CHAPTER 2

COMPUTATION OF PRECIPITABLE WATER IN THE ATMOSPHERE

2.1 Introduction

The important role played by atmospheric water vapour in the attenuation of extra-terrestrial radiation received at the surface of the earth is well documented. Moisture occurs in all three of its forms - vapour, liquid and solid - in the atmosphere and is the only major constituent of the atmosphere which varies markedly in time and space. The state of the atmosphere is controlled to a large degree by the content and form of water within it, and the exchanges of latent and sensible heat, which accompany changes in state, have direct effects on atmospheric circulation. A knowledge of the amount of water vapour in the atmosphere is therefore essential not only in basic studies of the atmosphere and its properties, but in weather forecasting. It is equally important in radar and microwave communication and long range propagation studies, remote sensing from aircraft and satellites and in astronomical observations in the sub-millbetre and millimetre wavelength range 300 μ to 3mm, in view of the refraction and attenuation of microwave radiation by moist layers and solid and liquid forms of water. The high variability of water vapour in time and space makes the continuous monitoring of the precipitable water vapour in the atmosphere an essential part of any scientific investigation involving the attenuation of electromagnetic radiation in the earth's atmosphere.

Continuous measurements of relative humidity at the surface of the earth are made at meteorological observatories using hygrographs and psychrometers and in the free atmosphere, two to four times a day, using radiosondes. The simplest method, therefore, of obtaining values of precipitable water in the atmosphere is by computation from either surface humidity values or by integrating the water vapour content in the atmosphere from radiosonde ascents. Both these were carried out in the course of the present study and the methods used, the errors involved and the results obtained are described in the sections that follow.

2.2 Derivation of precipitable water from surface humidity measurements

2.2.1 Historical

The existence of a simple correlation between the surface values of water vapour density and the total precipitable water in the atmosphere has been assumed by many workers. Using certain standard distribution functions derived from measurements made on research balloon flights, Hann (1894) proposed the following equation correlating ρ_0 the water vapour density at the surface, with ρ the water vapour density at height z.

$$\rho = \rho_0 e^{-\beta z} \qquad (2.1)$$

β is a coefficient having a value of about 4.5×10^{-6} cm^{-1}. However, it is now known that the factor β varies with the seasons and location, and the method gives only very approximate values for the integrated precipitable water.

This was confirmed by Fowle (1913), who discussed the problem in detail. In particular, he investigated the question as to whether precipitable water W could be determined using a relationship of the form:

$$W = K.P. \qquad (2.2)$$

where P is the absolute surface humidity in g m^{-3} and K is a constant, with a value of about 2. The relationship worked fairly well in the mean but was subject to large uncertainties for any particular day. He also found that K varied widely from site to site and the large variations in K are strong evidence that the relationship does not hold good for the data considered.

Kondratyev et al (1965) also came to the same conclusion, after a lengthy series of measurements in the Caucasus, that any attempt to find a stable relationship, even for specially selected observations and high altitude locations, between the two is futile.

Reitan (1963) had examined the relationship between mean monthly values of precipitable water and surface dew points for 15 stations in the U.S.A. and had found an empirical relationship of the form:

$$\log W = a + b . T_d \tag{2.3}$$

where W is the precipitable water, T_d is the dew point and a and b are constants. When W is expressed in cm and T_d in degrees Pahrenhert, the equation was found to be

$$\log W = 0.981 + 0.0341 \ T_d \tag{2.4}$$

Ananthakrishnan et al (1964) studied the correlation between surface humidity mixing ratio and surface dew point and precipitable water at 12 stations in India for the period 1956-61 and found that Reitan's empirical relation does not fit the results obtained for Indian stations. They showed, however, from theoretical considerations, that if the humidity mixing ratio r decreases exponentially with height, then a relatiqn of the type found by Reitan (1963) will be valid and precipitable water will be directly proportional to the surface humidity mixing ratio. The scatter diagrams in which monthly mean values of W are plotted against r showed the relationship to vary with the seasons, being distinctly different in the dry, cold and humid monsoon months. They found the relation

$$r = K_1 W + K_2 \tag{2.5}$$

where K_1 and K_2 are constants.

