Results of Sun Photometer–Derived Precipitable Water Content over a Tropical Indian Station

P. ERNEST RAJ, P. C. S. DEVARA, R. S. MAHESKUMAR, G. PANDITHURAI, K. K. DANI, S. K. SAHA,
S. M. SONBAWNE, AND Y. K. TIWARI

Indian Institute of Tropical Meteorology, Pune, India

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ABSTRACT

A compact, hand-held multiband sun photometer (ozone monitor) has been used to measure total precipitable water content (PWC) at the low-latitude tropical station in Pune, India (18°32′N, 73°51′E). Data collected in the daytime (0730–1800 LT) during the period from May 1998 to September 2001 have been used here. The daytime average PWC value at this station is 1.13 cm, and the average for only the clear-sky days is 0.75 cm. PWC values between 0.75 and 1.0 cm have the maximum frequency of occurrence. There is a large day-to-day variability due to varied sky and meteorological conditions. Mainly two types of diurnal variations in PWC are observed. The one occurs in the premonsoon summer months of April and May and shows that forenoon values are smaller than afternoon values. The other type occurs in November and December and shows a minimum around noontime. There is a diurnal asymmetry in PWC in which, on the majority of the days, the mean afternoon value is greater than the forenoon value. This asymmetry is more pronounced in the summer and southwest monsoon months (i.e., March–June). Monthly mean PWC is highest in September and lowest in December. The increase in PWC from the winter (December–February) to summer (March–May) seasons is about 50% and from the summer to southwest monsoon seasons (June–September) is almost 98%. Sun photometer–derived PWC shows a fairly good relationship with surface relative humidity and radiosonde-derived PWC, with a correlation coefficient as high as 0.80.

1. Introduction

Atmospheric water vapor content is an important component of the global climate system and plays an important role in the radiation balance of the earth–atmosphere system (e.g., Peixoto and Oort 1983). The radiative characteristics of water vapor permit it to act as the principal agent of energy loss from the atmosphere. It is the atmospheric absorption of solar radiation and the passage of energy to and from the atmosphere, coupled with all the accompanying dynamical processes, that govern the free air temperature. The depth in centimeters of liquid water that would result by the precipitation of water vapor present in the entire vertical atmospheric column of 1-cm^2 cross section is known as precipitable water vapor. Because it is a measure of the total moisture content of the atmosphere, its diurnal, seasonal, and geographical variations are of great importance, aiding investigators in several fields of scientific inquiry who have a direct interest in the global water cycle. Variability in the hydrological cycle is partly a result of the variability in atmospheric processes (e.g., Peixoto and Oort 1983). Water vapor in the atmosphere attenuates electromagnetic propagation and, thus, is important in the remote sensing of the earth from space. Precipitable water content (PWC) has wide applications in microwave communication as well (Bliss 1961).

Distribution of precipitable water is a good indicator of the dynamics of the circulation systems in the atmosphere. For example, large amounts are associated with uplifting convection, and lesser amounts are associated with subsidence. Latitudinally, there is a decrease of precipitable water from the equatorial regions, where it attains the highest values, to the north and south poles. This is because the water vapor pressure depends strongly on temperature. Precipitable water is higher over oceans than over continents, and over desert areas it is considerably smaller mainly because of strong subsidence. It is also much reduced over high-altitude mountainous regions because moisture content decreases with height because of the decrease in pressure. More than 90% of water vapor is confined to the layer below 500 hPa.

Water vapor absorption/transmission of solar radiation has been studied for almost a century. Solar radiometry is a widely established technique used to measure background atmospheric turbidity (Flowers et al. 1969; Volz 1969). This technique was successfully

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Corresponding author address: Dr. P. Ernest Raj, Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pune 411008, India.
E-mail: ernest@tropmet.res.in

adopted to measure aerosol and gaseous pollution and to indicate genesis of large volcanic eruptions. Several workers have used this optical technique to determine total precipitable water content in the atmosphere (e.g., Volz 1974; Tomasi and Guzzi 1974; Pitts et al. 1977; Bird and Hutton 1982; Reagan et al. 1987; Bruegge et al. 1992; Thome et al. 1992; Michalsky et al. 1995; Schmid et al. 1996; Halthore et al. 1997; Ingold et al. 2000; Morys et al. 2001). There are several advantages to using this technique for precipitable water measurements. Studies have shown that horizontal moisture gradients and incipient clouds that are invisible to the naked eye can be detected by this optical technique (Pitts et al. 1977). Precipitable water measurements can be derived from radiosonde soundings, but only at 12-h intervals as per the synoptic-hour (0000 and 1200 UTC) balloon ascents. It is known that precipitable water in the atmosphere can vary at time scales shorter than this (Bruegge et al. 1992). Also, radiosonde measurements have a relatively large uncertainty of about 10% (e.g., Halthore et al. 1997). The sun photometer allows one to monitor atmospheric precipitable water on a real-time scale.

