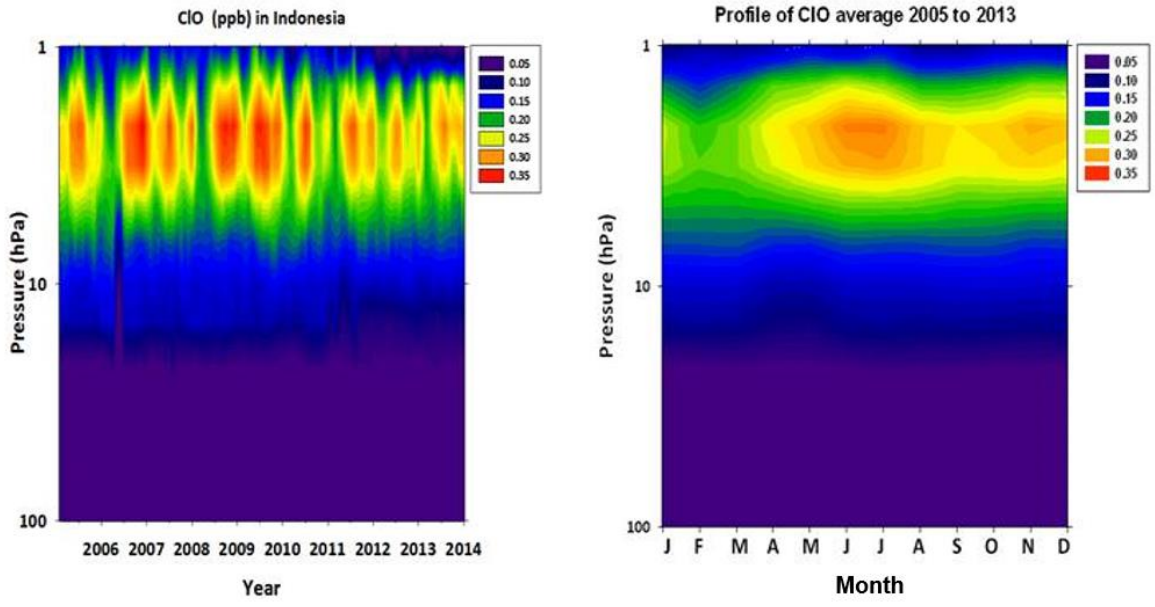


Figure 3-3: Time series graph of Indonesia's ClO profile from MLS in 2005 to 2013 (a) and CIO average annual pattern profile (b)

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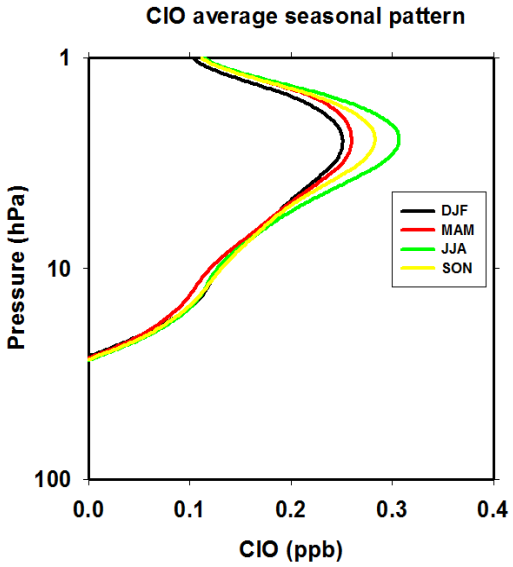

