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Trends in Water Vapor and Ozone Concentrations at Several Altitudes in the Indonesian Region due to the La Niña Phenomenon

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ABSTRACT

We observed the effect of the La Niña phenomenon on the concentration of water vapor and ozone in the Indonesian region. This aims to the value of water vapor and ozone concentrations due to the La Niña phenomenon using Microwave Limb Sounder (MLS) data from 2004-2022. The La Niña phenomenon was chosen because during La Niña, the sea surface temperature in Indonesia is warmer than normal, thus increasing the evaporation of sea water which result is an increase in the concentration of water vapor in the atmosphere. Concentration values are observed at altitudes of (25.7;30.5;35.3;40.1) km because there are trends in water vapor and ozone concentrations at these altitudes. The La Niña phenomenon is used to see anomalies in water vapor and ozone concentrations from their normal state. La Niña phenomenon is observed based on the ONI index. We found that during La Niña, the water vapor concentration increased from its normal state while the ozone concentration decreased from its normal state. These two concentration values were used to find trends using Mann Kendall and Sen's Slope methods. We found that the trend of water vapor concentration is statistically significant while the trend of ozone concentration is the opposite.

1. INTRODUCTION

Water vapor is a type of greenhouse gas that plays an important role in the Earth's radiation balance (Zhu et al., 2021). Water vapor in the stratosphere plays an important role in stratospheric ozone chemistry, although the amount is relatively small compared to the troposphere (Jiang et al., 2015). The concentration of water vapor in the atmosphere is much higher than other greenhouse gases, so variations or changes in water vapor concentration have an influence on the energy balance in the atmosphere and the depletion of the ozone layer (Peng et al., 2017). Variations in water vapor concentration in the atmosphere can be influenced by several factors, including temperature, humidity, and the ENSO (El-Niño Southern Oscillation) phenomenon. In the research conducted, ENSO phenomenon factors were observed, namely La Niña. La Niña is one of the ENSO phenomena that affects rainfall and climate around the world, including Indonesia. When La Niña occurs, rainfall in the Indonesian region generally increases from its normal state due to sea surface temperature anomalies during La Niña. In general, La Niña is triggered by cooling waters in the central and eastern tropical Pacific Ocean (Lu et al., 2019). The cooling of these waters weakens the easterly trade winds that normally dominate the region. As a result, upwelling (the lifting of cold deep ocean water to the surface) is reduced, resulting in less warm water supply to the atmosphere (Kelsey et al., 2022). This lack of warm water supply to the atmosphere leads to reduced evaporation and cloud formation over the central and eastern Pacific Ocean region. However, this effect is offset by increased convection activity and cloud formation over Indonesia.

The weakening of the easterly trade winds during La Niña allows moist westerly winds from the Indian Ocean to blow more strongly towards Indonesia. These moist winds supply large amounts of water vapor to Indonesia's atmosphere, further increasing the potential for rain cloud formation. As a result of increased convection activity and rain cloud formation, rainfall over Indonesia tends to increase during La Niña periods. This increase in rainfall is closely related to changes in the concentration of water vapor in the atmosphere. La Niña causes an increase in water vapor, especially in the Indonesian region, due to increased evaporation from stronger convection activity (Afyan, 2022). La Niña can also cause changes in atmospheric circulation patterns that can affect the distribution of water vapor in the atmosphere. These circulation patterns can bring water vapor from other regions into Indonesia. This can affect the concentration of water vapor in certain areas, further adding to the complexity of variations in water vapor concentration in Indonesia. Although La Niña is only one of many factors that affect atmospheric water vapor concentrations, its potential to increase water vapor distribution makes La Niña a crucial phenomenon to study. By understanding the La Niña phenomenon, it can improve the understanding of climate and weather in Indonesia. Therefore, La Niña is used to see the variation of increased water vapor concentration in the Indonesian region.

Variations in water vapor concentration can be used to predict long-term trends in atmospheric phenomena, such as ozone layer depletion. To see whether water vapor can cause depletion of the ozone layer, several heights in the stratosphere layer were selected, namely 25.7 km, 30.5 km, 35.3 km, and 40.1 km because at this height there are trends in water vapor and ozone. Water vapor found in the stratosphere layer can be split into hydroxyl radicals (OH) and oxygen atoms (O) through photodissociation (the process of breaking molecules by UV radiation). These hydroxyl radicals are the catalyst in the depletion of the ozone layer. Ozone is present in the stratospheric layer, which serves as a protective shield and absorbs harmful ultraviolet (UV) radiation. The La Niña phenomenon has a complex influence on ozone concentrations in the stratosphere of the Indonesian region. La Nina can increase or decrease ozone transport from the stratosphere to the troposphere and affect the thickness of the stratospheric ozone layer. La Niña weakens the vertical airflow (Hadley flow), which carries ozone from the stratosphere to the troposphere. This decrease in airflow leads to a decrease in ozone production in subtropical regions. La Niña generally causes an increase in ozone concentrations in equatorial regions, including Indonesia. This is due to an increase in vertical airflow, which carries ozone from the stratosphere to the troposphere (Ekwonu, 2016).

