CHARACTERIZATION OF COLUMNAR WATER VAPOR MEASUREMENTS AND ITS COMPARISON WITH MODEL ESTIMATES AND SURFACE METEOROLOGICAL PARAMETERS OVER MANILA, PHILIPPINES (14.567° N, 120.980° E)

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ABSTRACT: The temporal variation of precipitable water (PW_{meas}) in the near-infrared (936 nm) band at Manila, Philippines (14.567° N, 120.980° E) was investigated using a Microtops II Sun photometer and Ozone Meter (spectral radiometer) in 30-min interval observations (0900H – 1200H, 1300H – 1600H LT) from February to May 2014. Precipitable water (PW_{calc}) was also computed from surface meteorological measurements (i.e., relative humidity and surface temperature) and the Butler model. Results show a large day-to-day variability of the PW_{meas} values due to varied meteorological and sky conditions. PW_{meas} yielded a positively skewed distribution; 46.0 % of all the PW observations fall from 1.80 cm to 2.60 cm. The daytime median PW_{meas} was 2.79 cm at quartile deviation (QD)=0.608, with maximum PW_{meas}=4.35 cm and minimum PW_{meas}=1.88 cm. Kruskal-Wallis Analysis of Variance was performed to compare the PW_{meas} values for the (a) monthly observations, (b) daily measurements, and (c) morning (A.M.) & afternoon (P.M.) monitoring. A p-value of <0.05 was obtained for (a), showing a significant difference among PW_{meas} values for the months of February, March, April, and May. On the other hand, a p-value of 0.222 was obtained for (b), illustrating that there was no significant difference among PW_{meas} values at any of the 30-min interval observations. Moreover, a p-value of <0.05 was obtained for (c), indicating a significant difference between A.M. & P.M. PW_{meas} values. Further, the obtained PW was correlated using the Spearman Rank Order Correlation with relative humidity (r_S=0.0860), surface temperature (r_S=0.572), and dew-point temperature (r_S=0.822). Lastly, PW_{calc} was compared with PW_{meas} (r_S=0.823) revealing a strong correlation.

KEYWORDS: precipitable water, spectral radiometer, Butler model, atmospheric monitoring, passive sensing

1. INTRODUCTION

Atmospheric water vapor content or precipitable water (PW) plays an important part not only in meteorological but also in climatic scale. Accurate monitoring of precipitable water is essential in the success of most meteorological forecasting activities. The horizontal and vertical distributions of water vapor are an important component of the global climate system specifically its role in radiation balance and biogeochemical cycles. Some researches on climate change and global warming are particularly interested with atmospheric water vapor for it has great variability and constitutes the largest fraction among the greenhouse gases.

Water vapor is the key ingredient of tropospheric weather and is the atmosphere's principal greenhouse gas. Besides its role in cloud formation, water vapor condensed on sulfate, nitrate, and other hygroscopic aerosols significantly increases the optical thickness of the cloud-free atmosphere. Any of these factors provides ample justification to supplement measurements of ambient water vapor at the surface with long-term monitoring of changes and trends in the total column abundance of atmospheric water vapor (Brooks & Mims, 2001).

Brooks et al. (2007) mentioned in their paper that traditional techniques for directly measuring local PW with varying degrees of accuracy and vertical resolution include balloons (radiosondes), lidar, and aircraft. Further, the delay in transmission through the atmosphere of radio signals to global positioning satellite (GPS) receivers has been used to determine vertically integrated PW. Several authors (Reagan et al. 1995; Ichoku et al. 2002) also acknowledge the use of sun photometers to measure vertically integrated PW from ground-based sites by measuring the ratio of direct sunlight transmission through the atmosphere in and near water vapor absorption bands in the near IR. This method is routinely applied to data from robotic CIMEL sun photometers in the global Aerosol Robotic Network (AERONET). Several mathematical models have also been developed to simulate the amount of atmospheric water vapor given only surface measurements as input variables (Maghrabi & Al Dajani, 2013).

