Vertical profile variations of ozone in lower stratosphere in Indonesia and influence to upper troposphere ozone based on satellite

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Abstract. This study examined the vertical profile and ozone variation in the lower stratosphere in Indonesia using AQUA/AIRS and AURA/MLS satellite data. Ozone in the stratosphere as an important component in atmospheric chemistry as well as radiation and climate becomes important to learn. Seasonal vertical profiles, time-varying vertical profiles, ozone seasonal variations at pressures of 100 hPa and 70 hPa, ozone time series at pressures of 100 hPa and 70 hPa from 2002 to 2016, average zonal variation (influence latitude) ozone concentrations in Indonesia, and the comparison of the vertical profiles of ozone, HCl, and N₂O in the lower stratosphere layer in Indonesia from MLS/AURA satellite data have been done to understand the variation of ozone in the lower stratosphere in Indonesia. The results show that the vertical ozone profile increased from the tropopause then the lower stratosphere to the middle stratosphere with the highest concentration of up to 9 ppmv. The monthly variation of ozone climatology at 70 hPa shows a pattern with a maximum peak in August while at a pressure of 100 hPa it indicates the presence of two maximum peaks in June and September. Time series of ozone at 100 hPa and 70 hPa from 2002 to 2016 show that ozone concentration tended to be constant with very small concentration increase occurring at 70 hPa and 100 hPa. Zonal variation shows the lowest ozone concentration at zero degrees latitude compared to other latitudes, and the vertical profile of ozone has the same pattern as HCl while it is different from N₂O. Vertical-time series cross section of ozone and Potential Vorticity (PV) in upper troposphere show influenced of stratospheric air into upper tropospheric air which showed by higher ozone and PV value and can reach until pressure 150 hPa occurred in the same season.

1. Introduction
Ozone (O₃) in the stratosphere is known to shield the surface from harmful ultraviolet radiation, while in the middle and high troposphere ozone it is the third most important greenhouse gas after carbon dioxide (CO₂) and methane (CH₄). Scientific efforts to understand the trends and variation in ozone observed over the past few decades have demonstrated the role of both photochemical and meteorological factors in driving stratospheric ozone changes. It has been known that these stratospheric changes have altered the tropospheric ozone burden over the past few decades and will continue to affect it in the future [1]. The abundance of stratospheric ozone is sensitive to both chemical and dynamical factors and has been altered by anthropogenic activity [2].
The basic overturning of the stratosphere described by Brewer [3] more than fifty years ago, with low-ozone tropospheric air entering the stratosphere in the tropics and high-ozone air returning to the troposphere in the mid and high latitudes [3,4]. The characterization of troposphere and stratosphere had been done by different dynamical and chemical properties with strong gradients of Potential Vorticity (PV) and ozone at the tropopause. Some definitions of chemical tropopause are popular, such as ozone tropopause criterion which defines the tropopause as the altitude at which ozone mixing ratio is greater than 80 ppbv, at which ozone gradient exceeds 60 ppbv/km in a depth of 200 m, and the ozone above the tropopause exceeds 110 ppbv [5]. Lower stratospheric and upper tropospheric ozone air are highly correlated [6,7]. The stratosphere is characterised by high value of PV and ozone concentration, so intrusion of stratospheric air is expected to bring PV and ozone rich air into troposphere [8,9]. Stratospheric intrusions along the subtropical jet stream occur outside the tropics but can bring extratropical lower stratospheric air into the tropical middle and upper troposphere [10,11]. For ozone in the tropical lower stratosphere, the chemistry is dominated by ozone production from photolysis which contributes to annual cycle, and in lower stratospheric ozone concentrations has been linked to annual cycle in upwelling of the stratospheric residual circulation [12,13].

