Variations of precipitable water vapor from 2012 to 2019 over the Philippines using radiosondes

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Abstract. Precipitable Water Vapor (PWV) refers to the content of water vapor in the atmosphere which is significant in observing climate changes. The trends and variations of precipitable water vapor in Laoag, Legazpi, Mactan, and Puerto Princesa from 2012-2019, are presented through the use of radiosonde data derived from the database of the Integrated Global Radiosonde Archives (IGRA). These data were analyzed for possible patterns through a time series of its daily, monthly, and annual mean, together with a Lomb-Scargle periodogram, and Mann-Kendall test. The results observed varying trends and variability. Legazpi and Puerto Princesa with a minimum value of 20 mm, observed a gradual downward trend of PWV. Laoag and Mactan detected an upward trend of PWV with a minimum of 10 mm and 20 mm, respectively. It also showed an annual and bi-annual periodicity of PWV. Furthermore, all cities detected an increase of PWV during the wet months of May to September, while the dry months of October to April with slight variations over 8 years. In terms of seasonality, only Laoag observed a slightly different dry season, with January, February, and March experiencing around 5 mm less in monthly PWV variation compared to the other cities. The correlation of surface temperature and relative humidity of PWV observed an overall increasing trend while showing a general moderate positive correlation. This study can be used for future references for meteorologists for upcoming forecasting on the likelihood of different weather phenomena in the Philippines.

Keywords: Radiosondes, Variability, Trends, Precipitable Water Vapor

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1. Introduction

Water vapor is considered to be responsible for emitting around 60 % of the greenhouse effect which contributes to the global warming phenomenon. Precipitable water vapor (PWV) represents the content of water vapor in the atmosphere. It is defined as the height of liquid gathered from the top of the atmosphere by condensing its total in a column [1]. The characteristics and conditions of the atmosphere provided by PWV data are significant on predictions in meteorology, such as weather and climate forecasts [2]. Because of this, monitoring the variation of PWV is essential for observing climate variability [3].
PWV can be determined using various instruments. One of them are radiosondes. Radiosondes are meteorological instruments that have different sensors attached to a small radio transmitter. They are released into the sky with the use of helium-filled balloons. These sensors measure the vertical profile atmosphere as it ascends. This includes air temperature, pressure, atmospheric stability, humidity, wind speed, cosmic rays, and more [4]. Typically, radiosondes are launched twice a day (0000UT and 1200 UT). They usually reach up to an altitude of about 30 km. Thus, radiosondes are used to study much of the neutral gas in the atmosphere, including water vapor.

Several studies have shown the analysis of short-term variations in PWV using radiosondes and other techniques such as remote sensing. Macalalad and Macalalad [9] analyzed the variability of PWV in 2017 over Manila using Global Navigation Satellite System where it demonstrated the occurrences of dry and wet anomalies in certain months relative to the daily variability of rainfall [2]. In PWV data from GNSS was used to observe the atmospheric water vapor in Davao City, Philippines. Here, a threshold value of PWV was determined from historical data to potentially predict the probability of heavy and torrential rainfall occurrence in the future [5, 6]. A similar study investigated the variation of total PWV in climatic zones in Iran through the Moderate Resolution Imaging Spectroradiometer (MODIS). The researchers concluded that a notable increase of PW can be seen in the hot climatic areas in both summer and spring [7]. Similarly, Zhang et al.[8] discussed seasonal variation of PWV using the National Climatic Data Center and Integrated Global Radiosonde Archive (IGRA) database. It is discovered that warm seasons have larger PWV measurements (40 mm) compared to cold seasons (10 mm) denoting that there is an extensive rise of PWV above land in the past 10 years [8].

Other studies focused on the long-term changes or trends of PWV for a long period of time, using either radiosondes or remote sensing instruments. According to Wang et al. [9], the study analyzed global PW trends together with distinct spatial variations between land and ocean from 1988 to 2011. It is observed that there is an overall increase of PW in all datasets worldwide, while the ocean has a relatively larger spatial variability in the said period [9]. Also, Chen and Liu [3] studied PWV general trends worldwide from 1979-2014 using radiosonde data. The result showed that there is an overall increase in PWV trends in the past years and the possibility of a 13 % PWV addition in the atmosphere might be seen in the years to come [3].

In the past decade, there are inadequate work that studied water vapor trends over the Philippines using radiosonde data for a long period of time [10]. Therefore, this research aims to study possible trends of PWV using radiosonde data from 2012 to 2019 over Laoag, Legazpi, Mactan, and Puerto Princesa City. Spatial and temporal variation (interannual and seasonal) of PWV will also be studied.