This paper presents measurements provided by a handheld Sun photometer and Ozone Monitor (Microtops II by Solarlight Corporation) to assess temporal variations of precipitable water within the chosen research locale. This study also implemented a mathematical model (Butler, 1998) to estimate columnar atmospheric water vapor by incorporating measurements of surface meteorological parameters.

2. EXPERIMENTAL SITE, DATA SOURCES, AND METHODS

Since 2000, the Environment And RemoTe sensing research (EARTH) Group have been conducting sun photometric studies on the rooftop of a building at De La Salle University, Manila (14.567° N, 120.980° E; 35 m above sea level), Philippines. Although, it was only in 2011 that the group started to undertake multi-channel sun photometric studies involving a hand-held instrument with near-UV and near-IR detectors. The research locale is in the middle of a highly urbanized city with one of the key city traffic routes just a hundred meters away. Moreover, there is a large body of water (Manila Bay) more than a kilometre away from the sampling site. This environment gives a mixed urban and maritime character to the atmosphere under observation.

The Microtops II (manufactured by the Solar Light Co. Inc.,) used in this study is a handheld multiband sun photometer (spectral radiometer) that measures simultaneously the Total Ozone Column (TOC) using the 305-, 312- and 320-nm channels, the Aerosol Optical Thickness (AOT) via the 1020-nm channel, and the Precipitable Water (PW) at the 936-nm channel. Each channel has a maximum field of view (FOV) of 2.5°. Measurements are taken with the Microtops II mounted on a photographer's tripod stand. Precipitable water measurements ($\mathrm{PW_{meas}}$) were obtained using processed signals from the pair of IR radiometric channels. The 936-nm filter has strong water vapor absorption while the 1020-nm filter has negligible water vapor absorption and is only affected by aerosol scattering. Processed signals from these two channels yield PW values in centimeters. According to Morys et al. (2001), the near-IR filters have a full width at half maximum (FWHM) bandpass of 10 nm and a precision of ± 1.5 nm. Ingold et al. (2000) obtained a less than 10% retrieval error for columnar water vapor if the 946-nm sun photometer channel is used while errors of around 10 – 18% occur if the 719- or 817-nm channels are used.

In this paper, data collection was done on all clear sky days and as the weather condition permitted for the period February to May 2014. Observations were made at 30-minute time intervals within 0900H-1200H and 1300H-1600H (local time) yielding a possible daily maximum of 60 $\mathrm{PW_{meas}}$ values. Data obtained during partly cloudy days were included in the analysis as long as the sun's disk was not blocked by any visible hazy layer and cloud patches.

Simultaneous with the Microtops II measurements are readings of meteorological parameters (i.e. dew point temperature, surface temperature (T_O), and relative humidity(RH)) retrieved from the Davis Vantage Pro 2 (VP2) automatic weather station (AWS) of the EARTH Group. Using the mathematical model developed at the National Radio Astronomy Observatory (Butler, 1998), precipitable water at every 30-min interval was computed ($\mathrm{PW_{calc}}$). Spectral radiometer measured precipitable water ($\mathrm{PW_{meas}}$) were then compared with mathematically modelled PW ($\mathrm{PW_{calc}}$) and surface meteorological parameters.

If it is assumed that the water vapor is exponentially distributed in the atmosphere above a given location, the amount of precipitable water can be derived using surface meteorological measurements of temperature and relative humidity using an analytical expression by Butler (1998) and is given by:

$$\boldsymbol{h = \frac{m_w P_O H}{\rho_l k T_O}} \tag{1}$$

where m_w is the mass of each water molecule (m_w= 18 amu), P_O is the water vapor partial pressure at the surface, H is the scale height of water vapor (assumed to be 1.5 km), ρ_l is the mass density of liquid water (ρ_l= 1000 kg/m^3), k is the Boltzmann constant, and T_O is the surface temperature. Here, h is $\mathrm{PW_{calc}}$ and is in mm, P_O is in μbar, and T_O is in kelvin (K). Substituting all the constant values will yield

$$\boldsymbol{h \approx \frac{P_O}{3T_O}} \tag{2}$$

The surface water vapor partial pressure can be derived from the surface relative humidity via the equation below; where the value of RH is in percent, θ is inverse temperature (θ = 300/T_O, both in kelvin), and the resultant water vapor partial pressure is in μbar.