Atmospheric aerosols and various gases interact in different ways with water vapor in the atmosphere, producing various effects. As the relative humidity increases, water vapor condenses onto the particulates suspended in the atmosphere. This condensed water increases the size of the aerosols and changes their composition and their effective refractive index. The resulting effect of the aerosols on the absorption and scattering of light will correspondingly be modified. There have been a number of studies of the change of aerosol properties as a function of relative humidity (e.g., Hanel 1972; Shettle and Fenn 1979). Therefore, a continuous monitoring of precipitable water content with good temporal and spatial resolution is essential for understanding the various physical and dynamical processes taking place in different layers of the atmosphere. Such data and results are sparse in the low-latitude tropical monsoon region. It is to be mentioned here that satellite data are essential for a more complete spatial coverage, and Moderate Resolution Imaging Spectroradiometer (MODIS) precipitable water retrievals from the High Resolution Infrared Radiation Sounder (HIRS) satellite are a typical example that satisfies such a need (http://modis-atmos.gsfc.nasa.gov). An attempt is made in this study to examine the diurnal and seasonal variations in total atmospheric water vapor content derived from sun photometric/radiometric measurements made at a single tropical station.

2. Instrument, methodology, and data

The instrument used in the present study is the Microtops-II Version (Solar Light Co., Inc.), a hand-held multiband sun photometer (specifically an ozone monitor), which is capable of measuring the total ozone column and the water vapor column (precipitable water content) as well as aerosol optical depth (AOD) at 1020 nm. The water vapor measurement is based on a pair of radiometric measurements in the IR band. The 940-nm filter is located in a strong water vapor absorption band and the 1020-nm filter, which has negligible water vapor absorption but is affected only by aerosol scattering, is used in the sun photometer for retrieval of PWC in centimeters. Both of these filters have a bandwidth of 10-nm full width at half maximum (FWHM). Sensitivity studies by Ingold et al. (2000) have shown a sun photometric retrieval error of less than 10% for columnar water vapor values if the 946-nm channel is used and errors of 10%–18% if the 719- or 817-nm channels are used.

The above instrument is equipped with five optical collimators (three channels for ozone measurement and the other two for precipitable water) that are accurately aligned, with a full field of view (FOV) of 2.5° and internal baffles that minimize internal reflections. Along with the narrowband interference filters, each channel is fitted with a photodiode suitable for the particular wavelength range. All collimators are encapsulated in a cast aluminum optical block for stability. A quartz window provides access to the collimator tubes. A sun target and pointing assembly is permanently attached to the optical block and laser aligned to ensure accurate alignment with the optical channels.

In the early days, total atmospheric precipitable water was determined by the method of using band ratios of a water absorption line to a nearby window in the near-infrared. Later, Gates and Harrop (1963) found that the natural logarithm of the ratio between the center of a water vapor band and a nonabsorbing band was linearly related to the square root of precipitable water. Adopting the Bouger–Lambert–Beer law and the Langley method, in a recent publication, Morys et al. (2001) have given the following expression that is used for calculating the vertical water vapor column thickness or precipitable water content (u) in centimeters in the above sun photometer,

$$u = \frac{(\ln V_{01} - \ln V_1 - 1.16\tau_{a2} m)^{1/b}}{k m^b},$$

where V_1 is the ground-based irradiance at 940 nm, V_{01} is the extraterrestrial radiation, τ_{a2} is the aerosol scattering coefficient at 1020 nm, m is the air mass, and k and b are constants numerically derived for the filter. From the radiation transfer model, a relationship between τ_{a1} (aerosol scattering coefficient at 940 nm) and τ_{a2} is found for a standard atmosphere and is of the form $\tau_{a1} = 1.16\tau_{a2}$. The calibration technique used for the early versions of the Microtops sun photometer was developed by Reagan et al. (1987) and tested by Michalsky et al. (1995), and the complete design and calibration of the Microtops-II ozone monitor version used in the present study, and its formulation for retrieval of PWC, are described by Morys et al. (2001).