Various chemical and dynamical process that control concentration of upper tropospheric and lower stratospheric ozone such as photochemical production within the troposphere, downward/upward transport from the stratosphere/troposphere through Stratosphere-Troposphere-Exchange (STE) [14], deep convection [15], and transport process within the troposphere [16]. Long term trends in tropospheric and lower stratospheric ozone show a complex pattern over the globe and in some cases are driven by regional influences. There are few focused studies reporting ozone trends in the lower stratosphere over the tropical region. Randel and Thompson [17] reported statistically significant negative trends between 0.2-0.4% per year in the tropical lower stratosphere (17-21 km) using Stratospheric Aerosol and Gas Experiment (SAGE II) data (1984-2005) and Southern Hemisphere Additional Ozonesondes (SHADOZ) measurements (1998-2009). Another result about decreasing ozone trends in the tropics (-10% below 20 km) has been reported by Randel and Wu [18]. Another research about seasonal variation of ozone in the lower stratosphere has been done by Stolarski [19]. The research has shown that the seasonal cycle of ozone is stronger in the northern tropical lower stratosphere than that in southern tropical lower stratosphere. These differences in the seasonal variations between hemispheres imply hemispheric differences in the transport in the tropical lower stratosphere [19].

This study focuses on analyses variation of vertical profile ozone in lower stratosphere and the influence of ozone from lower stratosphere to upper troposphere in Indonesia using AQUA/AIRS satellite data. This paper also reports the vertical profile of ozone in lower stratosphere compared with another trace gases that are nitrous oxide (N$_2$O) and hydrochloride acid (HCl) from AURA/MLS satellite data. To determine the influence of ozone from lower stratosphere to upper troposphere, we compare the vertical profile-time series and seasonal for ozone and PV data from Modern Era Retrospective-analysis for Research and Application (MERRA) reanalysis in the upper troposphere.

2. Data and Methodology
We examined the behaviour of vertical profile lower stratospheric ozone over Indonesia using Atmospheric Infra-Red Sounders (AIRS) sensors on AQUA satellite data from 2002 to 2016. We chose vertical profile ozone area average from 90° E – 150 °E and 15 °South – 15 °North at pressure 100 hPa to 10 hPa for analysis of lower stratospheric ozone profile over Indonesia. We compared behaviour of ozone at 70 hPa as the initial pressure of the lower stratosphere layer after the tropopause (100 hPa) measured by AIRS/AQUA sensor, with behaviour of ozone in the tropopause layer. The change of ozone concentration in lower stratosphere compared with tropopause was analysed by time series (trend) ozone concentration at 70 hPa and 100 hPa. The influence of geographic position (latitude) on changes of ozone concentration was analysed by zonal variation of ozone concentration at 70 hPa and 100 hPa. We also compared the vertical profile of ozone with vertical profile of another trace gases that are Nitrous oxide (N$_2$O) and Hydrochlorid Acid (HCl) from Microwave Limb Sounder.
(MLS) sensor data on AURA satellite to know the differences of their behaviour in lower stratosphere layer. Influences of lower stratospheric ozone concentration into upper tropospheric ozone were analysed by comparing vertical profile-time series and seasonal of ozone in upper troposphere at pressure 250 hPa until 100 hPa from AQUA/AIRS data with Potential Vorticity (PV) variation from MERRA reanalysis data as the tracer of stratospheric air influence with the higher PV value.

AIRS was launched on May 4, 2002 installed on the Aqua satellite with the primary objective was to accurately measure the vertical profile of temperature and water vapor in the Earth's atmosphere. The AIRS scientific team then developed methods for measuring the physical and chemical parameters of temperature, water vapor, ozone, and CO. The ozone data from AIRS used in this paper are version 6 level 3 gridded with 1° x 1 spatial resolution [20]. Vertical profile ozone and temperature data from AIRS have been validated using ozonesonde data in Watukosek Jawa Timur. The comparison result show good agreement with the AQUA-AIRS satellite overpass data with correlation coefficient of 0.98 for ozone mixing ratio and 0.99 for temperature [21].