Attempts were then made by various workers to use more elaborate formulae to fit the relationship between precipitable water and surface humidity or surface dew point. Smith (1966) used an empirical relationship having the form $W = \exp. (0.07074 T_d + r)$, where $r = -0.02290$ from April to June and $r = +0.02023$ for the remaining months. Fitting higher order curves to these data did not produce significantly larger correlation coefficients. Reber and Swope (1972) concluded that surface measurements were too unreliable to allow one to infer the total precipitable water. Hanson and Caimanque (1975), found that the large scatter they observed at Cerro Tololo is typical for what all observers have found and is intrinsic to the physical circumstances and not the method. This is to be expected, since routine radiosonde ascents made at meteorological stations do not generally show a smooth distribution of water vapour with altitude, but instead reveal a complex structure with substantial day-to-day variations. This is confirmed by the results of very high altitude ascents made.

Atwater and Ball (1976) computed precipitable water using both techniques, from surface dew point values and from radiosonde observations at 11 stations for a*two-year period in the USA. The results indicated that both on an annual and on a monthly basis, the computed total solar radiation is usually slightly higher, when the surface dew point is used to estimate precipitable water. However, annual differences were 1%, or less than 2%, at all stations for both years. Differences in individual months were also less than 2% at all stations with few exceptions.

The same result was obtained by Roosen and

Angione (1977), who showed that precipitable water in the atmosphere is not simply related to surface humidity values, from a study of observations made at nine field stations of the Astrophysical Observatory of the Smithsonian Institution during 1912-1952. They found a strong positive correlation between precipitable water and surface humidity, but the variance was found to be so large that they concluded that surface humidity is not a reliable indicator of precipitable water for any particular day and agreed with Fowle (1913) that "any formula for determining the amount of atmospheric water vapour from observed surface humidities is absolutely unsafe".

Robson and Rowan-Robinson (1979), however, claim that there is a reasonable correlation between the zenith line-of-sight precipitable water and the surface absolute humidity, consistent with an exponential distribution with a scale height of 2 km, for two stations in the USA and UX. They argued that if the distribution of water vapour density with height in the atmosphere had always the same relative distribution they should expect a correlation between the zenith precipitable water content W_{zen} and the absolute humidity at the surface of the earth X g m^{-3}. Again, they argued that if the water vapour density falls off with height as

$\exp(-h/H)$, where H is the scale height in km,

$$W_{zen} = H.X \text{ (mm)}$$

Assuming H = 2 km to be a reasonable fit, they claimed that W_{zen} can be estimated from X to an accuracy better than ± 50%. Even with this wide discrepancy, they claim that for inland and desert sites in on-summer months, the exponential atmosphere with a scale height for water vapour of 2 km is a good approximation.

2.2.2 Computation of precipitable water from surface humidity measurements at Bangalore and Nandi Hills

Regular records of relative humidity were made using hair hygrographs at the two meteorological observatories established at the Raman Research Institute, Bangalore, (Lat. 12° 58'N Long. 77°35'E, 950 m. amsl) and on Nandi Hills (Lat. 13° 22' Long. 77° 41'E 1479 m. amsl) for three years from 1977-80. Dry and wet bulb temperature measurements were made every three hours using dry and wet bulb thermometers exposed in louvred thermometer screens as well as with aspirated Assmann and whirling psychrometers. The daily mean values of absolute humidity d_v at the two stations for each of the 12 months for the period May 1977 to May 1980, are given in Tables 21 and 2.2.