Research related to variations in water vapor and ozone concentrations has been carried out by several researchers in the world such as Jiang et al. (2015) analyzed water vapor using MERRA, ECMWF (European Centre for Medium-Range Weather Forecasts), and MLS (Microwave Limb Sounder) data. In this study, it was found that the results of water vapor analysis using MLS data were better than other data. Therefore, Microwave Limb Sounder (MLS) data was used to find the value of water vapor and ozone concentrations from 2004 to 2022. However, this study did not find a link between water vapor and ozone. Then, Davis et al. (2017) used MERRA-2 (Modern Era Retrospective Analysis for Research and Applications version 2), ERA-40, ERA-Interim, JRA-25, and JRA-55 data to analyze variations in water vapor and ozone in the troposphere and stratosphere layers. In this study, it was found that vertical variations in ozone were found in both layers, while variations in water vapor in the stratosphere layer were not found. Research on variations in water vapor concentration in relation to ozone layer depletion in Indonesia is still rare. Therefore, this study will analyze the variation of water vapor and ozone concentrations in the stratosphere of the Indonesian region. The La Niña phenomenon is used to see its influence on variations in water vapor and ozone concentrations. Then, the trend of water vapor and ozone concentrations was sought using the Mann Kendall and Sen's Slope methods.

2. METHOD

2.1 Conversion of Pressure Value to Altitude

Water vapor and ozone concentration data are obtained from the Microwave Limb Sounder (MLS) observation instrument. This instrument was installed on the Aura satellite launched by NASA

(National Aeronautics and Space Administration) in 2004. Water vapor and ozone concentration data from MLS were downloaded from the website https://disc.gsfc.nasa.gov/datasets/ML3MBH2O_004/summary?keywords=mls (water vapor) and https://disc.gsfc.nasa.gov/datasets/ML3MBO3_004/summary?keywords=mls (ozone). MLS data has the ability to measure water vapor and ozone concentrations at various observed pressures (Bresciani et al., 2018). This data has a spatial resolution of about 1-2 km and a temporal resolution of 1 hour. Since water vapor and ozone concentration values will be observed at several altitude levels in the atmosphere, it is necessary to convert pressure values from MLS data to altitude. This value conversion uses the hydrostatic equation.

The hydrostatic equation describes the relationship between atmospheric pressure, air density, and the Earth's gravitational acceleration under static conditions in the atmosphere (Kawo et al., 2022). In this condition, there is a balance of gravity and force due to the pressure gradient which causes atmospheric pressure to decrease with height above the earth's surface (Pittock, 2009), so the hydrostatic equation is obtained as follows:

$$\frac{dp}{dz} = -g\rho \tag{1}$$

Equation (1) shows that the higher the altitude in the atmosphere, the lower the atmospheric pressure. The negative sign in the equation above indicates that the pressure decreases with increasing altitude (Liou, 2002). In addition, this equation also shows that the density of air in the atmosphere will decrease with increasing altitude. Since $\rho = p/R'T$, Equation (1) can be converted into Equation (2).

$$dp = -\frac{gp}{R'T}dz \tag{2}$$

If the pressure at height z is $p(z)$, Equation (2) becomes:

$$\int_{p(0)}^{p(z)} \frac{1}{p} dp = \int_0^z -\frac{g}{R'T} dz \tag{3}$$

Since $g/R'T = H_0$, Equation (3) can be written as:

$$p(z) = p(0)e^{(-z/H_0)}, \tag{4}$$

where the pressure $p(0)$ used is 1 atm (1013.25 hPa) and the value of H_0 used is -0.00012. Thus Equation (4) can be made into:

$$z = \frac{\ln\frac{p(z)}{p(0)}}{-0,00012}. \tag{5}$$

In the vertical structure of the atmosphere, the hydrostatic equation is useful for understanding how the temperature, pressure, and density of air change with increasing altitude in the atmosphere (Hewitt & Jackson, 2003). In the research conducted, the conversion of pressure values to altitude uses a program application called Python. First, all MLS data variables contained in the water vapor and ozone data that have been downloaded from the website are read. Then, the region was cut (only Indonesia was taken). Then, several pressure values were selected: 46.4159 hPa, 26.1016 hPa, 14.678 hPa, and 8.25404 hPa which were then converted to altitude using Equation (5) as follows:

$$z = \frac{\ln\frac{p(z)}{p(0)}}{-0,00012} = \frac{\ln\frac{46.4159}{1013.25}}{-0.00012} = \frac{\ln 0.0458}{-0.00012} = \frac{-3.08347119}{-0.00012} = 25695.59 \text{ m} = 25.69559 \text{ km} = 25.7 \text{ km}$$

The same method is used to find the conversion of the pressure value to the next altitude value.

2.2 Determination of the La Niña phenomenon

The La Niña phenomenon is determined based on the ONI index (Oceanic Nino Index). Negative ONI values indicate La Niña conditions (ONI index value ≤ –0.5°C) (Zaini et al., 2024).