Figure 3-4: Graph of the average seasonal pattern profile of ClO Indonesia

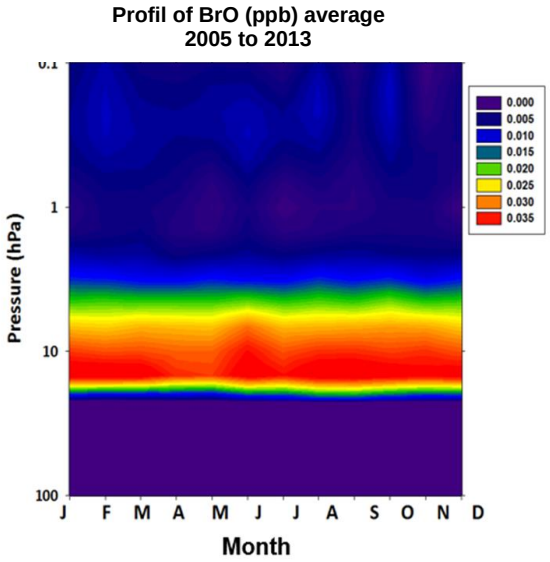

Figure 3-6: Graph of BrO average annual pattern profile

BrO monthly profile time series in Indonesia from 2005 to 2013 can be seen in figure 3-5. BrO highest peak concentration occurred in February 2005 to 2013 at a pressure of 14 hPa with a concentration 0.04 ppbv and the lowest peak occurred in May 2005 to 2013 at a concentration 0.02 ppbv. The monthly average of BrO concentration shows a maximum value in February, while the minimum occurred in May 2005-2013 at 100 hPa pressure (Figure 3-6).

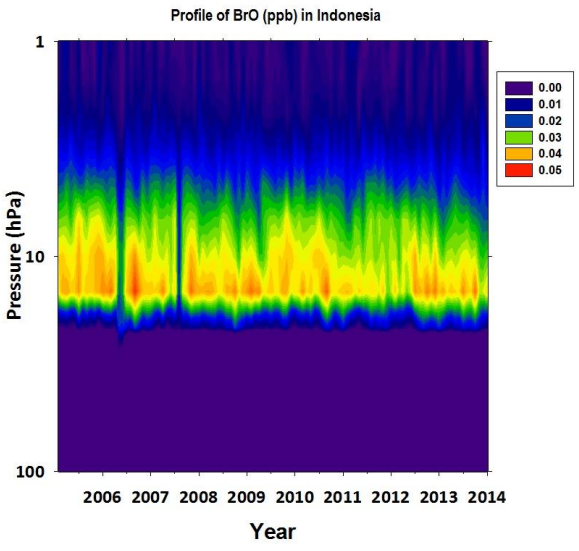

Figure 3-5: Time series graph of Indonesia's BrO profile from MLS in 2005 to 2013

Seasonal variations average reached a peak in December-January-February (DJF) and the minimum occurred in March-April-May (MAM) (Figure 3-7).

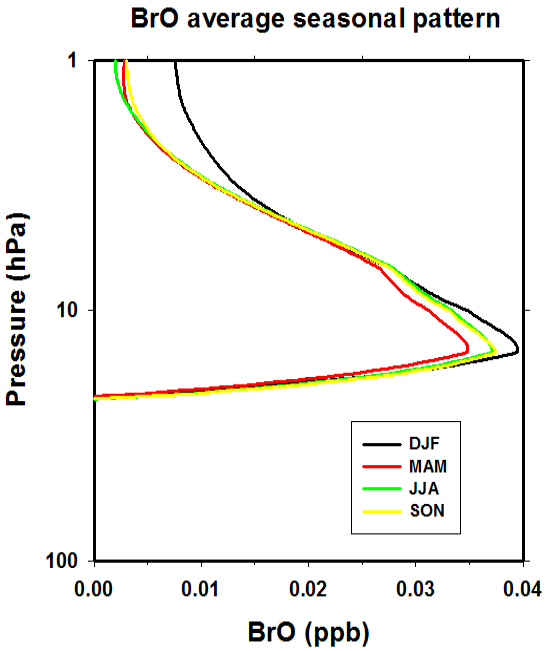

Figure 3-7: The BrO average seasonal pattern profile in Indonesia

Ozone concentration time series, ClO and BrO is at 14 hpa, 10 hPa and 2 hPa. Time series were taken at a height of 14 hPa, when BrO in Indonesia reached maximum, at 10 hPa this is a condition in which ozone reached the peak, while 2

hPa height—when the concentration of ClO reached peak. From these analyzes, we can see the effect of ODS on ozone.

Figure 3-8 tells the time series of ozone in Indonesia at 14 hpa, 10 hPa and 2 hPa. Ozone time series in Indonesia at 14 hPa shows the ozone concentrations ranging from 9 ppm to 10 ppm. At 10 hPa, ozone reaches 10 ppm to 11 ppm. At 2 hPa, ozone is detected at 3.5 ppm to 6.2 ppm.

