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Seasonal Variations in the Vertical Structure of Water Vapor Optical Depth in the Lower Troposphere over a Tropical Station

P. Ernest Raj and *P.C.S. Devara*
Indian Institute of Tropical Meteorology, Pune-411008, India

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ABSTRACT

Spatio-temporal variations of water vapor optical depth in the lower troposphere (450-3850 m) over Pune (18°32'N, 73°51'E, 559 m Above Mean Sea Level), India have been studied over a period of five years. The mean vertical structure showed that the moisture content is greatest at the lowest level and decreases with increasing altitude, except in the south-west monsoon season (June to September) where an increase upto 950 m has been found. Optical depths are maximum in the monsoon season. The increase from pre-monsoon (March-May) to monsoon season in moisture content on an average is by about 58% in the above altitude range. The temporal variations in surface Relative Humidity and optical depth at 450 m show positive correlation. The amplitude of seasonal oscillation is the largest at 1465 m altitude. The time-height cross-sections of water vapor optical depths in the lower troposphere showed a contrast between years of good and bad monsoon.

Key words: Optical depth, Precipitable water

I. INTRODUCTION

Water vapor in the earth's atmosphere plays an important role in the radiation balance of the earth-atmosphere system. It has strong and wide absorption bands in the infrared region and so affects the incoming solar radiation and outgoing terrestrial longwave radiation. A useful measure of total moisture in the atmosphere is precipitable water, the depth to which liquid water would stand if all the water vapor in a column of air of unit area were condensed. This precipitable water or integrated water vapor content has got wide applications in microwave communication problems (Bliss, 1961). In many areas of meteorology like weather prediction, climatology and agricultural meteorology, knowledge of precipitable water is of great importance. Also, the amount of water vapor in the atmosphere is a good indicator of the dynamic state of the atmospheric circulation. A large amount of water vapor is expected in a region of prevailing convection, where intense vertical transport of water vapor from surface takes place. In contrast, one might expect a relatively dry atmosphere in the region of large-scale subsidence (Hsu and Blanchard, 1989).

The seasonal and geographical variations in precipitable water content values over some of the Indian stations have been studied by Ananthakrishnan et al. (1965). Several workers have found relationship of surface moisture parameters like dew-point temperature, water vapor pressure etc. with the atmospheric total precipitable water (for instance Reitan, 1963; Smith, 1966; Reber and Swope, 1972; Tomasi, 1977; Tuller, 1977; Parameswaran, 1988). From the balloon-borne radiometersonde data obtained from India Meteorological Department (IMD), Pune, water vapor optical depths between different height intervals / slabs have been computed and an attempt is made in this paper to study the seasonal variation of the vertical structure of the moisture content over Pune, a low latitude tropical station.

II. DATA

If k_λ is the absorption coefficient per unit precipitable water w, then the vertical optical path (water vapor optical depth) U_z is given by

$$U_z = k_\lambda w$$

and $w = (\bar{q}\Delta p) / g$, where q is the specific humidity, Δp is the pressure (Δp always taken positive), and g is the acceleration due to gravity (Johnson, 1974).

Pune is not a routine aerological station. But there is a radiometersonde ascent every alternate Thursday, at Pune in the evening, generally between 1900 and 2100 hours local time. The radiometersonde is a Suomi–Kuhn type instrument used for measurement of the vertical distribution of the infra–red radiative fluxes in the atmosphere (Suomi et al., 1958; Kuhn, 1961). It consists of a radiometer head which senses the downward and upward infra–red radiation, a rod thermister for the measurement of ambient air temperature and a lithium chloride hygrister for measuring atmospheric humidity. All the measurements are made in the red and infra–red regions (2 to about 18 μm) of the solar spectrum where absorption by atmospheric water vapor is considerable. Using the vertical profiles of temperature, dew–point temperature and pressure thus obtained from these radiometersonde ascents of IMD available once–in–a fortnight, water vapor optical depths (the precipitable water vapor between two height intervals) at seven altitudes between 450 and 3850 m, have been computed using the above expression. The data for the five–year period 1987, 1989–1992 have been used in the present study.

The station Pune is about 100 km inland from the west coast of India and is located on the lee–side of the Western Ghats. The air flow in the lower troposphere is predominantly westerly during the SW monsoon season when there is the influx of moisture from the Arabian Sea. Westerlies become weak and easterly flow sets in from October onwards.