2. Data
This study obtained PWV data calculated from radiosonde observations from IGRA (v2) from 2012-2019 from four stations in the Philippines, namely, Laoag, Legazpi, Mactan, and Puerto Princesa City. Figure 1 shows the station IDs and geographic information of each station. In this study, time series of PWV data is determined. From this, the Lomb-Scargle periodogram is calculated to estimate the main periodicity of the data set. This technique is mostly useful to calculate periodicities of unevenly spaced data set [11–13]. Monthly mean and standard deviation are also calculated to evaluate its average monthly variation over the 8-year period. This is correlated with monthly average values of surface meteorological parameters, such as relative humidity, and surface temperature. These are also obtained from the radiosonde profiles provided by IGRA. Here, correlation between these variables with PWV is explored.
3. Results and Discussion

Figure 2 shows the daily time series of PWV in the four cities from 2012-2019. Laoag saw an increase of PWV, observed in 2012, 2016, and 2017, which exceeded the 70 mm value. On the other hand, a decrease was observed in 2014, with the lowest PWV data in 2014 reaching below 10 mm. Mactan also observed a slightly increasing trend with PWV peaks surpassing 60 mm between 2014-2017. The daily PWV in Legazpi showed majority of data peaked above 60 mm, signifying rainfall within a certain period, while the lack of rainfall was observed in the PWV in 2014 and 2019 which reached below 20 mm. A slightly decreasing trend is observed due to numerous drops of the PWV measurements around the 20 mm level. PWV data in Puerto Princesa peaked in measurement above the 60 mm mark together with the decrease of PWV data at the beginning of each year of 2012-2019. In addition, PWV data slightly shows a downward trend which is seen in the dips of PWV, reaching 20 mm compared to its previous years. The four daily time series continue to present normal data, with only slight irregularities or surges in PWV. Finally, the data presented agree on the climate of their respective area, observing two different seasons in which PWV behaves according to either the dry or wet seasons from 2012 to 2019.

Similar to the studies of Domingo and Macalalad [14], PWV shows recurring patterns without distinctive behaviors while showing a variation of PWV occurrences during pre-monsoon periods. High
variability can indicate the occasional increase in moisture due to local weather events such as thunderstorms that may have contributed to the high variability of PWV during a particular season, which presents a relation to the results from the daily time series in Laoag. On the other hand, the indication of a PWV decrease after significant rainfall is caused by the occurrence of thunderstorms or typhoons [14].

The periodicity of PWV over Laoag, Legazpi, Mactan, and Puerto Princesa City which was shown through a Lomb-Scargle periodogram is shown in Figure 3. The behavior was observed to check the periodic variations or if the data occurs at intervals on unevenly sampled data. Here, Laoag, Legazpi, Mactan, and Puerto Princesa had peaks of about 365 days, with Laoag showing the strongest spectrum. This shows that PWV for these stations primarily vary annually. Secondary peaks are also observed at 182.5 days which indicates bi-annual periodicities over the four stations.

![Lomb-Scargle periodogram](image)

**Figure 3.** Lomb-Scargle periodogram (in arbitrary units) from 2012-2019 of (a) Laoag, (b) Legaspi, (c) Mactan, and (d) Puerto Princesa.

These results are consistent to Zhao et al. [15]. Here, a similar annual and bi-annual periodicities were observed from 4 global stations using Lomb-Scargle periodograms. However, in contrast with the annual observation of this research, the study of Zhao et al. [15] also observed seasonal periods in some areas [15]. This annual and semi-annual variability of PWV has also been observed in a series of stations over Turkey [16].

Figure 4 represented the annual mean of the four provinces using error bars provided by the standard deviation of each year. The annual mean PWV of Laoag from 2012-2013 and from 2016-2018 has shown concentrated data with PWV ranging from 40 mm-50 mm and years 2014-2015 and 2019 has indicated the values are more spread or it is likely less reliable with a PWV ranging from 40 mm-45 mm. While in Legaspi, we could see that there is a downfall despite having high PWV which ranges from 45 mm in 2012 to 50 mm in 2019. Mactan’s annual mean has more likely concentrated data from 2013-2014 with a PWV data ranging from 50 mm-53 mm. An upward movement was observed from 2015-2017 with a range of 45 mm-50 mm and falling movement from 2018-2019 with a PWV from 50 mm-45 mm. Lastly, Puerto Princesa has started a downward movement that started from 2013 to 2015.
and similar to 2018-2019 with a PWV ranging from 50 mm-45 mm. The only upward movement was observed in 2016-2017 with a low variability yet with the highest point of the PWV ranging from 50 mm-53 mm.

Figure 4. Annual mean variation of PWV for (a) Laoag, (b) Legaspi, (c) Mactan, and (d) Puerto Princesa. The error bars represent standard deviation.

The characteristics of the monthly variation with PWV is seen in Figure 5. This figure represents the results of how PWV from each month is seen in the 8-year observation. As observed, PWV rises from April to May which results in its peak in June and July and finally decreases as August ends. The approximate numerical values for each part of the rising and falling behavior of PWV data are 45-50 mm (i.e. rising; April-May), 55 mm (i.e. peak; June-July), and 50-40 mm (i.e. falling; August and succeeding months). Due to the high values of PWV in months from April to September, it could be concluded that the four cities have a cool climate during these months, particularly Legazpi. Mactan did not show a slight decrease in PWV after it peaked in April to September. On the other hand, Puerto Princesa has shown a great decrease compared to the other cities in August to September. In general, all the four cities had decreases in PWV values after the months wherein it peaked, yet these cities just varied in how much it lost compared to the maximum value of PWV.