Table 1 ONI Index.

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2004	0,4	0,3	0,2	0,2	0,2	0,3	0,5	0,6	0,7	0,7	0,7	0,7
2005	0,6	0,6	0,4	0,4	0,3	0,1	-0,1	-0,1	-0,1	-0,3	-0,6	-0,8
2006	-0,9	-0,8	-0,6	-0,4	-0,1	0,0	0,1	0,3	0,5	0,8	0,9	0,9
2007	0,7	0,2	-0,1	-0,4	-0,4	-0,5	-0,6	-0,8	-1,1	-1,3	-1,5	-1,6
2008	-1,6	-1,5	-1,3	-1,0	-0,8	-0,6	-0,4	-0,2	-0,2	-0,4	-0,6	-0,7
2009	-0,8	-0,8	-0,6	-0,3	0,0	0,3	0,5	0,6	0,7	1,0	1,4	1,6
2010	1,5	1,2	0,8	0,4	-0,2	-0,7	-1,0	-1,3	-1,6	-1,6	-1,6	-1,6
2011	-1,4	-1,2	-0,9	-0,7	-0,6	-0,4	-0,5	-0,6	-0,8	-1,0	-1,1	-1,0
2012	-0,9	-0,7	-0,6	-0,5	-0,3	0,0	0,2	0,4	0,4	0,3	0,1	-0,2
2013	-0,4	-0,4	-0,3	-0,3	-0,4	-0,4	-0,4	-0,3	-0,3	-0,2	-0,2	-0,3
2014	-0,4	-0,5	-0,3	0,0	0,2	0,2	0,0	0,1	0,2	0,5	0,6	0,7
2015	0,5	0,5	0,5	0,7	0,9	1,2	1,5	1,9	2,2	2,4	2,6	2,6
2016	2,5	2,1	1,6	0,9	0,4	-0,1	-0,4	-0,5	-0,5	-0,7	-0,7	-0,6
2017	-0,3	-0,2	0,1	0,2	0,3	0,3	0,1	-0,1	-0,4	-0,7	-0,8	-1,0
2018	-0,9	-0,9	-0,7	-0,5	-0,2	0,0	0,1	0,2	0,5	0,8	0,9	0,8
2019	0,7	0,7	0,7	0,7	0,5	0,5	0,3	0,1	0,2	0,3	0,5	0,5
2020	0,5	0,5	0,4	0,2	-0,1	-0,3	-0,4	-0,6	-0,9	-1,2	-1,3	-1,2
2021	-1,0	-0,9	-0,8	-0,7	-0,5	-0,4	-0,4	-0,5	-0,7	-0,8	-1,0	-1,0
2022	-1,0	-0,9	-1,0	-1,1	-1,0	-0,9	-0,8	-0,9	-1,0	-1,0	-0,9	-0,8

2.3 Mann Kendall Trend Test

The Mann-Kendall trend test is a non-parametric method used to test for the presence of monotonic trends in time-sorted data (Gedefaw et al., 2018). A monotonic trend is defined as a consistently increasing or decreasing trend in time series data (Susanto et al., 2014). Time series data is given in x_1, x_2, …., x_n, where n is the amount of data used and there are x_i (data at time i) and x_j (data at time j), so the Mann-Kendall trend test is expressed as follows

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i) \tag{6}$$

Where S is the Mann Kendall trend test and $sign(x_j - x_i)$ is obtained from Equation (6)

$$sign(x_j - x_i) = \begin{cases} +1, if\ (x_j - x_i) > 0 \\ 0, if\ (x_j - x_i) = 0 \\ -1, if\ (x_j - x_i) < 0 \end{cases}. \tag{7}$$

If the resulting S value is positive, it indicates that the trend is upward and if the resulting S value is negative, it indicates that the trend is downward. Variance and Z test statistics are calculated to determine whether or not the trend in the data is statistically significant (El Kasri et al., 2021).

$$Var\ (S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18}, \tag{8}$$

where n is the number of data, m is the number of same valued data, and t_i is the number of same valued data in the i-th time series.

$$Z = \begin{cases} \frac{S-1}{Var\ (S)^{1/2}}, if\ S > 0 \\ 0, \qquad if\ S = 0 \\ \frac{S+1}{Var\ (S)^{1/2}}, if S < 0 \end{cases} \tag{9}$$

The Z value is used to determine if the observed trend is statistically significant. In the Z statistical test, hypotheses are used to identify significant trends, namely H_0 (there is no significant trend) and H_1 (there is a significant trend) (Sam et al., 2022).