CIO time series at 14 hpa, 10 hPa and 2 hPa are displayed in Figure 3-9. At 14 hPa ClO was detected between 0.10 ppb to 0.12 ppb. At 10 hPa ClO, the concentration ClO is between 0.13 ppb to 0.17 ppb. At 2 hPa ClO over Indonesia reaches a maximum at a concentration of 0.2 ppb to 0.36 ppb. Observation in the Arctic, ClO mixing ratio is detected up to 2.2 ppb (Connors et al., 2007). In Indonesia, ClO at 2 hPa has same concentration with Arctic, so that at 2 hPa ClO is potentially damaging ozone.

BrO time series at 14 hpa, 10 hPa and 2 hPa are displayed in Figure 3-10. At 14 hPa, BrO is detected between 0.028 ppb to 0.048 ppb. At this level, BrO is detected reach the highest concentration. At 10 hPa BrO concentration is between 0.015 ppb to 0.04 ppb. At 2 hPa, BrO over Indonesia is detected minimum with 0.002 ppb to 0.01 ppb concentration. According to Martinez (1999), BrO at normal levels in the atmosphere is 15 ppt. It is equivalent to 0.015 ppb. At 10 hPa and 14 hPa, BrO in Indonesia is higher than the normal value, so BrO at 10 hPa and 14 hPa is potentially depleting ozone.