The AURA MLS sensor has the ability to measure atmospheric chemical parameters including HNO$_3$, N$_2$O, and ozone with global coverage area and with good enough data resolution with 3 km vertical resolution and 200 km spatial resolution [22]. MLS observes thermal radiation on Earth-emitted micro waves and records data from surface to a height of 90 km. MLS measures vertical profiles at 3500 locations in the world every 24 hours [22]. The MLS instrumentation is equipped with four types of radiometers operated at ambient temperatures in five spectral regions which are capable of detecting the O$_2$ spectrum including measuring temperature and pressure, H$_2$O, HNO$_3$, O$_3$ in the upper troposphere, CO, HCl, ClO, BrO, HO$_2$, N$_2$O, and OH [23].

The Modern Era Retrospective-Analysis for Research and Applications (MERRA) was undertaken by NASA's Global Modeling and Assimilation Office with two primary objectives: to place observations from NASA's Earth Observing System satellites into a climate context and to improve upon the hydrologic cycle represented in earlier generations of reanalyses. MERRA was generated with version 5.2.0 of the Goddard Earth Observing System (GEOS) atmospheric model and data assimilation system (DAS), and has covered the modern satellite era from 1979 to the present [24]. In this study, we use Potential Vorticity (PV) data from MERRA monthly averages in upper troposphere with spatial resolution 0.5° x 0.625°.

3. Result and Discussion
3.1 Lower stratosphere ozone vertical profile variation
Time series-vertical cross section variation and seasonal ozone vertical profile at lower stratosphere for December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON) are shown in Figure 1. Ozone concentrations show higher value at higher altitude or lower pressure with maximum ozone shows at pressure 10 hPa, where the ozone layer exists, the values reached 9000 ppbv or 9 ppmv (Figure 1a). Vertical profile of ozone concentrations shows small differences in tropopause (pressure 100 hPa) while higher differences are shown in upper part of lower stratosphere (pressure 10 hPa). At pressure 10 hPa the minimum value of ozone in JJA reached 8891 ppbv or 8,891 ppmv and the maximum value of ozone in MAM reached 9479 ppbv or 9,479 ppmv (Figure 1b). Ozone in lower stratosphere over Indonesia also shows annual and semi-annual variation due to the annual variation of Brewer Dobson Circulation (BDC) and Quasi Biennial Oscillation (QBO) [12,25].

Monthly variation of ozone and temperature in tropopause (pressure 100 hPa Figure 1a) and in lower stratosphere (pressure 70 hPa Figure 1b) is shown in Figure 2 and Figure 3. Ozone in tropopause as a boundary layer between troposphere and stratosphere is influenced by tropospheric and stratospheric air characteristics [26]. While in the lower stratosphere, the characteristics of the troposphere air are diminished with the stratospheric air characteristics, so comparing the monthly variations of ozone in the tropopause and in the lower stratosphere is important to recognize differences in ozone characteristics in both regions. Due to both radiative and dynamical processes, there is a strong positive correlation between ozone and temperature in lower stratosphere [27]. We
can see from Figure 2 and Figure 3 that monthly ozone variation in the tropopause has 2 maximum peaks in June and September with value around 0.16 ppmv which is also consistent with monthly variation of tropopause temperature (Figure 3). Monthly variation of ozone in the lower stratosphere at pressure 70 hPa (Figure 2b) also shows similar feature with temperature at the same level pressure (Figure 3b) which has one maximum peak value in Augustus with value around 0.5 ppmv.

![Figure 1. (a) Time series-vertical cross section and (b) seasonal vertical profile ozone concentration (ppbv) at lower stratosphere (pressure 100 hPa until 10 hPa) over Indonesia from 2002 to 2016.](image-url)
Figure 2. Monthly average climatology variation of ozone concentration (ppmv) (2002-2016) over Indonesia at pressure (a) 100 hPa and (b) 70 hPa.