The ozone monitor used here is a compact, portable instrument that has been mounted on a photographer's tripod stand along with another identical sun photometer that retrieves the AOD at five wavelengths in the range 380–870 nm. The quartz window, as mentioned above, provides access to the collimator tubes for the five photodiodes and the sun alignment target. A spring-loaded door protects this window when the instrument is not in use. Initially the date, universal time, and geographic coordinates of the location of observation are entered manually into the instrument's keypad or even automatically by using a global positioning system (GPS) receiver that is available. Operation of the instrument involves first applying power (from four 1.5-V dry battery cells) with the window closed. The instrument adjusts the offset of each channel to zero while the photodiodes view the inner black surface of the window door. Now with the window opened, the instrument is pointed toward the sun until a bright spot of light is centered over a crosshair arrangement in the sun target window. A scan button is then pressed to initiate a programmable number of rapid scans of each of the five channels. The photodetector output is amplified, digitized, and numerically processed in the signal processor. The self-contained microcomputer automatically calculates the total column amounts of ozone and water vapor, the aerosol optical depth at 1020 nm, and the irradiance at each wavelength. These and other data can be viewed immediately after the scan on a digital readout, or the data can be downloaded onto an external computer. This instrument can store in nonvolatile memory up to 800 scans of the raw and calculated data. Each scan includes the time and date, the temperature inside the instrument, the barometric pressure, and the geographic coordinates.

The above-described sun photometer/ozone monitor has been in operation at the tropical urban station in Pune, India (18°32′N, 73°51′E, and 559 m above mean sea level), since May 1998. The precipitable water content data collected on 413 days during the 41-month period from May 1998 to September 2001 have been used in this study. The data have been collected during the daytime from around 0730 to 1800 local time (LT) at time intervals varying from 10 to 30 min. So on each day there are about 20–30 values of PWC along with AOD at 1020 nm and column content of ozone, and a total of 8972 individual datasets are available for further analysis. Data are available for a fairly good number of days during the months from January to May and again from October to December. Data are sparse during the southwest monsoon months of June–September, and, in fact, data are not available for the month of August because of persistent cloudiness in all three of the years.

Diurnal or temporal variations in precipitable water cannot be investigated from observations of regular radiosonde ascents made at the two synoptic hours of 0000 and 1200 UTC. The sun photometer used in this study enables one to make measurements at short time intervals of even minutes, which is useful to study diurnal/temporal variations. Precipitable water content data, thus collected, have been analyzed here, and the results are presented and discussed in the following section.

3. Results and discussion

In the present study, precipitable water content during daytime (0730–1800 LT) showed a consistent and systematic diurnal variation on a majority of the days. A scan of the entire data of the above 41 months revealed that there exist mainly two types of diurnal variations—one that was observed during the postmonsoon/winter months of November and December, and the other observed during the summer/premonsoon months of April and May. The diurnal variation that was typically observed during the postmonsoon/winter months is shown in Fig. 1a. Here, PWC shows a morning peak and an evening peak with a clear-cut minimum around the noontime hours. Occurrence of morning haze (foglike, but of lesser intensity) in the surface layers during winter months is a common feature at this station. The observing site is surrounded on three sides by low-level hillocks and the terrain is almost like a small valley, but shallow. The haze tends to be confined to the surface layers in the sunrise hours because of nocturnal inversions during winter months. AODs in the wavelength range of 380–870 nm measured simultaneously with the other identical sun photometer are also generally observed to be higher in the morning hours during such occasions, implying a larger extinction of incoming solar radiation. Visibility in the surface layer is poor during such occasions. About 1–2 h following sunrise, one can visually see the spreading (horizontally) and lifting of surface-laden haze layers in the postsunrise hours as the nocturnal capping inversion lifts upward and the convective boundary layer (mixed layer) starts forming. Also, surface wind speeds increase after sunrise, and a drier air mass can be entrained or advected into the region by surface mixing. Under certain conditions there is the possibility of water vapor mass transfer from the atmosphere to the ground. These could be some plausible reasons for the observation of higher values of PWC in the morning and the subsequent decrease in PWC as the haze starts dissipating. Daily surface relative humidity (RH) observations of the India Meteorological Department (IMD) in Pune made at 0830 LT showed that the RH values are higher (above 80%) during the months of November, December, January, and February (which is shown and further discussed in the later part of this section). Once the moisture content disperses and spreads out spatially because of increased air temperature, entrainment of drier air, and vertical mixing, smaller values of PWC values are recorded until the noontime hours. In the afternoon hours, because of evaporation and moist convection, there is again an addition of moisture content into the lower atmosphere,