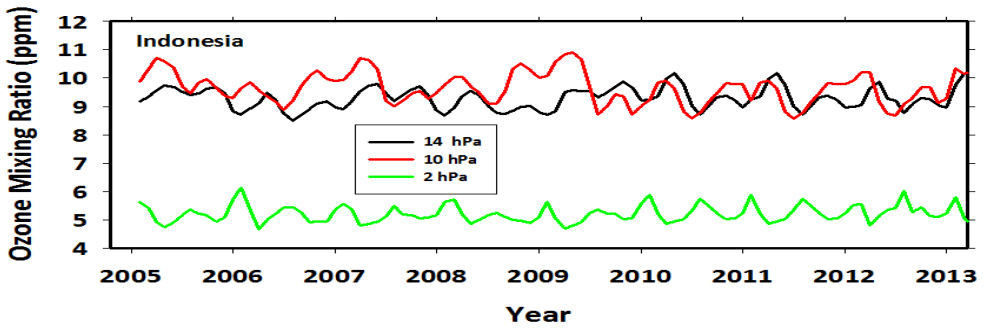

Figure 3-8: Time series of ozone Indonesia at 14 hPa, 10 hPa and 2 hPa

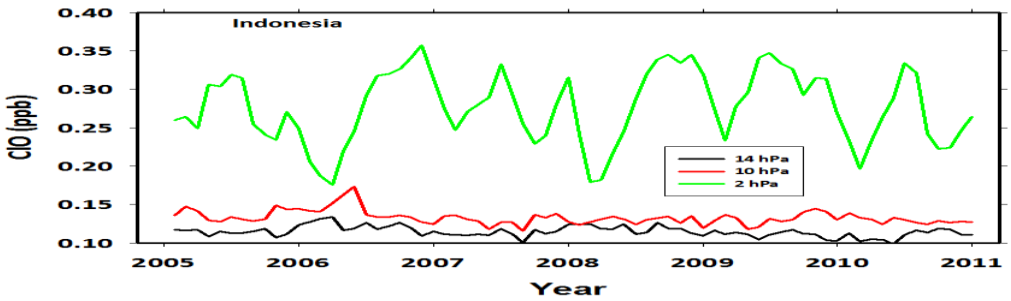

Figure 3-9: ClO Time series in Indonesia at 14 hPa, 10 hPa and 2 hPa

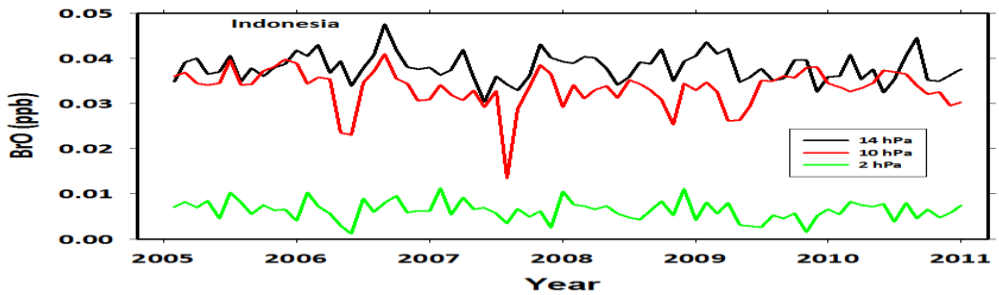

Figure 3-10: BrO time series Indonesia at a height of 14 hPa, 10 hPa and 2 hPa

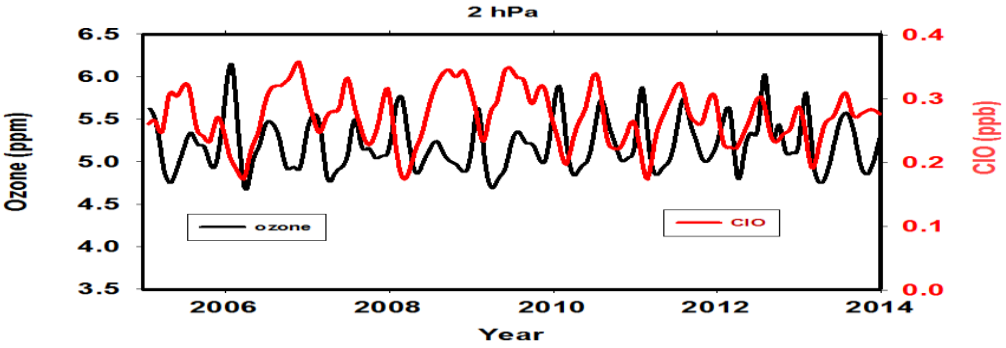

Figure 3-11: Graph of ozone and ClO time series in Indonesia at 2 hPa latitude

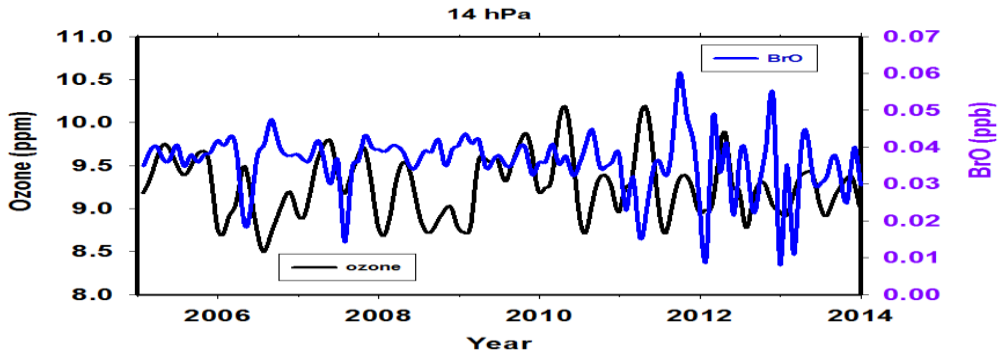

Figure 3-12: Graph Ozone and BrO time series in Indonesia at 14 hPa

ClO time series and ozone is at 2 hPa when the ClO concentration reaches the maximum as shown in Figure 3-11. At this altitude, the concentration of ozone in Indonesia is detected at 3.5 to 6.2 ppm and the ClO concentration is between 0.05 to 0.35 ppb. We can see that there is a tendency of minimum ozone when the ClO reached its maximum, especially in January and July. Nonetheless, we still require studies on chemical processes and dynamics that affect ClO in the atmosphere and its effect on ozone.

Ozone time series compared with BrO at 14 hPa pressure when BrO reaches the peak is shown in figure 3-12. The opposite pattern is shown in the graph when BrO has high concentration and ozone concentrations tend to be low. Conversely, when BrO concentration is low, the ozone concentration is increased. BrO and ozone time series is at 14 hPa, when BrO concentration reached a maximum. At this altitude the ozone in Indonesia shows 8 ppm to 10.5 ppm and BrO is between 0.001 ppb to 0.06 ppb. In Figure 3-12, we can see there is a tendency of minimum ozone when BrO reaches its maximum.