Figure 3. Monthly average climatology variation of temperature (K) (2002-2016) over Indonesia at pressure (a) 100 hPa and (b) 70 hPa.

The changes of ozone concentration in tropopause and lower stratosphere are shown in Figure 4. Ozone concentration at two different level pressure shows higher value of ozone at lower stratosphere (pressure 70 hPa) than at tropopause (pressure 100 hPa). It happened because ozone in mid-stratosphere is actually very rich on pressure 10 hPa that makes ozone becomes higher in lower stratosphere than in tropopause. Ozone concentration in lower stratosphere shows the value around 0.3 ppmv until 0.5 ppmv with linear trend shows very small increase around 0.01 ppmv for 14 years of measurement. Comparing to ozone in lower stratosphere, ozone in tropopause (pressure 100 hPa) shows a lower value around 0.1 ppmv until 0.165 ppmv with a smaller increase only 0.0035 ppmv for 14 years measurement. The increase of ozone concentration in the stratosphere was estimated because of several factors, which are the decreased amount of ozone depleting substances (ODS) and the decrease of stratospheric temperature due to the increased amount of greenhouse gases in troposphere [28]. Ozone in lower stratosphere and tropopause shows similar pattern to annual and semi-annual variation with peak value occurs around Augustus-September and minimum value occurs around February-March.
Figure 4. Time series ozone concentration (ppmv) at pressure 100 hPa and 70 hPa from 2002 to 2016 over Indonesia.

The differences of ozone variation also depend on geographic positions or latitude as shown in Figure 5. Ozone over Indonesia on latitude -15 °S to 15 °N shows that the concentration of ozone is higher in Northern part than in Southern part of Indonesia, while over the equator on latitude 0 degree ozone shows minimum peak value. Stolarski [19] shows the same result on ozone concentration which is higher in the Northern hemisphere than Southern hemisphere due to the interhemispheric differences in both magnitude and phase of variation in the upwelling and mixing.

Figure 5. Zonal mean (based on latitude) of ozone concentration (ppmv) in 2002-2016 at pressure 100 hPa and 70 hPa over Indonesia.

The same phenomenon occurs at two different level pressure in the tropopause (100 hPa) and in the lower stratosphere (70 hPa) with ozone concentration higher in lower stratosphere compared to tropopause. Based on zonal mean variation, ozone concentration in lower stratosphere (70 hPa) shows value around 0.26 ppmv until 0.61 ppmv, while ozone concentration in tropopause (100 hPa) shows lower value around 0.1 ppmv until 0.2 ppmv. The concentration of ozone also shows higher value on July compared to January due to the rainy season over Indonesia occurs on January that makes ozone destructed by water vapour.

Ozone is a stratospheric tracer which is dominantly formed in the middle to upper stratosphere and then transported to the rest of the stratosphere. This feature also similar with HCl which is a long lived reservoir for chlorine in the stratosphere, while N₂O has different feature that is released in the
troposphere and transported up to the stratosphere [19]. To compare ozone at lower stratosphere with another trace gases which are HCl and N$_2$O is shown on vertical profile of ozone, HCl, and N$_2$O in the lower stratosphere from AURA/MLS satellite data shown on **Figure 6**. We can see that ozone and HCl vertical profile has similar pattern which has lower concentration at lower stratosphere then increase until the middle stratosphere, while N$_2$O shows higher concentration in lower stratosphere then decrease until the middle stratosphere. It is correlated with the source that is dominantly in the middle stratosphere for ozone and HCl, while N$_2$O sources is dominantly from the troposphere.

**Figure 6.** Vertical profile mean of ozone, HCl, and N$_2$O concentration at lower stratosphere for January and July at pressure 100 hPa until 10 hPa from MLS/AURA satellite.