Figure 5. Monthly mean variation of PWV. The errors bars represent 1 standard deviation.

Similarly, the study of Macalalad and Macalalad (2019) used GNSS-derived PWV data over Manila in 2017. The monthly mean variation with error bars, shows a low variability in Manila despite having high PWV in the wet season, specifically in July with 3.9 mm and May with July 3.9 mm. However, this research concluded that it had a cool climate from April to September along with a rising action with high PWV [2]. In terms of climate as seen in the monthly variation of both studies, Laoag, Legazpi,
Mactan, Puerto Princesa, and Manila both have considered November to April as a dry season due to the lack of rainfall during these months. In comparison, the dry seasons of Manila generally observe less than 50 mm PWV measurements, while Laoag presents less than 45 mm. The dry season of Manila showed higher variability in April ranging from 6.2 mm to January with 9.9 mm. On the other hand, the cities of Legazpi, Mactan, and Puerto Princesa share nearly the same variability of PWV with the dry months of Manila.

The results of the Mann Kendall Test and Statistic was also computed, in which the PWV trend is achieved. The results noted that Kendall's $\tau$ coefficient will determine the behavior of the trend of PWV if it is increasing ($\tau > 0$), decreasing ($\tau < 0$), or monotonic ($\tau = 0$). Both Laoag and Mactan showed an increasing trend with the $\tau$ value being 0.6 and 0.2, respectively. On the other hand, Legazpi and Puerto Princesa presented a decreasing trend having a $\tau$ value of $-0.05$ and $-0.01$, respectively.

Similarly, the study of Merrikphour and Rahimzadegan [7] used the Mann-Kendall Test to scrutinize the behavior of the trend of PWV. The only notable is that radiosondes were not the primary source for their PWV data as they utilized the Moderate Resolution Imaging Spectroradiometer (MODIS) of Western Iran. Their investigation and analysis on the spatial and temporal variations of PWV in Western Iran supported the results of the Mann-Kendall test [7]. Both studies apply the Mann-Kendall Test and Statistic as a secondary method in getting the behavior of a trend of data, which in the case of this research is the radiosonde data of PWV over the four cities of the Philippines.

Figure 6 shows the correlation and comparison of monthly PWV, surface temperature, and relative humidity from 2012-2019 for the four stations. Moreover, the approximate ranges of each variable are shown within the four correlation graphs above, namely, surface temperature ($^\circ$ C) having 30 as the maximum and 20 as the minimum; relative humidity (%) showing 70 as the lowest data to 95 as the highest, which ranges from 20 mm or 25 mm to 55 mm or 70 mm. Laoag shows a strong positive correlation between PWV and RH ($R= +0.690$) and it is expected in both parameters to describe the moisture content in the air, meanwhile, the strong positive correlation between PWV and temperature ($R= +0.654$) defines the formation of water vapor that is likely related to the [2]. However, Legaspi, Mactan and Puerto Princesa have weak-to-moderate positive correlation with RH with $R$-values ranged from 0.166 to 0.401. They also correlated with temperature whose $R$-values vary from 0.261 to 0.433. This indicates that at the monthly scale, PWV is affected by these variables in a multifaceted manner. Thus, it is recommended to correlate these using multi-variate correlation techniques to explore their complex relationship.

![Figure 6](image.png)

**Figure 6.** Correlation of Monthly PWV with Surface Temperature and Relative Humidity for (a) Laoag, (b) Legaspi, (c) Mactan, and (d) Puerto Princesa.
4. Summary and Recommendations

In this study, the general trend of daily PWV data derived from radiosonde observations from IGRA (v2) in Laoag has shown a range of peaks that reached 70 mm which signified rainfall, along with a measurement of PWV in 10 mm which presented the lack of rainfall. Similarly, radiosondes from Legazpi have shown the daily measurement of PWV that peaked above 60 mm and a minimum of 20 mm. Mactan showed an upward trend reaching up to 70 mm, and Puerto Princesa at approximately 60 mm. Mactan and Puerto Princesa shared a minimum of PWV data at the beginning of each year of 2011-2019 at 20 mm. The daily PWV has shown graphs with the upward or downward trend of PWV, as well as the monthly and annual mean variation with standard deviation error bars.

It has been shown that all four stations have annual and bi-annual periodicities as illustrated in their Lomb-Scargle periodograms. Other periodograms may also be explored in the future to extract (if any) smaller or larger scaled periodicities which may not be observed by the abovementioned technique. The Mann-Kendall test that was accomplished showed that Laoag and Mactan had an increasing trend throughout the study. While Legazpi and Puerto Princesa had a decreasing trend in the years 2012-2019.

In addition, the correlation of PWV with surface temperature and relative humidity showed a strong relationship in which these two variables (i.e., ST & RH) contribute greatly to the PWV output. The relationship of these three variables (i.e., PWV, ST, and RH) is shown through to the low temperatures that result in increased moisture in the air which contributed to the high production of PWV. It is also seen at times wherein the PWV is at a minimum, this means that the temperatures are high and the moisture in the air has decreased. With this, it is recommended to use multi-variable correlation approach to show that inter-relationship of theses parameters.

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