2.4 Sen's Slope Trend Test

Sen's Slope trend test is a non-parametric method developed by Sen in 1968 to estimate the slope of a trend or linear trend in data (El Kasri et al., 2021). Sen's trend test has the ability to accommodate the influence of anomalous values (outliers) on the data (Gul et al., 2018). This trend test is expressed in Equation (9).

$$Q_i = \frac{(x_j - x_i)}{j-i}; i = 1,2,3, \dots, 1 \leq i < j \leq N \tag{10}$$

Where Q_i is the magnitude of the trend change in the time series, x_i and x_j are data values at time i and j respectively. The median of the N values is calculated using Equation (10).

$$Q_{med} = \begin{cases} Q_{\left[\frac{N+1}{2}\right]}, if\ N = \text{odd} \\ \frac{Q_{\left[\frac{N+1}{2}\right]} + Q_{\left[\frac{N+1}{2}\right]}}{2}, if\ N = \text{even} \end{cases} \tag{11}$$

A positive Q_{med} value indicates that the trend is increasing, while a negative Q_{med} value indicates that the trend is decreasing (Yanfatriani et al., 2024).

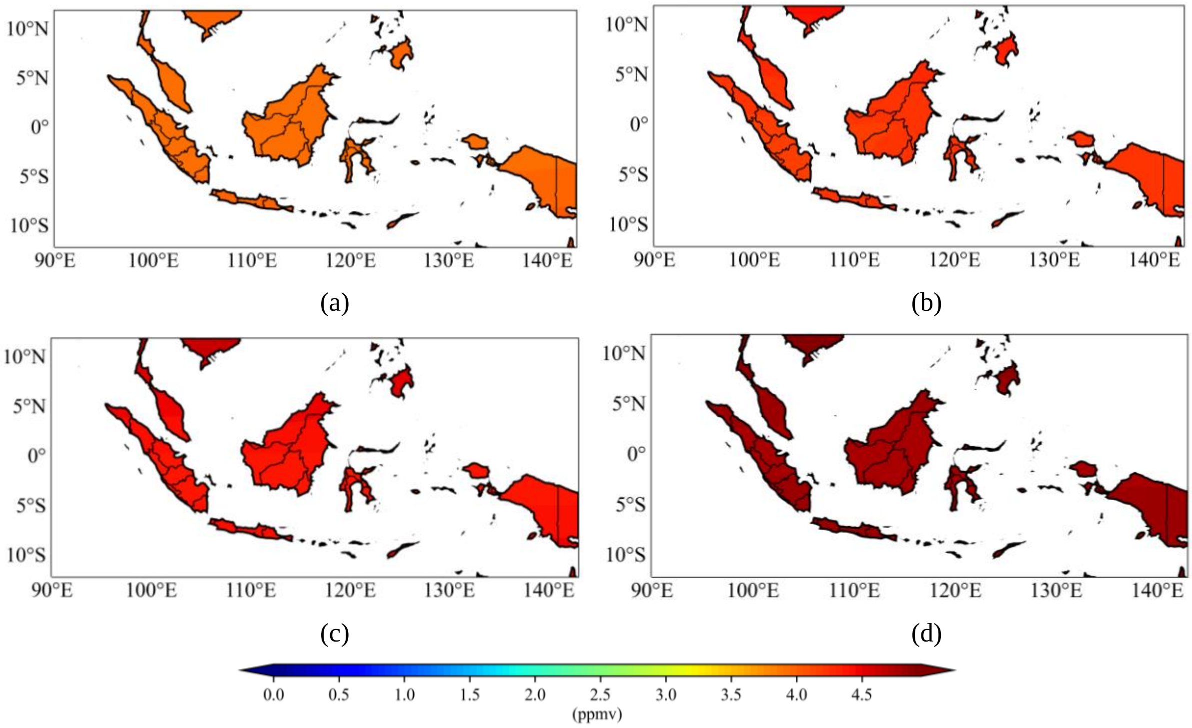

Figure 1 Average water vapor concentration from 2004-2022 under normal conditions at altitudes of (a) 25.7 km, (b) 30.5 km, (c) 35.3 km, and (d) 40.1 km.

3. RESULTS AND DISCUSSION

3.1 Effect of La Niña Phenomenon on Water Vapor and Ozone Concentrations

Figure 1 shows the spatial pattern of average water vapor concentration during normal conditions in Indonesia from 2004 to 2022. The average water vapor concentration was observed at several altitudes in the stratospheric layer. The average value of water vapor concentration varies with altitude. Based on the processing of the research data, the water vapor concentration value increases with increasing altitude in the atmosphere.