The differences between ozone, HCl, and N$_2$O also shown on seasonal variation on **Figure 7**. Ozone and HCl show similar pattern on seasonal variation which has maximum peak value around Augustus-September, while N$_2$O occurs minimum value on the same season when ozone and HCl reach maximum concentration. The similar pattern also shown by PV value seasonal variation which show maximum value around June.

**Figure 7.** Seasonal variation of ozone, HCl, and N$_2$O concentration and PV value in lower stratosphere at pressure 68 hPa from MLS/AURA satellite and MERRA data reanalysis.

This different behaviour between ozone, HCl, and N$_2$O in the tropical lower stratosphere over Indonesia is also shown in the result by Stolarski’s study [19]. It happens due to seasonality of transport operating on tracer gradients. Transport in tropical lower stratosphere is primarily due to a combination of vertical advection and mixing between the tropics and extra tropics. The phase and relative amplitude of the tracer annual cycles will depend on the seasonality of the upwelling and mixing between the tropics and extra tropics as well as the vertical and horizontal tracer gradients [19].
3.2 Influence of lower stratospheric ozone into upper tropospheric ozone in Indonesia

Time series-vertical cross section of ozone and potential vorticity in the upper troposphere are shown in **Figure 8**. It can be seen that ozone in the tropopause at pressure 100 hPa shows higher value and it can reach until upper tropopause at pressure 150 hPa. This feature also shows the variation of PV value in the tropopause which also shows higher value and it reaches until the upper troposphere at pressure 150 hPa. It indicates that ozone from the lower stratosphere can also influence ozone in the upper troposphere. Higher ozone and PV value indicate stratospheric air characteristics which can be transported into upper troposphere through stratosphere-troposphere transport.

![Figure 8](image1.png)

**Figure 8.** Time series-vertical cross section for ozone concentration (a) and Potential Vorticity (PV) (b) in the upper troposphere from pressure 250 hPa until 100 hPa.

Similar feature also can be seen in the seasonal variation in time series-vertical cross section of ozone and PV in 2014-2015 as shown in **Figure 9**. It can be seen clearly that higher concentration of ozone ~150 ppbv in the tropopause can crosses and enters the upper troposphere until pressure 150 hPa.

![Figure 9](image2.png)

**Figure 9.** Seasonal vertical cross section of ozone concentration (a) and Potential Vorticity (PV) (b) from year 2014-2015 in the upper troposphere from pressure 250 hPa until 100 hPa.
The pattern also happens to variations of PV in which higher value was reached until upper troposphere and consistent with ozone variations. **Figure 9** shows the same season when higher concentration of ozone reaches the upper troposphere from Mei to October when high PV also reached the upper troposphere. It indicates that some of stratospheric air has been influenced to upper tropospheric air.

4. Conclusions
Vertical profile variation of ozone in the lower stratosphere Indonesia shows higher value at higher altitude with the maximum peak occurred at pressure 10 hPa (middle stratosphere), the value reached 9000 ppbv or 9 ppmv. Monthly variation of ozone and temperature at lower stratosphere and tropopause shows consistently 2 maximum peaks in June and September which occurred in tropopause, while 1 maximum peak occurred in Augustus-September in lower stratosphere. The changes of lower stratosphere ozone concentration show a very small value around 0,01 ppmv for 14-year measurement, smaller changes occurred in the tropopause. Ozone variation in lower stratosphere Indonesia is also influenced by geographic position which is shown that ozone in Northern part of Indonesia is higher than in equatorial region. Ozone and another trace gases, HCl and N$_2$O, shows that ozone and HCl have the same pattern in vertical profile with lower value in lower stratosphere and get increased until middle stratosphere, and seasonal variation shows maximum value around Augustus. Different pattern occurred to N$_2$O. The influence of stratospheric ozone into upper tropospheric ozone has been from time series vertical cross section of ozone and PV which shows that higher ozone and PV from tropopause could reach the upper troposphere until pressure 150 hPa occurred for the same season.

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