III. RESULTS AND DISCUSSION

Vertical profiles of water vapor optical depth, at seven heights in the altitude range 450–3850 m, obtained on about 105 days during the five–year period, 1987, 1989–1992, have been used to investigate the vertical structure during different seasons. For this purpose, monthly averages as well as the overall five–year monthly and seasonal averages of the profiles have been obtained.

The mean (5–year) vertical structure of water vapor optical depth during the pre–monsoon (March, April, May), SW monsoon (June, July, August, September), the post–monsoon (October, November), and the winter (December, January, February) seasons is shown in Figure 1. Generally the moisture content is expected to be greatest at the surface and to decrease with height. The same expected vertical structure can be seen in all the four seasonal profiles shown here, except that during monsoon season, optical depths increased upto 950 m and thereafter decreased. It is also seen that optical depths are the highest in magnitude at all the heights during monsoon season compared to the other three seasons. The increase in optical depth from pre–monsoon to monsoon season in the 450–3850 m altitude range, on an average, is by about 58%, the highest increase being about 80% in the 1465–2000 m altitude range. During the three seasons other than monsoon, the optical depths are nearly same in magnitude. During the pre–monsoon seasons slightly higher values are observed in the 450–1465 m altitude range and during the winter season there is a little broad increase around 2000 m.

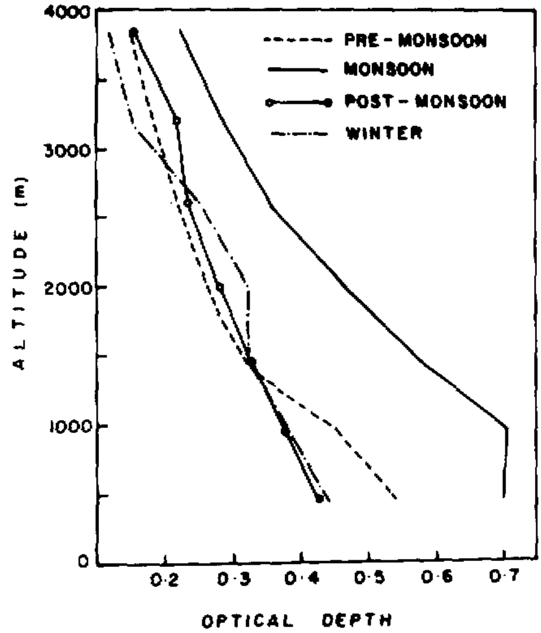

Fig. 1. Mean vertical profiles of water vapor optical depth for the pre–monsoon, monsoon, post–monsoon and winter seasons.

To study the seasonal variations at different altitudes, the 5–year monthly means separately for the seven altitudes are plotted and shown in Figure 2. A very clear annual oscillation can be seen at all the altitudes. Optical depths start increasing steadily from February / March and reach a maximum in July / August. After August, there is a sharp decline in the values especially at lower altitudes. Minimum optical depths are obtained in the winter months of December and January. Optical depth values during June, July and August at 950 m are the highest observed and even exceed those corresponding values at 450 m. This feature can also be seen in the seasonal mean vertical profiles (Fig. 1). The amplitude of the seasonal oscillation is the largest at 1465 m and it decreases with increasing altitude above. It is further observed that at lower altitudes (<2600 m) maximum optical depth is in the month of August and at upper altitudes the seasonal maximum is in the month of July. Parameswaran (1988) has shown that the integrated water vapour content (upto 10 km) was maximum in May at Trivandrum, in July at Madras and in August at Visakhapatnam and Delhi. The observed maximum in July / August in optical depths at Pune in this study, along with the above reported results show the progress of the south west monsoon flow and influx of moisture in the lower troposphere around the time of onset of monsoon at different locations.

From the daily data of surface Relative Humidity (RH) at Pune for the years 1987 to 1992 (IMD publications), the monthly mean RH has been computed. The time series of the monthly mean RH during the above period along with the monthly mean optical depth at 450 m is shown plotted in Figure 3. It can be seen that both the parameters vary more or less similarly. The scatter plot of monthly mean surface RH and corresponding water vapor optical depth at 450 m is shown in Figure 4 along with the best fit straight line. Though the points seem rather scattered, there is the evidence of a positive correlation with the correlation coefficient being 0.46. Lag correlation analysis shows that RH at the surface is lagging behind optical depth at 450 m with a maximum correlation coefficient of 0.57 at a lag of one month.