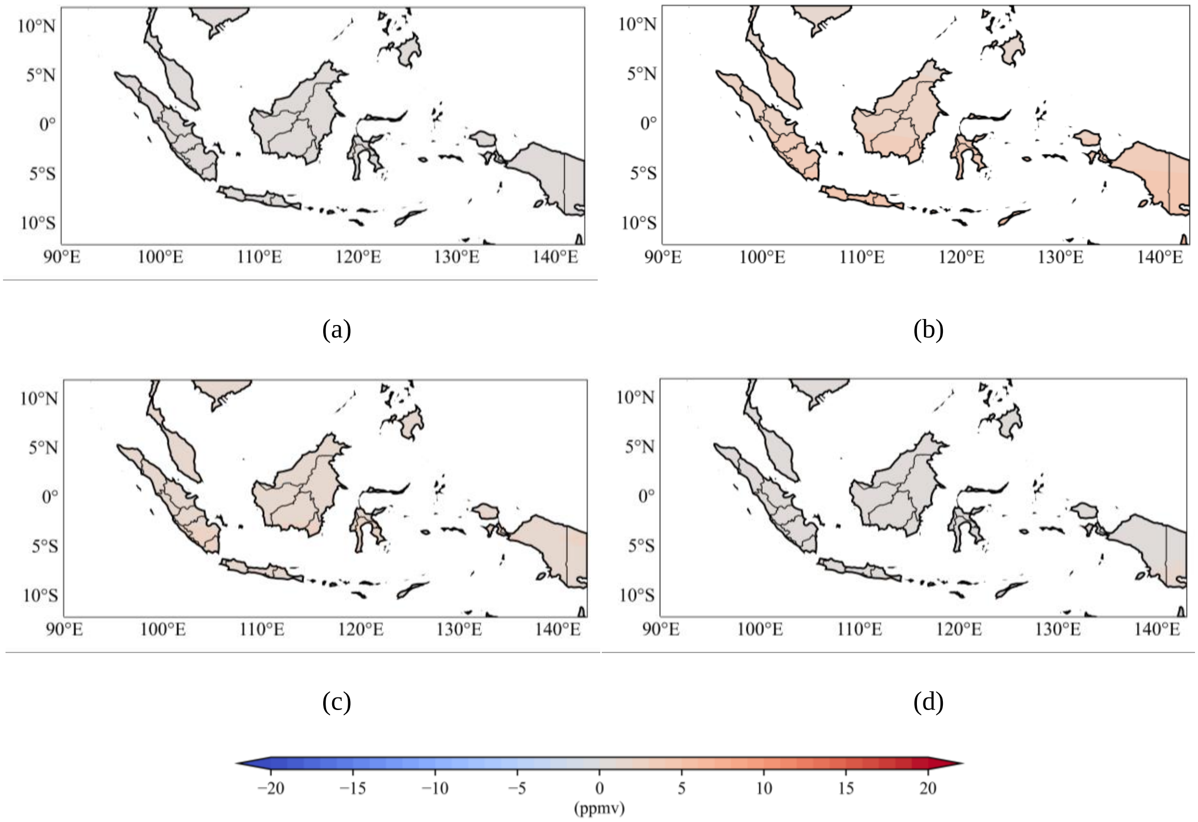

Figure 2 Spatial distribution of water vapor concentration anomalies from 2004-2022 during La Niña at altitudes of (a) 25.7 km, (b) 30.5 km, (c) 35.3 km, and (d) 40.1 km

Water vapor concentration anomalies are seen based on the La-Niña phenomenon because it affects the variation of water vapor concentration in Indonesia. The La-Niña phenomenon has been determined based on sea surface temperature anomalies using the ONI index (Oceanic Nino Index). The La-Niña phenomenon examined is during strong La-Niña (year 2022). Water vapor concentration in the Indonesian region generally increases during La-Niña from normal conditions. Figure 2 shows the spatial distribution of water vapor concentration anomalies from 2004-2022 during the strong La Niña in 2022 at several altitudes in the stratospheric layer. in Figures 2(a) and 2(d) the increase in water vapor concentration is around 1.5 ppmv - 3 ppmv while in Figures 2(b) and 2(c) the increase in water vapor concentration is around 5 ppmv - 10 ppmv. The increase in water vapor concentration is evenly distributed throughout Indonesia.

During the La Niña phenomenon, sea surface temperatures in Indonesia are warmer than normal. Warmer sea surface temperatures can cause stronger convection so that the concentration of water vapor in the atmosphere tends to increase (Rosenlof & Reid, 2018). An increase in water vapor concentration can also be triggered by the oxidation of methane (CH_4). Methane is a greenhouse gas that results from various human activities, such as fossil fuel combustion, agriculture and livestock farming. When methane is released into the atmosphere, it can be oxidized through a complex chemical process. Methane oxidation involves reactions with hydroxyl radicals (OH) and ozone (O_3), producing carbon dioxide (CO_2) and water vapor (H_2O) (Kiat et al., 2019).

Meanwhile, the La Niña phenomenon has a complex impact on atmospheric ozone concentrations and its effects can be different at different altitudes as shown in Figure 3. Ozone concentrations have increased and decreased. This increase and decrease in ozone concentration is evenly distributed throughout Indonesia. Ozone concentrations increased by 1 ppmv as the La Niña phenomenon strengthened the vertical airflow (Hadley flow) in the tropical Pacific Ocean.