DATE	JANUARY					FEBRUARY					MARCH					APRIL				
	1977	1978	1979	1980	MEAN	1977	1978	1979	1980	MEAN	1977	1978	1979	1980	MEAN	1977	1978	1979	1980	MEAN
1		13.3	12.2	10.4	12.0		12.7	11.8	9.2	11.2		10.6	11.5	11.1	11.1		13.4	11.8	15.7	13.6
2		13.1	12.4	12.6	12.7		12.1	12.2	11.0	11.8		9.9	10.7	13.2	11.3		13.3	10.9	13.0	12.1
3		12.4	11.3	11.1	11.6		13.1	13.6	12.4	13.0		9.3	12.8	11.1	11.1		11.9	9.6	12.2	11.2
4		12.4	10.7	11.2	11.4		12.6	12.9	12.7	12.7		9.8	13.3	10.6	11.2		10.4	11.9	13.1	11.8
5		12.3	10.4	11.2	11.3		13.0	11.6	12.3	12.3		12.2	13.9	9.6	11.9		11.8	12.3	13.7	12.6
6		11.9	10.6	12.1	11.5		13.3	13.2	11.1	12.5		11.5	13.6	10.4	11.8		12.7	11.7	13.9	12.8
7		1 2 7	1	11.7	11.9		14.1	13.0	10.2	12.4		12.7	12.1	10.5	11.8		14.6	9.6	15.2	13.1
8		12.3	11.4	11.7	11.8		13.7	13.3	9.3	12.1		14.9	13.8	11.8	13.8		15.0	9.6	13.5	12.7
9		12.0	11.3	11.9	11.7		14.3	13.4	9.1	12.3		13.2	11.9	9.7	11.6		14.3	9.0	13.7	12.3
10		11.1	10.9	11.6	11.2		13.1	13.4	8.8	11.8		12.2	11.6	11.7	11.8		14.8	10.0	14.9	13.2
11		12.3	11.3.	10.	11.3		13.3	13.7	10.6	12.5		11.7	9.8	14.7	12.1		13.4	13.8	14.5	13.9
12		13.4	10.4	11.1	11.6		12.0	15.0	9.9	12.3		12.1	7.3	14.3	11.2		12.4	13.4	11.3	12.4
13		11.5	10.2	10.7	10.8		11.7	15.3	9.7	12.2		14.5	10.0	11.5	12.0		11.3	12.8	10.6	11.6
14		10.5	10.4	11.0	10.6		9.6	13.7	8.7	10.6		13.3	8.3	9.9	10.5		16.4	13.6	11.4	13.8
15		10.0	10.9	10.8	10.6		11.4	13.5	9.1	11.3		13.8	10.5	10.5	11.6		15.1	14.8	14.4	14.8
16		11.2	11.2	10.9	11.1		13.2	12.2	10.5	12.0		13.6	10.0	9.7	11.1		16.6	15.2	12.0	14.6
17		10.1	11.3	10.7	10.7		11.2	10.9	10.0	10.7		13.5	9.6	8.8	10.6		15.3	15.6	11.1	14.0
18		8.1	12.9	10.3	10.4		15.2	14.4	9.2	12.9		14.3	10.4	7.0	10.6		15.4	15.2	12.6	14.4
19		8.4	13.9	11.2	11.2		14.4	16.0	8.9	13.1		13.1	12.0	7.1	10.7		13.7	12.8	14.2	13.6
20		8.9	13.8	11.3	11.3		14.4	16.1	9.8	13.4		14.3	10.9	7.5	10.9		13.6	12.8	-	13.2
21		11.8	12.6	9.8	11.4		14.0	14.8	9.8	12.9		14.0	11.6	8.6	11.4		15.9	14.1	15.7	15.2
22		11.8	12.2	9.8	11.3		15.7	15.5	9.2	13.5		13.5	11.7	8.0	11.1		14.4	12.1	17.2	14.6
23		11.4	13.4	9.2	11.3		14.2	14.0	9.0	12.4		13.0	12.5	8.4	11.3		16.0	13.1	13.3	14.1
24		12.1	13.4	8.6	11.4		13.7	15.8	8.1	12.5		12.2	10.1	10.4	10.9		13.8	12.3	17.1	14.4
25		11.5	12.5	8.9	11.0		11.3	14.2	8.5	11.3		12.6	10.9	7.6	10.4		15.4	12.5	13.9	13.9
26		11.9	12.0	8.4	10.8		10.5	14.3	8.7	11.2		14.0	11.3	10.4	11.9		15.7	13.3	19.6	16.2
27		10.8	11.0	8.7	10.2		11.8	13.5	9.2	11.5		13.6	9.6	7.2	10.1		15.6	12.7	15.6	14.6
28		9.6	11.4	8.0	9.7		11.7	13.9	9.9	11.8		12.9	10.4	9.0	10.8		14.7	14.8	14.6	14.7
29		10.0	10.4	10.0	10.1				10.9	10.9		12.6	12.1	14.2	13.0		14.9	16.5	16.4	14.9
30		9.3	12.5	10.2	10.7							11.6	12.7	15.6	13.3		14.4	16.2	12.7	14.4
31		11.2	12.0	10.6	11.3							11.9	12.7	15.5	13.4					
MEAN		11.3	11.7	10.5	11.2		12.9	13.7	9.8	12.1		12.7	11.3	10.5	11.5		14.2	12.8	13.9	13.6