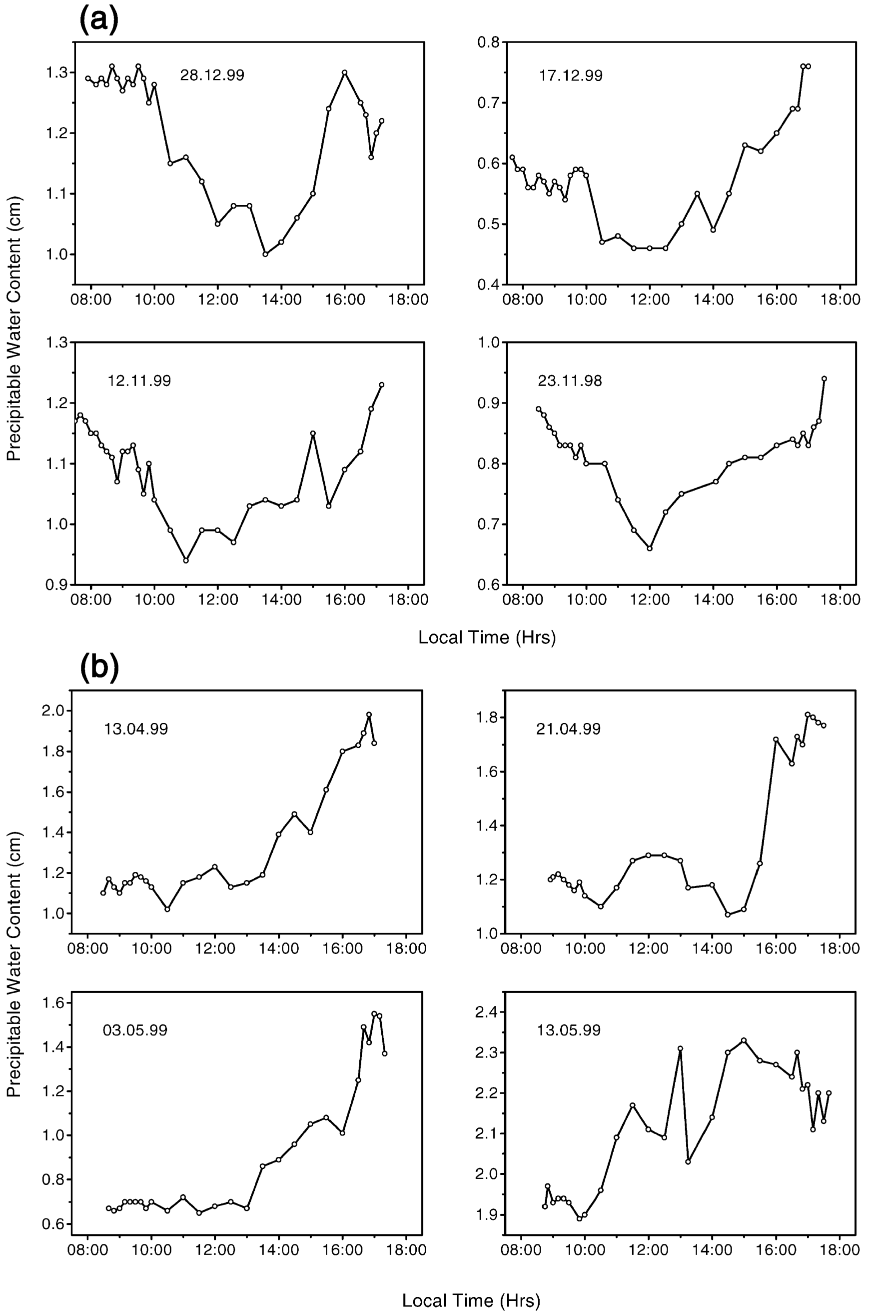

FIG. 1. Typical diurnal variations of sun photometer–derived precipitable water content on 4 days during the months of (a) Nov and Dec and (b) Apr and May.

thereby resulting in the observation of a second peak in PWC.