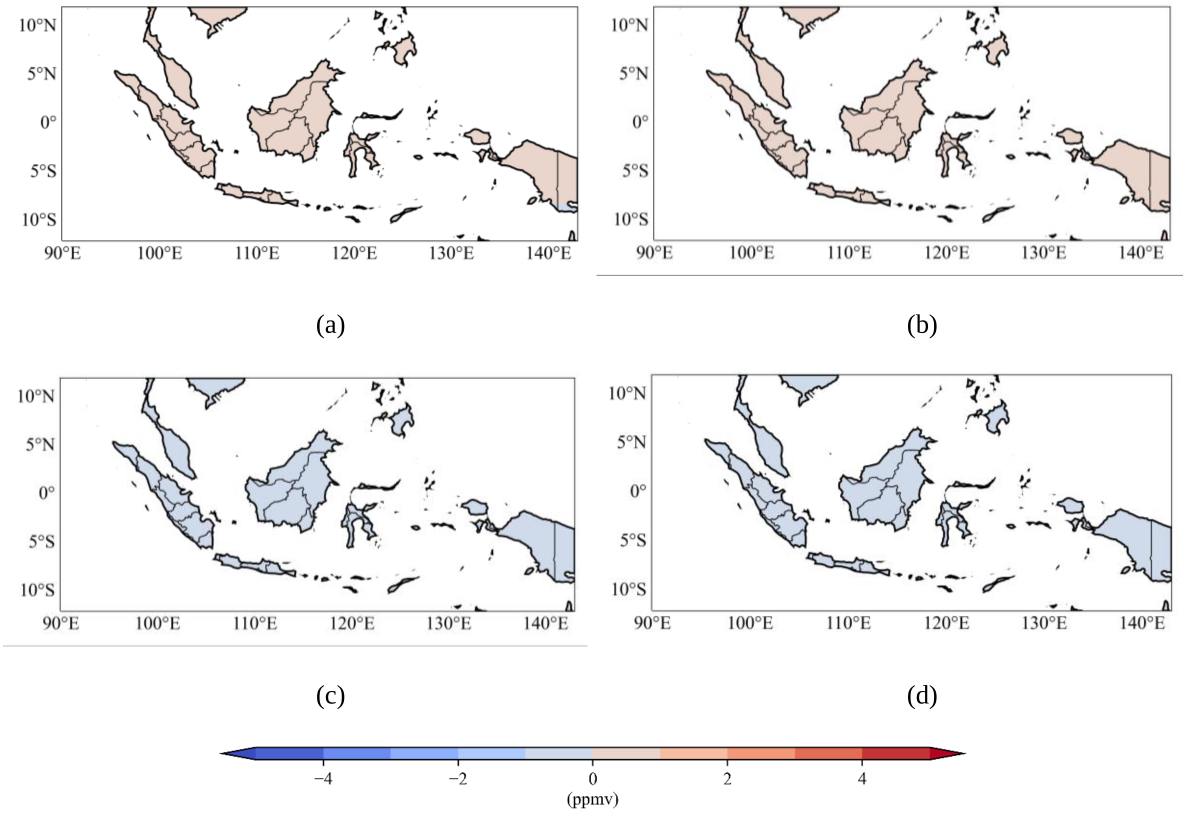

Figure 3 Spatial distribution of ozone concentration anomalies from 2004-2022 during La Niña at altitudes of (a) 25.7 km, (b) 30.5 km, (c) 35.3 km, and (d) 40.1 km

This vertical airflow (Hadley flow) carries ozone from the upper stratosphere to the lower stratosphere, increasing ozone concentrations at 25.7 km and 30.5 km altitudes. Meanwhile, the ozone concentration decreased by 2 ppmv from normal conditions. To see the relationship between water vapor and ozone layer depletion, the results reviewed are when the ozone concentration decreases. The decrease in ozone concentration is found at an altitude of 35.3 km and 40.1 km. The decrease in ozone concentration value can be caused by an increase in water vapor concentration. This is due to the chemical reaction that occurs between ozone and water vapor.

3.2 Trends in Water Vapor and Ozone Concentrations during La Niña

Trends in water vapor (H_2O) concentration and ozone (O_3) concentration have been determined using the Mann-Kendall and Sen's Slope methods shown in Equation (6)-(11). Figure 4 shows the trend of water vapor concentration during La Niña at altitudes of 25.7 km, 30.5 km, 35.3 km, and 40.1 km in the stratospheric layer of the Indonesian region from 2004 to 2022. This altitude value was chosen because there is a trend of water vapor and ozone at this altitude. Based on research data processing, the slope values obtained in Figures 4(a)-(d) are positive, so it can be concluded that there is an increasing trend in water vapor concentration with a slope value of < 0.033 ppmv/year. This small slope value indicates that the rate of increase in water vapor concentration is quite slow at each observed altitude. Meanwhile, the p value obtained at each altitude is smaller than the value of α (0.05). The p-value < 0.05 indicates that the increasing trend of water vapor concentration is statistically significant at each observed altitude (Tridaiana & Marzuki, 2024).