TABLE 2.1: Daily mean values of absolute humidity (g m^{-3}) during the period 1977–80 for Bangalore.

DATE	MAY					JUNE					JULY					AUGUST				
	1977	1978	1979	1980	MEAN	1977	1978	1979	1980	MEAN	1977	1978	1979	1980	MEAN	1977	1978	1979	1980	MEAN
1	-	13.8	16.7	15.1	15.2	16.0	16.4	16.5	-	16.3	15.9	15.3	15.4	-	15.5	16.8	16.4	16.8	-	16.7
2	-	13.8	16.3	16.4	15.3	15.7	15.5	16.9	-	16.0	15.7	15.2	15.8	-	15.6	16.0	16.1	16.7	-	16.3
3	-	15.3	15.4	17.6	16.1	17.0	15.7	16.0	-	16.2	16.2	15.5	16.2	-	16.0	<5.2	16.4	16 6	-	16.1
4	-	15.6	15.7	17.5	16.3	16.5	15.5	16.1	-	16.0	16.3	15.6	15.6	-	15.8	15.3	15.8	16.3	-	15.8
5	-	17.3	13.4	16.8	15.8	16.4	16.5	17.3	-	16.7	16.2	15.8	16.0	-	16.0	14.6	16.0	16 8	-	15.8
6	-	15.6	14.2	17.9	15.9	17.3	15.7	16.6	-	16.5	16.1	16.2	15.9	-	16.1	<4.7	15.9	16.4	-	15.7
7	17.5	17.8	14.6	18.0	17.0	15.9	15.5	16.6	-	16.0	15.9	16.4	15.0	-	15.8	15.2	16.4	14.7	-	15.4
8	17.1	14.7	13.4	15.3	15.1	15.3	15.4	18.2	-	16.3	16.2	16.8	15.4	-	16.1	15.9	16.4	14.5	-	15.6
9	16.9	16.3	12.9	14.9	15.3	15.0	15.3	16.3	-	15.5	15.7	15.8	15.7	-	15.7	16.6	16.0	15.1	-	15.9
10	15.4	15.5	13.4	16.7	15.3	14.8	15.6	17.5	-	16.0	15.9	15.5	15.9	-	15.9	16.5	16.0	14.9	-	15.8
11	1E.1	06.7	17.1	-	16.6	15.6	16.0	17.6	-	16.4	16.2	16.2	16.3	-	16.2	16.9	15.7	14.9	-	15.8
12	15.7	17.0	15.7	-	16.6	15.5	16.2	17.5	-	16.4	16.7	16.0	15.8	-	16.2	16.4	15.0	14.4	-	15.3
13	16.3	16.9	15.4	-	16.2	16.2	16.2	17.8	-	16.7	16.4	16.5	15.9	-	16.3	17.4	14.4	14.4	-	15.4
14	16.6	17.5	14 2	-	16.1	16.3	15.7	17.4	-	16 5	16.4	16.5	16.0	-	<6.3	16.9	14.0	15.4	-	15.4
15	15.7	17.3	11.9	-	15.0	17.0	16.0	<5.6	-	1E.2	16.5	16.1	15.7	-	16.1	17.2	13.E	14.8	-	15.3
16	15.5	16.0	10.6	-	14.0	17.1	16.8	16.1	-	16.7	16.0	17.4	15.2	-	16.2	17.1	15.8	14.6	-	15.8
17	15.3	15.3	11.4	-	14.0	16.3	16.3	16.0	-	16.3	16.1	16.7	14.8	-	15.9	17.0	15.9	14.3	-	15.7
18	15.5	16.6	13.4	-	15.2	17.2	16 2	15.5	-	16.3	16.3	16.7	15.1	-	16.0	16 5	16.5	15.4	-	.1
19	15.4	15.5	13.2	-	14.7	15.3	16.3	<6.1	-	15 9	17.2	16.0	14.3	-	15.8	16 5	16.5	16.2	-	.4
20	15.6	17.3	13.0	-	15 3	15.6	16.3	15 .	-	15.9	17.4	16.6	16.0	-	16.7	16 4	16.1	15 9	-	.1
21	15.7	17 3	14.4	-	15.8	15.7	15.7	16 .	-	1E.0	16.6	16.7	16.0	-	16.4	16.2	16.5	14.8	-	.8
22	16.5	17.0	14.9	-	16.1	16.7	15.4	16.6	-	16.2	16.3	17.1	17.4	-	16.9	16.0	16.5	14.2	-	15.6
23	16.2	17.0	12.4	-	15.2	16.7	15.8	15.8	-	16.1	16.7	16.3	17.3	-	16.8	16.2	16.5	14.3	-	15.7
24	14.8	16.9	13.7	-	15.1	17.0	17.2	16.0	-	16.7	16.9	16.8	17.1	-	16.9	16.4	16.2	14.5	-	15.7
25	16.0	18.3	12.0	-	15.4	18.1	17.0	15.4	-	16.8	16.3	16.6	16.4	-	16.4	16.1	15,9	15.3	-	15.8
26	15.0	17.1	12.7	-	14.9	16.2	17.0	15.9	-	16.4	16.7	16.7	15.6	-	16.3	16.2	15.6	15,4	-	15.7
27	16.8	17.7	14.0	-	16.2	16.5	15.6	15.5	-	15.9	16.3	16.2	15.4	-	16.0	16.0	15.6	16.0	-	15.9
28	16.3	16.9	14.0	-	15.7	15.8	15.5	15.4	-	15.6	16.4	16.2	16.1	-	16.2	15.8	15.9	17.4	-	16.4
29	17.0	16.7	15.7	-	16.5	16.0	15.7	14.7	-	15.5	16.2	15.6	16.5	-	16<	15.5	16.1	17.1	-	16.2
30	16.6	16.8	16.2	-	16.5	16.3	15.1	14.8	-	15.4	16.1	15.3	16.9	-	16.1	15.3	16.0	16.6	-	16.0
31	17.2	16.5	16.4	-	16.7						15.4	15.6	17.2	-	16<	<5.6	15.2	15.7	-	15.5
MEAN	16.1	16.4	14.1	-	15.8	16.2	16.0	16.3	-	16.2	16.2	16.2	15.9	-	16 1	16.1	15.8	15.4	-	15.8