The overall 5-year monthly mean vertical profiles of water vapor optical depth are taken to examine the time evolution of the vertical structure. For this purpose, isolines of equal

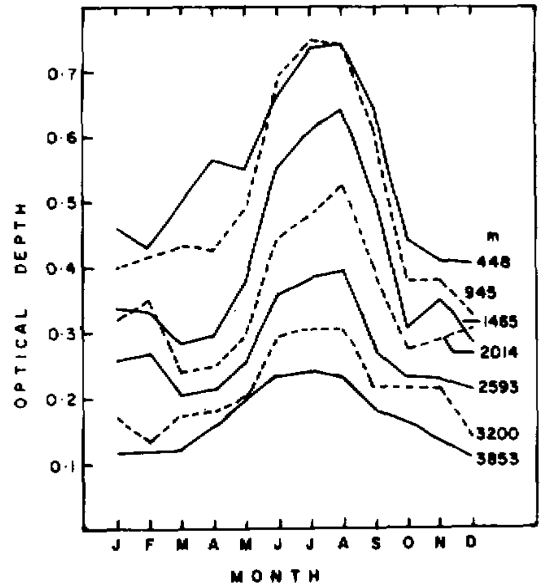

Fig. 2. Mean month-to-month variation of optical depth at seven altitudes.

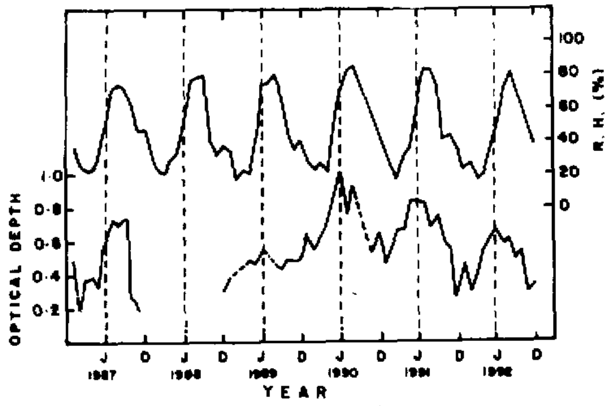

Fig. 3. Time-series of monthly mean surface Relative Humidity and water vapor optical depth at 450 m.

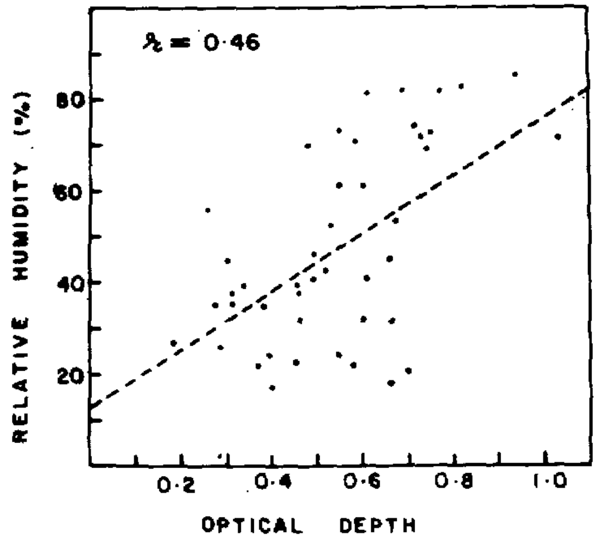

Fig. 4. Scatter diagram of monthly mean surface R.H. versus optical depth at 450 m.

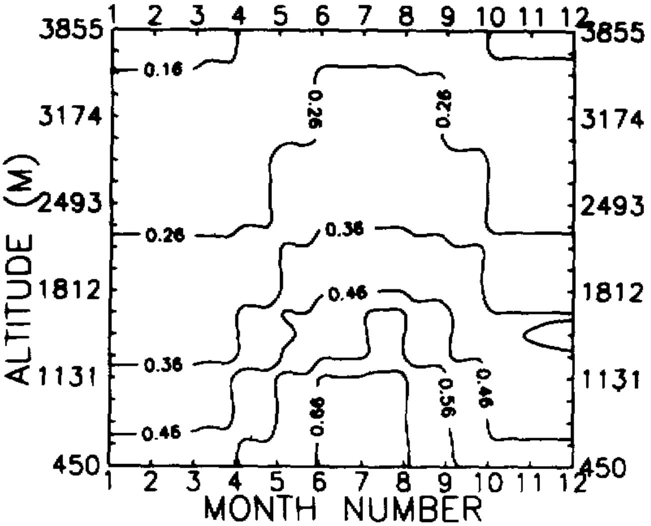

Fig. 5. Time-height variations of five-year mean water vapor optical depth.

optical depth are drawn and shown in Figure 5. It can be seen that upward transport of moisture from lower levels begins as early as March. A high optical depth value of 0.6 from 450 to 1100 m is attained by the first month of the SW monsoon season i.e. June. The upward transport of moisture is slower and steady and begins prior to the monsoon season, whereas the fall in the optical depth values at all levels is faster and abrupt soon after the month of September. The highest optical depth values are observed in the altitude range 450–1130 m in the months of June, July and August.