On the other hand, diurnal variations in the summer/premonsoon months of April and May are different from those described above. Some typical examples of this type of diurnal variation are shown in Fig. 1b. Unlike in the previous case, here there is only one maximum in PWC in the afternoon hours. PWC values remain almost constant in the forenoon hours up to noontime and then start increasing, sometimes quite abruptly and rapidly. Michalsky et al. (1995) have also shown a similar diurnal variation in total column water vapor in the month of May when it increased constantly from the morning to evening hours. Convective activity during summer/premonsoon months at this tropical station is relatively stronger, resulting in an increase in moisture content in the lower atmosphere, culminating in the development of clouds in the afternoon period. This is

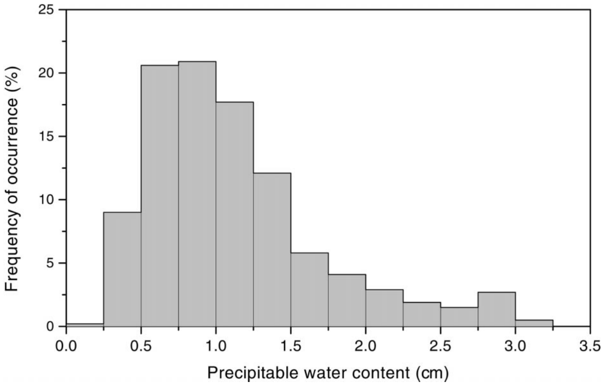

FIG. 2. Frequency distribution of daily mean precipitable water content.

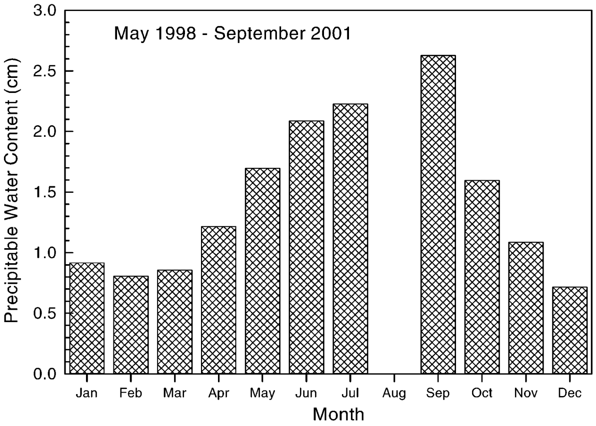

FIG. 3. Monthly mean sun photometer–derived PWC for the period May 1998–Sep 2001.

seen to be a common feature, and it also results in the formation of premonsoon thunderstorms fairly frequently. It may be noted here that sun photometric observations are made only as long as the sun's disk is not obscured by visible cloud patches and the FOV is clear. That means that observations are continued even if the cloud patches are scattered around and are not directly in the sun–ozonometer path, or if the very thin invisible cirrus-type cloud layer is present. Observations are discontinued if unusually high AOD values are recorded in the other sun photometer in the visible wavelength range, indicating extinction by cloud. It is assumed that multiple scattering effects inside thin layers of clouds are minimum because precipitable water content retrievals are made by comparing received solar radiation at two close wavelengths of 940 and 1020 nm.

As mentioned above, daily, about 20–30 observations of PWC are made, depending on the prevailing sky conditions. From these data, daily averages are computed for the available 413 days of observation during the period of May 1998–September 2001 to study day-to-day and seasonal variations in PWC. The daytime average PWC value for the 3-yr period at this tropical station is 1.13 cm. It is observed that the day-to-day variability is considerably high, with the coefficient of variation being 52%. This is because of the large variations in the sky conditions and seasonal variability in the lower atmosphere at a low-latitude tropical location. If only the very clear sky days are considered [that is, only those days when cloud amount is 0 octa over Pune, as reported in the Indian Daily Weather Report (IDWR) of the IMD], then the daily average clear-sky precipitable water content for Pune comes out to be 0.75 cm with a relatively lower coefficient of variation of 33%. The frequency distribution of daily mean PWC is plotted and shown in Fig. 2. It is observed that there is a large range of variation (from 0.20 to 3.25 cm) in the daily average value of PWC. The distribution shows a near-normal distribution, slightly skewed toward the larger PWC value side. The precipitable water content values between 0.75 and 1.0 cm have the maximum frequency of occurrence at this station.