The the results obtained are in accordance with research conducted by Scherer et al. (2016). They have conducted a study related Trends and Variability of Midlatitude Stratospheric Water Vapour Deduced from the re-evaluated Boulder Balloon Series and HALOE. They found that the water vapor trend was statistically significant for the observation years 1981-2006. The water vapor trend in their study was sought using a linear method. Meanwhile, the research that has been done uses the Mann Kendall and Sen's Slope methods. The results showed that the water vapor trend was also statistically significant. This trend of water vapor in the stratospheric layer of the Indonesian region can be caused by changes in the fraction of oxidised methane (which depends mainly on the age of air distribution), and changes in the entry mixing ratios of methane and water vapor (Scherer et al., 2016).

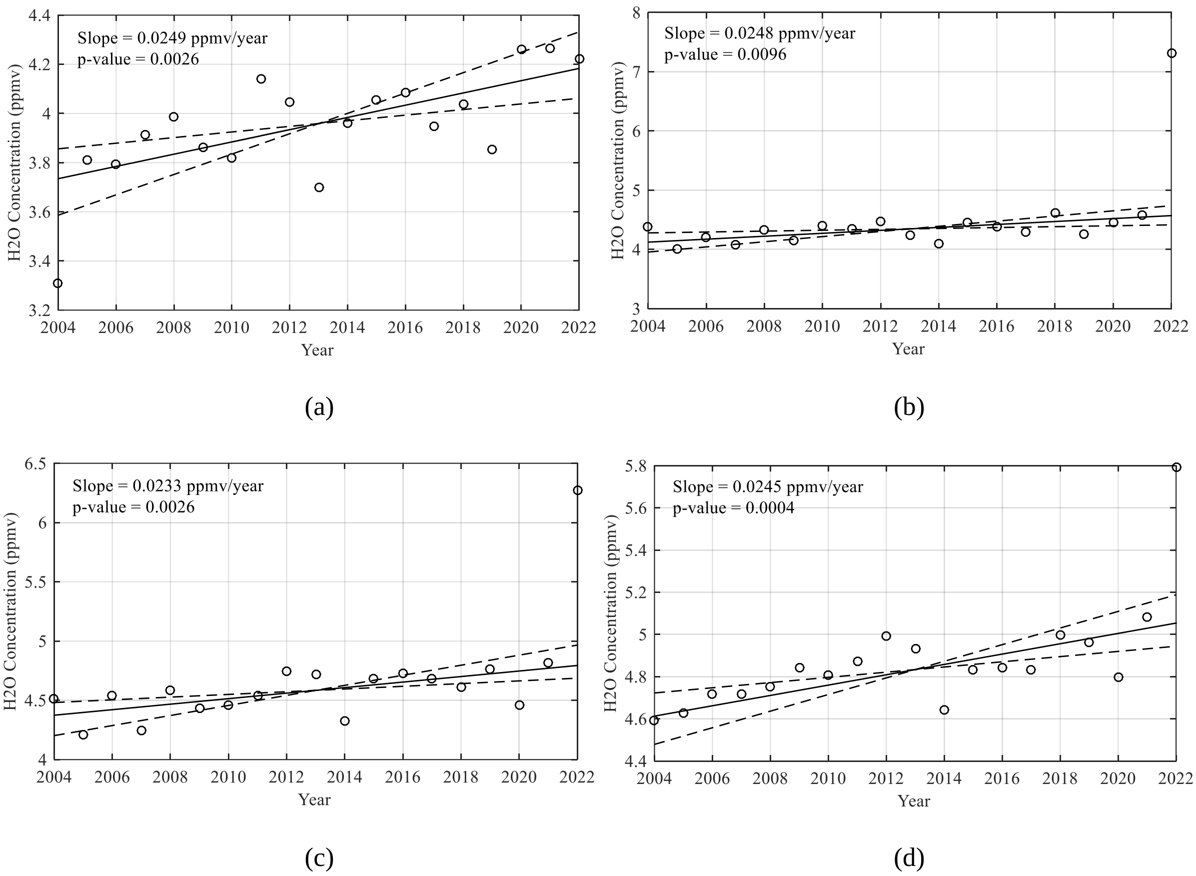

Figure 4 Trend of water vapor concentration during La Niña at altitudes of (a) 25.7 km, (b) 30.5 km, (c) 35.3 km, and (d) 40.1 km.

Figure 5 shows the trend of ozone concentration at several altitudes in the stratosphere layer of the Indonesian region from 2004 to 2022. The slope value is positive at 25.7 km (Figure 5(a)) and 30.5 km (Figure 5(b)), while at 35.3 km (Figure 5(c)) and 40.1 km (Figure 5(d)) the slope value is negative. The negative slope value indicates that there is a downward trend in ozone concentration at that altitude. Meanwhile, the p value obtained is greater than the value of α (0.05). The p-value > 0.05 indicates that the downward trend in ozone concentration is not statistically significant. The decrease in ozone concentration can be caused by the presence of ozone-depleting substances such as chlorofluorocsrbon (CFC) and hydroxyl radicals (OH) derived from water vapor. These ozone-depleting substances react with ultraviolet (UV) light to break down ozone molecules (O_3) into oxygen molecules (O_2) (Sivasakthivel et al., 2017). Since the decrease in ozone concentration obtained in the study is not statistically significant, it can be concluded that the increased water vapor concentration during La Nina does not have a strong influence on the depletion of the ozone layer.