To examine the time–height cross–section of optical depth during the years of contrasting monsoon seasons, two years, 1991 and 1987 have been considered which have recorded relatively higher and lower seasonal rainfall amounts respectively, at Pune. During 1991, Pune recorded a seasonal total rainfall of 924 mm and it was 380 mm during the monsoon season of 1987. The normal monsoon total rainfall at Pune has been reported to be about 508 mm (IMD, 1962). Figure 6a shows the month–to–month evolution of the vertical structure of optical depth, in the lower troposphere, in the year 1991. As observed in the five–year mean picture, upward transport of moisture started before the onset of monsoon and as early as March during 1991. Until the end of September the optical depth values were high and values greater than 0.6 were observed upto an altitude of 1130 m (dashed area in the figure). This seems to be the reason for the good rainfall amount recorded during the monsoon season of 1991. A contrasting behavior is seen during the year of 1987 as shown in Figure 6b. There is no evidence of upward transport of moisture as late as May. Optical depth values greater than 0.6 were observed only for a brief period, in the months of July and August. The resulting seasonal rainfall (380 mm) was much below the climatological normal rainfall of 508 mm at Pune. Thus the time–height structure of water vapor optical depths shows a clear contrast between the years of good and bad monsoon over a station.

Srinivasan and Sadasivan (1975) have reported that the moisture content in the lower tropospheric levels (upto about 4 km) remains high without any appreciable variation whatever be the monsoon activity. This may be true for variations within a monsoon season (June to September) and that too during a fairly good monsoon year. Parasnis (1994) has shown that within a monsoon season, an increase in monsoon activity is preceded by an increase in total precipitable water content in the lower troposphere. The present results show that the

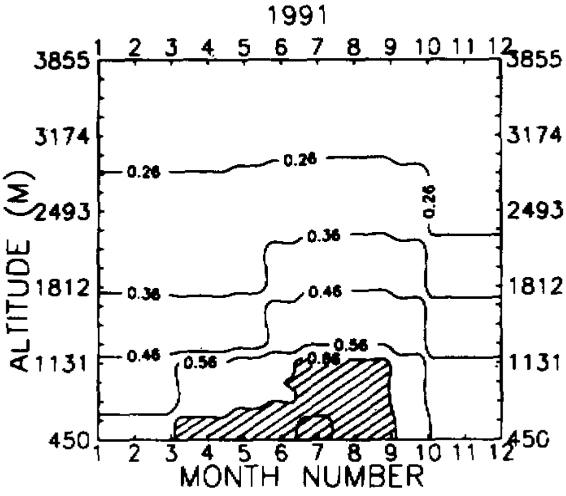

Fig. 6a. Time–height variations of water vapor optical depth during the year 1991.

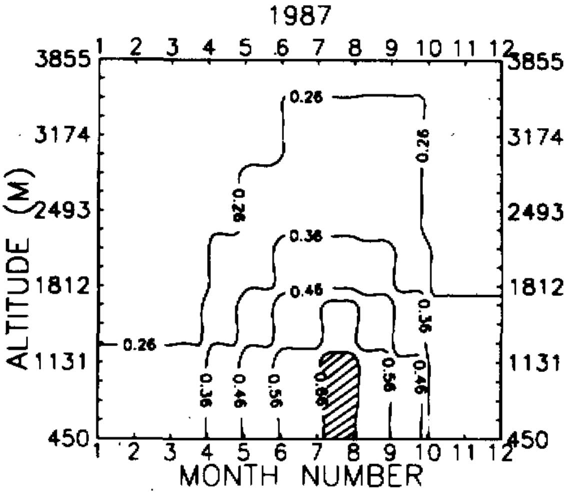

Fig.6b. Same as Fig. 6(a) but during the year 1987.

variations in vertical structure of moisture content, not only during the four months of the SW monsoon season, but also during the pre-monsoon have a relationship with the ensuring monsoon activity and the rainfall amount during that season. The results also show that there is a variability in the time evolution of moisture content in the lower troposphere from year to year at a typical tropical station like Pune. Thus the type of spatio-temporal evolutions shown here gives an insight into the distribution of moisture content in the lower troposphere and more closer interval (in both time and space) data would give the fine scale structure and short-term variations and a better understanding of the phenomenon.

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