Monthly averages have been obtained from the above daily data of PWC to examine the seasonal variations. Figure 3 shows the overall month-to-month variation in PWC for the 3-yr period. It is observed that PWC is small during the months of December, January, February, and March. It starts increasing from April with the onset of the hot summer season and reaches maximum during the months of the southwest monsoon season (June–September). However, the number of days of observations during June–September is less because of a smaller number of clear/partly clear sky days. There were practically no observations during the month of August because of persistent cloudy conditions. Therefore, the relative magnitude of PWC during these 4 months could be partly due to sampling bias. However, the average value of PWC during the monsoon season is still significantly higher when compared with that in other seasons. PWC starts decreasing once the monsoon season ends in September. Thus, the lowest daily mean PWC (0.72 cm) was in the month of December and the highest mean (2.63 cm) was in September. Analysis of 5-yr radiosonde data at the same station (Ernest Raj and Devara 1997) showed that precipitable water content in the lower troposphere was maximum in the month of August and minimum during December–January. On a seasonal scale, the increase in sun photometer–derived PWC from the winter (December–February) to premonsoon/summer (March–May) seasons is about 50% and from the summer to southwest monsoon (June–September) seasons is as high as 98%. The day-to-day variability in PWC is relatively higher during the months from October to March and is lower during the months from April to September.

It is known that a relationship exists between some measure of the water vapor content of the air near the surface and the amount of moisture aloft (e.g., Reitan 1963). The processes of airmass formation and of vertical mixing would tend to produce either moist or dry

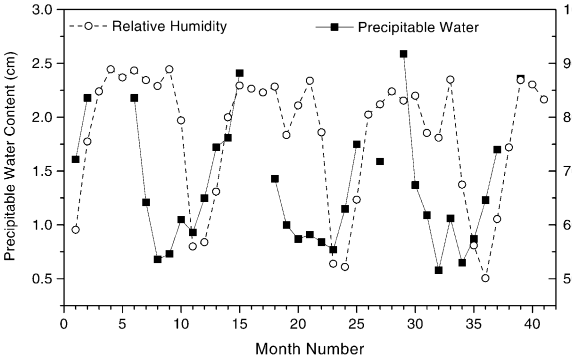

FIG. 4. Month-to-month variation of simultaneously observed mean sun photometer PWC and surface relative humidity from May 1998 to Sep 2001.

conditions throughout the vertical extent of the atmosphere. If the moisture content of the air at any upper level is related to the amount of moisture at the surface, then it follows that the total water vapor content of the air would also be related to a measure of surface moisture. Precipitable water can be used as a good indicator of total moisture. A fairly good relationship has been reported in the literature between surface moisture parameters like relative humidity, dewpoint temperature, water vapor pressure, etc., with radiosonde-derived atmospheric total precipitable water (e.g., Reitan 1963; Smith 1966; Reber and Swope 1972; Tuller 1977; Hsu and Blanchard 1989). However, some other studies related to the comparison of total precipitable water and surface dewpoint temperature showed either low correlations (Bolsenga 1965; Viswanadham 1981; Sinha and Sinha 1981) or large errors in estimations of precipitable water from such a relationship (Schwarz 1968). To examine if a relationship exists between the sun photometer–derived precipitable water content and surface relative humidity, daily data of RH from the IMD for Pune have been collected, and monthly means have been obtained. Figure 4 shows the month-to-month variations in surface RH and sun photometer–derived PWC (monthly means) for the period of May 1998–September 2001. Here, month number 1 on the *x* axis corresponds to May 1998. It is observed that the increase in PWC from March to July (month number 11–15) follows closely that in surface RH. During the months of November–February when low values of PWC are recorded, surface RH remains high. One of the reasons could be that RH observations are reported by IMD for one instance only in the morning hours (0830 LT), whereas the PWC values are the average for the daytime (0730–1800 LT) data. During the winter season higher values of RH are observed in the early morning hours (presunrise), which may consequently decrease as the day progresses. Figure 5 shows the scatterplot of PWC versus surface RH for the data of months from March to October only, excluding the data for the months of November–February. There is a positive correlation (correlation coefficient of about 0.60) between the two parameters, showing the possible influence/association of surface relative humidity on/with the total atmospheric water vapor content.