The linkage between ClO and ozone at 2 hPa can be seen in figure 3-13. The linear regression equation of the link between ClO and ozone at 2 hPa is $y = -0.583x + 5.363$.

By using this equation, in each additional 0.01 ppb, the ClO will reduce 0.00583 ppm (= 5.83 ppb) of ozone.

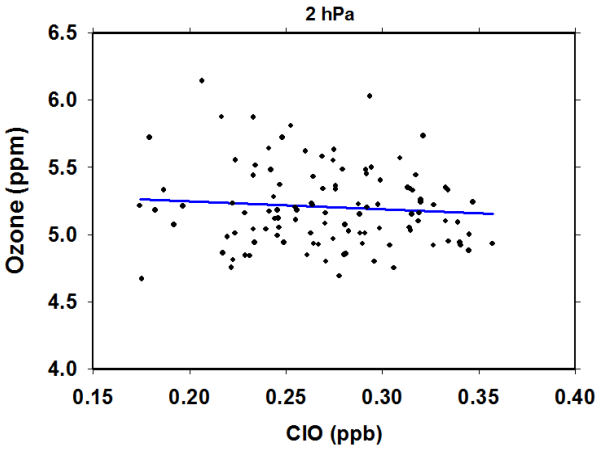

Figure 3-13: Graph of ozone and ClO correlation in Indonesia at 2 hPa

The correlation between BrO and ozone at 14 hPa is shown in Figure 3-14

with the linear regression: y = - 0.003 x + 0067. From this equation, every addition 0.01 ppb of BrO can reduce 0.03 ppb ozone.

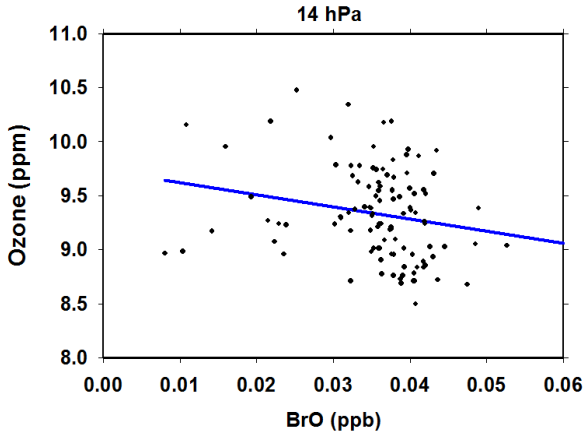

Figure 3-14: Graph of ozone and BrO correlation in Indonesia at 14 hPa

From the analysis, we can compare that 0.01 ppb of ClO can reduce ozone at 5.83 ppb, while 0.01 ppb of BrO can reduce 0.03 ppb ozone. From the results of this analysis, we see that the ClO is 194 greater in depleting ozone compare with BrO.

4 CONCLUSIONS

The results of the analysis of ozone monthly profile time series in Indonesia from MLS AURA in 2005 to 2013, and the average profiles in 2005 to 2013, we obtained peak of ozone profiles which occurs at 10 hPa between 9.04 ppm to 10.24 ppm. The Ozone Depleting Substances (ODS) which were studied are ClO and BrO. The ClO profile peak occurs at 2.1 hPa pressures or 30.6 km altitude and BrO reaches peak at 14 hPa pressure or altitude of 24.5 km. ClO and BrO reaching a maximum concentration at stratospheric altitude are potentially damaging the ozone molecules in stratosphere.

Ozone temporal variations and ODS show that there is a decrease tendency of ozone concentration when ODS (ClO and BrO) is increased.

The linear regression between ozone and ODS showed negative correlation coefficients, it means there is a strong relationship between the decrease of ozone concentration with an increase of BrO in 14 hPa pressure, when the BrO reaches its peak. Likewise for ClO which showed a negative correlation between the increase of ClO at 2 hPa with a decrease of ozone concentration.

ClO contributes to the reduction of ozone in Indonesia. It will occur when there is an increase 0.01 ppb of ClO, it will reduce ozone at 0.00583 ppm (5.83 ppb). Whereas any increase 0.01 ppb of BrO will reduce 0.03 ppb of ozone. From the results of this analysis, we see that the ClO is 194 greater in depleting ozone compare with BrO.

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