4. CONCLUSION

The results show that the La Niña phenomenon causes sea surface temperatures in Indonesia to increase with an anomaly of 0.5 – 1.5 K. This causes a lot of evaporation at the sea surface so that the concentration of water vapor tends to increase from normal conditions. However, things are different with ozone concentrations. If adjusted to the theory, then when La Niña occurs, the ozone concentration in the Indonesian region should increase. However, the results obtained are that ozone concentrations increase and decrease from normal conditions (irregular) during La Niña. This decrease in ozone concentration can be caused by an increase in water vapor concentration due to chemical reactions that occur between ozone and water vapor. This is consistent with the trend of water vapor and ozone concentrations that have been searched using Mann Kendall and Sen's Slope, where the results obtained are an increasing trend in water vapor concentration. This increasing trend in water vapor concentration is statistically significant. However, the trend in ozone concentration obtained is not statistically significant. This indicates that water vapor does not have a strong influence on reducing ozone concentrations in the stratosphere layer (at the four observed altitudes). The results showed that water vapor does not contribute directly to ozone layer depletion. Therefore, to see the relationship between water vapor and ozone layer depletion, it is necessary to consider other factors that affect ozone layer depletion, such as methane oxidation.

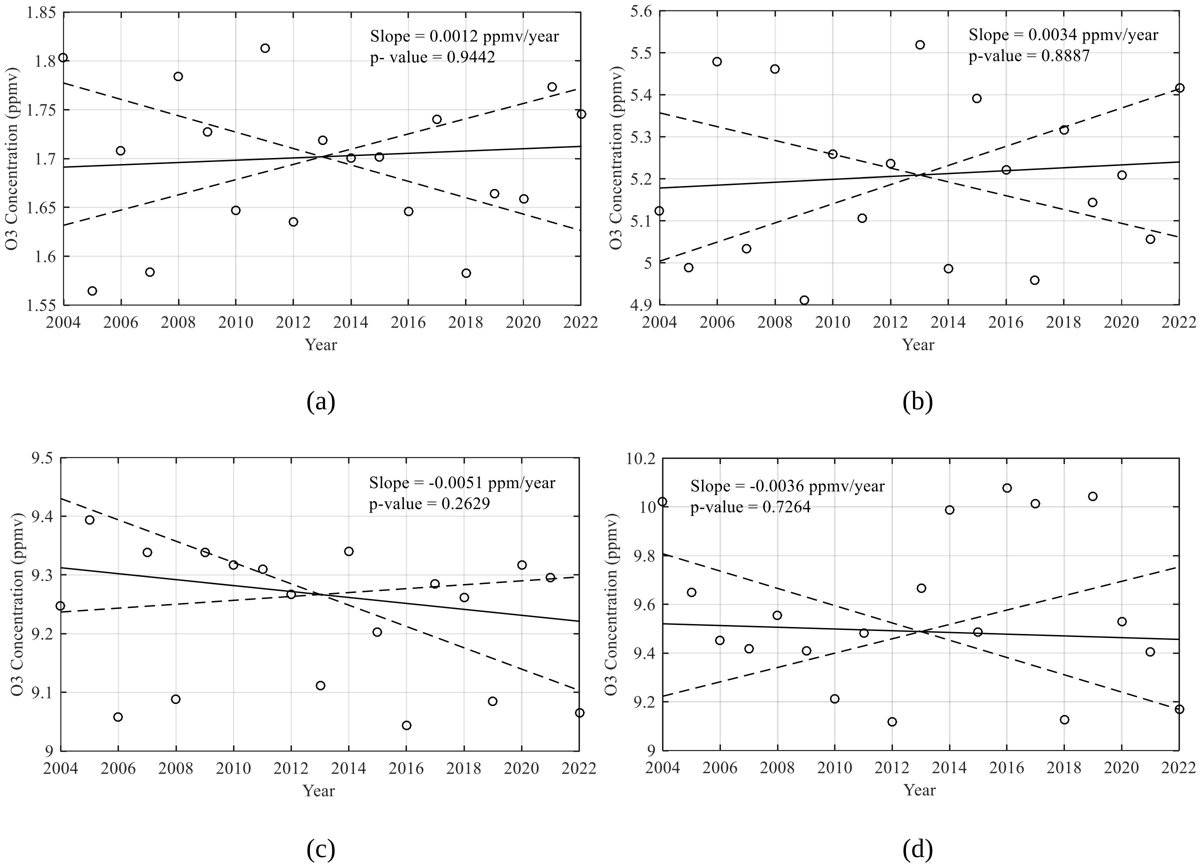

Figure 5 Trend of ozone concentration during La Niña at altitudes of (a) 25.7 km, (b) 30.5 km, (c) 35.3 km, and (d) 40.1 km.

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