$$\boldsymbol{P_O = (2.409 \times 10^{12})(RH)(\theta^4)e^{-22.64\theta}} \tag{3}$$

3. RESULTS AND DISCUSSION

The measured precipitable water (PW_{meas}) for the months of February, March, April, and May showed a non-normal frequency distribution (Fig. 1) signifying that nonparametric methods of statistical analysis must be employed. Table 1 summarizes the statistics that describe the obtained overall and temporal-scale-specific precipitable water data.

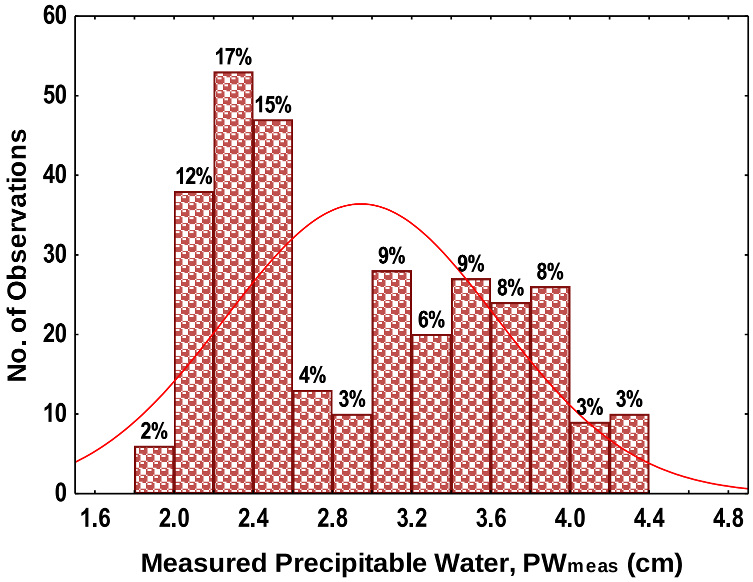

Figure 1. Frequency histogram of PW measurements (Feb-May 2014). A positively skewed (s=0.339) distribution was obtained by plotting the precipitable water measurements from February to May 2014. Forty-six per cent (46 %) of the values fall between 1.8-2.6 cm with the median at 2.9 cm (QD=0.608) with PW_{max}=4.35 cm and PW_{min}=1.88 cm. Since the distribution of the data set is non-normal, non-parametric statistical methods were employed in the subsequent data analyses. Performance of Shapiro-Wilks test at $p<0.05$ also support the claim that the distribution fails the test of normality. The deviation of the histogram from the superimposed Gaussian curve exemplifies the non-normality of the distribution.

3.1 Temporal Variation of Precipitable Water

A series of independent-samples Kruskal-Wallis analysis of variance or H-statistics were run to determine whether there were differences in the columnar water vapor content in different temporal scales: monthly observations, daily 30-min interval observations, morning (A.M.)–afternoon (P.M.) observations. K-W ANOVA is the nonparametric analogue of ANOVA; p-values compare the likeness of the distributions instead of the means. More to this, there were no outliers in the data as assessed by inspection of the boxplots in Fig. 2. The requency of precipitable water values for the different groupings showed non-normal distributions as evidenced by the values of skewness (Table 1) and by the results of a series of Shapiro-Wilks test ($p < 0.05$).

Monthly Observations. Kruskal-Wallis H statistics showed that there were significant differences in the values of precipitable water among all the observation months, H (3, N= 311) = 214.20, p = 0.000; with a mean rank PW value of 67.78 for February, 98.01 for March, 267.08 for April, and 209.42 for May. Post-hoc test revealed that the values of precipitable water was statistically significantly lower in February (2.291 ± 0.121 cm, p = 0.000) and in March (2.399 ± 0.185 min, p = 0.000) compared to values in April (3.856 ± 0.256 cm) and in May (3.288 ± 0.311 cm). There were no statistically significant differences on the amount of water vapor between February and March (p = 0.2706) while April and May PW values significantly differ (p = 0.959E-3). Therefore, monthly precipitable water in Manila from February to May 2014 are non-identical populations. It can be seen from the boxplot (Fig. 2b) that PW values between February and March are fairly equivalent, then suddenly increased from March to April, and a gradual decrease from April to May. April data might have been compromised since monitoring was done only during the last week which may have led to the drastic increase (March-April) of PW data.