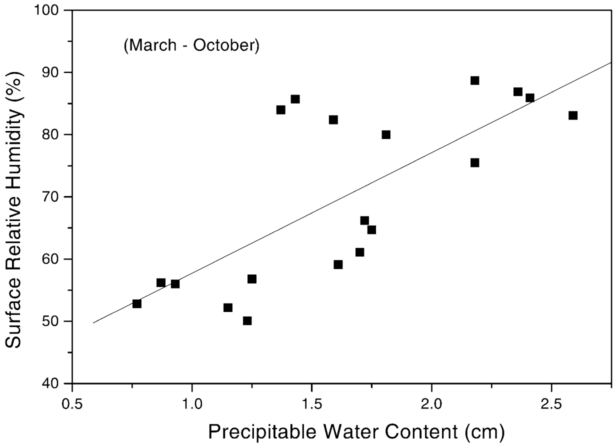

FIG. 5. Relationship between precipitable water content and surface RH for the data collected from Mar to Oct.

As mentioned previously, sun photometric measurements have been made as long as the sun's disk is not obscured, and the FOV is clear even if some cloud patches are scattered around or the sky is partly cloudy. Observations are made only for the duration of the day when clear-sky conditions existed. Cloud amount (in octa) data reported in the IDWR of the India Meteorological Department for the Pune station for those days on which sun photometer data are available are collected. The daily average PWC values have been categorized into the eight reported cloud conditions, and the mean PWC for each cloud condition is obtained. Figure 6 shows the variation of this mean PWC for the eight cloud conditions (0–8 octa). Very few days' PWC data were available when cloud amount was 7 and 8 octa, but for continuity the mean of these data was also

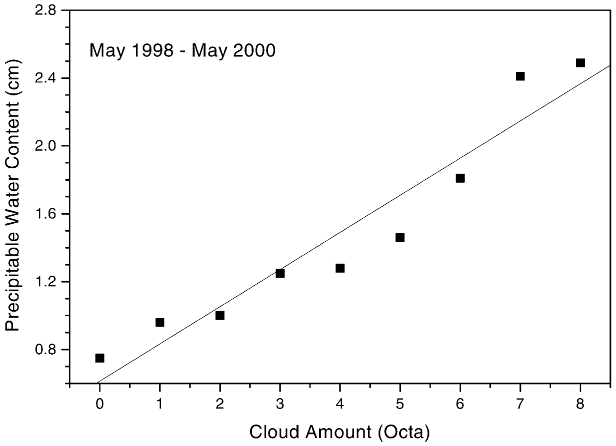

FIG. 6. Relationship between mean precipitable water content and cloud amount.

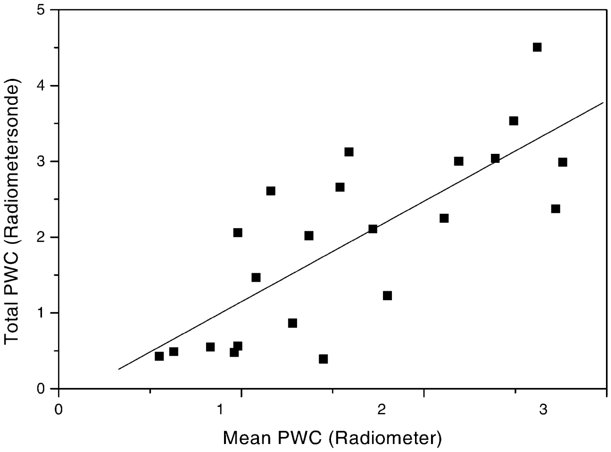

FIG. 7. Relationship between sun photometer–derived PWC and radiosonde-derived PWC.