30-min Interval Observations. There was NO statistically significant difference in the values of precipitable water among the different 30-min interval observations as shown by the Kruskal-Wallis analysis of variance, H (11, N= 311) = 14.21, p = 0.2216; with a mean rank PW value 161.89 for A (0900H-0930H), 163.30 for B (0930H-1000H), 160.54 for C (1000H-1030H), 183.80 for D (1030H-1100H), 178.25 for E (1100H-1130H), 178.48 for F (1130H-1200H), 158.30 for G (1300H-1330H), 145.23 for H (1330H-1400H), 138.83 for I (1400H-1430H), 138.12 for J (1430H-1500H), 132.40 for K (1500H-1530H), and 116.98 for L (1530H-1600H). The closeness of the mean ranks for the different groups (A-L) support the 22.16 % high p-value. This shows that, for the entire data set of this study, values of PW from the daily measurements done for every 30-min interval do not greatly differ from each other. It is highly likely that the PW values come from the same distribution relative to the daily 30-min interval observations. Thus, daily 30-min interval precipitable water in Manila from 0900H to 1600H are identical populations. The boxplot (Fig. 2c) shows an increasing trend in the values of PW as the day approaches noon and a decreasing trend as it approaches dusk.

Table 1. Numerical summary measures of PW measurements (Manila, Feb-May 2014) for diff. temporal scales

	N	Sum	Median	Min	Max	Q1	Q3	IQR	QD	Skewness
Overall	311	913.381	2.788	1.882	4.354	2.326	3.542	1.216	0.608	0.339
Monthly Observation										
February	52	118.889	2.291	2.054	2.562	2.158	2.400	0.242	0.121	0.054
March	112	277.434	2.399	1.882	3.832	2.204	2.574	0.370	0.185	1.456
April	56	215.009	3.856	3.394	4.354	3.542	4.053	0.511	0.256	0.146
May	91	302.049	3.288	2.376	4.008	3.084	3.707	0.623	0.311	-0.221
Daytime Observation										
AM (Morning)	163	496.486	2.984	2.050	4.354	2.388	3.768	1.380	0.690	0.211
PM (Afternoon)	148	416.895	2.554	1.882	4.276	2.234	3.428	1.194	0.597	0.458
30-min Interval Observation										
A: 0900H-0930H	28	82.831	2.758	2.136	4.332	2.353	3.598	1.245	0.622	0.514
B: 0930H-1000H	27	80.230	2.790	2.134	4.252	2.312	3.742	1.430	0.715	0.533
C: 1000H-1030H	26	76.790	2.768	2.052	3.976	2.406	3.707	1.301	0.650	0.340
D: 1030H-1100H	27	85.203	3.160	2.058	4.346	2.375	3.910	1.535	0.768	-0.041
E: 1100H-1130H	28	87.319	3.170	2.050	4.354	2.370	3.809	1.439	0.720	0.035
F: 1130H-1200H	27	84.112	3.168	2.092	4.274	2.446	3.744	1.298	0.649	-0.053
G: 1300H-1330H	28	83.433	3.074	1.995	4.276	2.358	3.599	1.241	0.620	0.207
H: 1330H-1400H	26	74.544	2.667	1.958	4.214	2.292	3.540	1.248	0.624	0.333
I: 1400H-1430H	24	67.281	2.529	1.894	4.190	2.214	3.405	1.191	0.596	0.526
J: 1430H-1500H	25	70.052	2.694	1.882	4.206	2.286	3.296	1.010	0.505	0.507
K: 1500H-1530H	24	66.015	2.519	1.956	4.042	2.195	3.317	1.122	0.561	0.608
L: 1530H-1600H	21	55.570	2.490	1.980	3.650	2.212	3.112	0.900	0.450	0.549

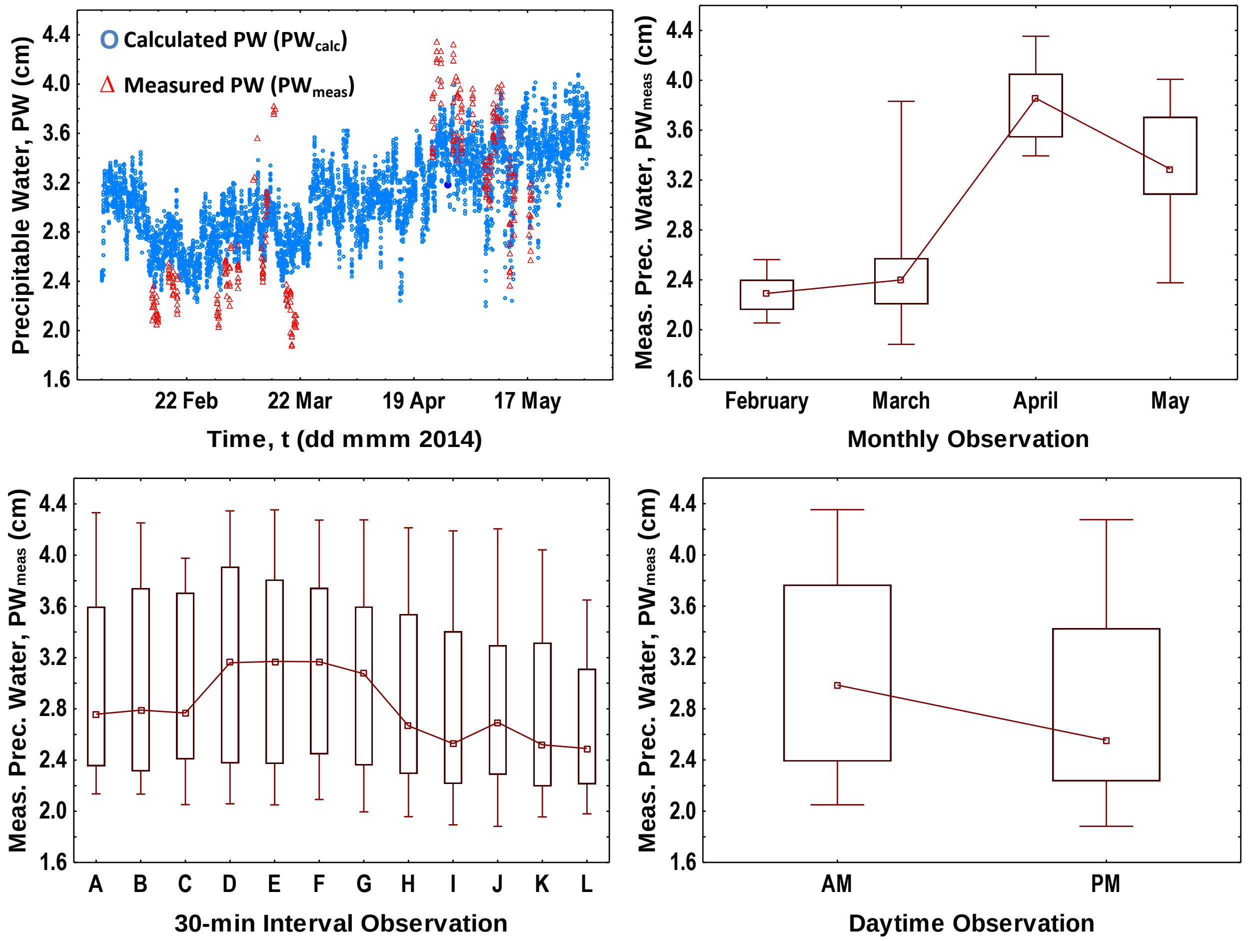

Figure 2. Temporal variation of precipitable water (PW) in Manila from February to May 2014. (a) ***Top-Left:*** Time series scatter plot of the measured (**△** PW_{meas}) and estimated (○ PW_{calc}) PW values. During the months of February and March, measured PW were less than the estimated values; for the month of April, it was higher; for the month of May, there was a good agreement between instrument and the model. **(b)** ***Top-Right:*** Box plot representation of the measured PW for monthly observations. **(c)** ***Bottom-Left:*** Box plot representation of measured PW for each of the 30-min interval observation. **(d)** ***Bottom-Right:*** Box plot representation of measured PW for morning (A.M.) and afternoon (P.M.) observations.

Morning (A.M.)–Afternoon (P.M.) Observations. Mann-Whitney U Test (non-parametric analogue of t-test) is a simplified Kruskal-Wallis analysis of variance when the latter is applied to only two independent groups. For uniformity, K-W ANOVA was still employed in the analysis of the difference between A.M. and P.M. observations; it showed that there was a statistically significant difference in the values of precipitable water between the morning (A.M.) and afternoon (P.M.) observations, H (1, N= 311) = 9.652, p = 0.0019; with a mean rank PW value of 171.10 for morning (A.M.) and 139.38 for afternoon (P.M.). This reveals that the groups were sampled from populations of non-identical distribution. This illustrates that morning (A.M.) and afternoon (P.M.) precipitable water in Manila are non-identical populations. The boxplot (Fig. 2d) also shows a downtrend between morning (A.M.) and afternoon (P.M.) data. However, separate performance of K-W ANOVA on PW values for groups A-F (morning) and G-L (afternoon) showed NO significant differences among groups with H (5, N= 163) = 1.931 at p = 0.8586 and H (5, N= 146) = 3.236 at p = 0.6637, respectively. This demonstrates that multiple PW measurements done any time in the morning (0900H to 1200H) will provide statistically identical values, so as any time in the afternoon (1300H-1600H). Accordingly, these results suggest that one-time measurement both for morning (A.M.) and afternoon (P.M.) would have sufficed a day-worth of PW data.