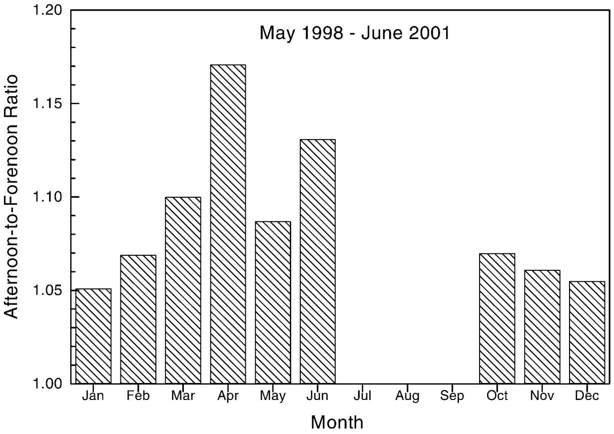

FIG. 8. Monthly mean afternoon-to-forenoon ratio of PWC for the period May 1998–Sep 2001.

considered for plotting purposes. It can be readily seen that there exists a good one-to-one relationship between PWC and cloud amount. When cloud amount is zero (clear sky), the mean PWC is calculated to be 0.75 cm, and it increases steadily with an increase in cloud amount. Precipitable water content value in the atmosphere is more than 1.5 times the clear-sky value when the cloud amount is observed to be 3 octa; it doubles when the cloud amount is 5 octa, and it is 3 times the clear-sky value if the cloud amount is 7 octa. Thus, the sun photometric observations show that total atmospheric water vapor content and cloud formation are two closely related phenomena.

From radiosonde measurements of temperature, pressure, and dewpoint temperature, one can first compute specific humidity and then precipitable water content between different pressure levels up to the altitude where detectable water vapor exists. Pune is not a regular/routine radiosonde station. There is a radiometersonde ascent every alternate Thursday (fortnightly) at this station in the evening hours, generally between 1900 and 2030 LT. These balloonborne radiometersonde data from Pune are collected, and precipitable water at different heights has been computed. For the 41-month period under consideration above, there are about 22 days for which simultaneous observations of radiosonde- and sunphotometer (radiometer)-derived precipitable water content are available. Sun photometric observations of PWC generally end by about 1800 LT, near local sunset, and on some days even before, depending on the sky conditions. However, for a one-to-one comparison, the last instantaneous sun photometric observation of PWC of the day in the late afternoon hours is taken for comparison with radiosonde measurement. Figure 7 shows the variation of radiometersonde-derived total PWC with the sun photometer–derived instantaneous value of PWC. There is a good agreement between the two, with a correlation coefficient of about 0.80, though the radiometersonde estimates seem to be slightly on the higher side. One of the reasons could be the time difference between the two observations. Also the location of the IMD radiosonde balloon ascent is more than 5 km away from the Indian Institute of Tropical Meteorology (IITM) campus site where the sun photometer is operated. Because the balloon while ascending can drift with the wind, and the sampled air volumes by the above two techniques are different, it is possible to record different amounts of water vapor. Michalsky et al. (1995) suggested that most of the rms differences in such a comparison result from the measurement path difference. The comparisons in the present study show that the altitude up to which moisture (PWC) measurements could be obtained (detectable by the instrument) by the radiosonde is highly variable, anywhere between 500 and 8000 m, and it is also closely related to the precipitable water content measured with the sun photometer.

A scan of the sun photometer–derived precipitable water content obtained during the daytime showed that, in general, the afternoon values of PWC are higher in magnitude when compared with the forenoon values. To see the nature of this kind of diurnal asymmetry, on each day, the average forenoon (FN) and average afternoon (AN) values of PWC are computed. It is observed that 70% of the days show higher values of PWC in the afternoon (positive AN-to-FN ratio). Monthly means of the AN-to-FN ratio are obtained to examine the seasonal variation of this diurnal asymmetry and are shown in Fig. 8. Data for the full day are not available during the months of July, August, and September, and so it was not possible to get this ratio in these months. It is seen that during all the months, on average, the AN-to-FN ratio is greater than unity. Further, the diurnal asymmetry is more pronounced in the summer and monsoon months of April, May, and June. Very small diurnal asymmetry is seen in the months of November, December, and January. Using radiosonde-derived precipitable water at 0000 and 1200 UTC, Ananthakrishnan et al. (1965) have shown that the evening value of precipitable water is a few percent higher than the morning value for all of the Indian stations considered and almost throughout the year. The result obtained in the present study with a better time resolution confirms their observations. The diurnal asymmetry again relates to the strong convective activity that occurs in the afternoon hours because of surface heating at a tropical low-latitude station like Pune. Sun photometric data of the total precipitable water described above are being acquired on a continuous basis at this station, which will be useful for various applications.

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