3.2 Comparison of Precipitable Water Measurements (PW_{meas}) with Precipitable Water Estimates (PW_{calc})

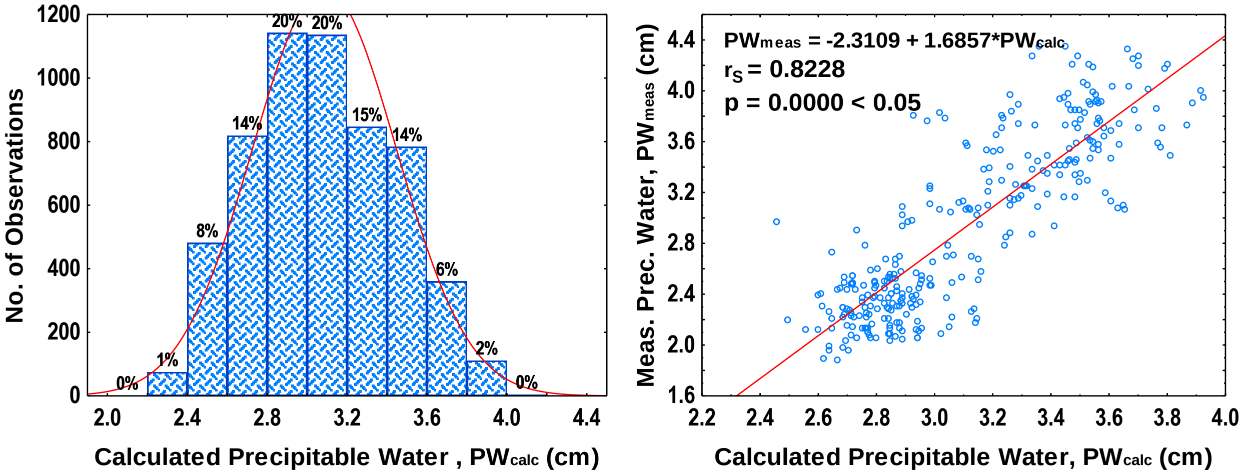

Figure 3. Correlation between measured and estimated PW values. (a) ***Left:*** Frequency distribution diagram of the estimated values of precipitable water using the Butler Model. **(b)** ***Right:*** The scatter plot is a visual way for comparing two physical parameters; it allows easy examination of such features in the data as trends, curvature in the relationship, clustering of one or both variables, changes of spread of one variable as a function of the other, and extraordinary points or outliers **(Wilks, 2011)**. All the points lie close to the linear fit which indicates that the estimates and measurements are highly and significantly correlated (r_S=0.8228, p=0.000).

A Spearman's rank-order correlation was run to determine the relationship between 311 values of PW_{meas} and PW_{calc}. There was a strong, positive correlation between Butler Model's estimates and Microtops II's measurements, which was statistically significant, t (309) = 25.45, r_S = 0.8228, p = 0.000, with regression equation PW_{meas} (cm) = -2.311 + 1.686*PW_{calc} (cm). This high correlation, despite the disagreement of PW values for February & March (measured < estimated) and April (measured > estimated), was caused by the normalization of both disagreements relative to the entire data set (See Fig. 2). This suggests that the Butler Model is a good method to estimate columnar water vapor (at high temporal resolution) based on accurate measurements of surface meteorological parameters; in the absence of a sun photometer or a radiosonde. This result also follows the comparison between the PW values of the Butler Model and Microtops II done by Raj et al. (2008) which had a coefficient of correlation equal to 0.85 (N=896) for a six-year worth of data

3.3 Comparison of Precipitable Water Measurements with Surface Meteorological Parameters

Spearman's rank-order correlation was also used to determine the relationship between 311 values of PW_{meas} and their corresponding surface meteorological measurements using a Davis Vantage Pro 2 AWS. There was a strong, positive correlation between precipitable water and dew point temperature, which was statistically significant at t (309) = 25.34, r_S = 0.8217, p = 0.000. Like the Butler Model, dew point temperature is also derivable from surface temperature and relative humidity. Reitan (1963) and Smith (1966) published empirically derived globally or seasonally/latitudinally-averaged relationships between PW and dew point temperature. This strong correlation follows the innate link between atmospheric water vapor and surface dew point temperature. Notwithstanding the dependence of Butler Model and dew point temperature to surface temperature and relative humidity, the correlation of measured PW values with these two surface meteorological parameters is not staggeringly high. There was a fairly strong, positive correlation between precipitable water and surface temperature, which was statistically significant at t (309) = 12.26, $r_S = 0.5721$, p = 0.000. However, there was a weak positive correlation between precipitable water and relative humidity, which was statistically insignificant at t (309) = 1.517, $r_S = 0.0860$, p = 0.1302.

4. CONCLUSION

Temporal variations of precipitable water over a maritime-urban site in Manila, Philippines were investigated in the near-infrared (936 nm) using a spectral radiometer (Microtops II) for the period February-May 2014. Surface measurements were also done using an automatic weather station (Davis Vantage Pro 2) which provided the needed input variables to implement the mathematical modelling (Butler Model) of columnar water vapor content. Thus, following are the summary of the findings in this present study:

- There is a large day-to-day variability on the amount of precipitable water due to varied meteorological and sky conditions. Monthly comparison showed that PW values differ significantly between February-March and April-May. Statistical tests proved no significant diurnal variation among the 30-min interval observations. Values of precipitable water are identical in the morning (A.M) and in the afternoon (P.M.) but morning-afternoon comparison showed a statistically significant difference.
- The measured and calculated values of precipitable water demonstrated a high correlation with each other suggesting that the Butler Model can be utilized to approximate, to an acceptable degree, the real value of precipitable water, in the absence of sophisticated PW measuring instruments.
- Lastly, measured PW exhibited high positive correlation with dew point temperature, a fairly strong correlation with surface temperature, but a weak and statistically insignificant correlation with relative humidity.

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