Table 2.1 contd.

DATE	SEPTEMBER					OCTOBER					NOVEMBER					DECEMBER				
	1977	1978	1979	1980	MEAN	1977	1978	1979	1980	MEAN	1977	1978	1979	1980	MEAN	1977	1978	1979	1980	MEAN
1	16.0	14.9	16.4		15.8	1 1	16.1	1	6	16.4	16.2	16.2	14.0		15.5	14.3	13.6	15.3		14.4
2	15.6	14.62	15.7		15.3	16.8	14.1	16.4		15.8	15.4	15.3	15.8		15.5	15.4	13.9	13.7		14.3
3	15.8	15.2	15.7		15.6	16.1	13.7	16.9		15.6	16.1	16.7	16.9		16.6	14.4	14.4	14.3		14.4
4	15.7	14.7	16.8		15.7	17.2	14.6	17.0		16.3	15.7	17.0	16.5		16.4	14.0	13.3	15.1		14.1
5	15.4	15.2	16.9		15.8	15.8	14.5	16.9		15.7	15.5	17.0	16.2		16.2	13.9	13.7	15.1		14.2
6	95.9	15.0	16.6		15.7	17.0	15.3	17.4		16.6	16.8	17.5	15.6		16.6	13.0	13.7	14.7	n	13.8
7	15.5	15.0	16.6		15.7	16.5	15.8	17.1		16.5	17.0	17.1	15.7		16.6	9.4	14.0	15.1		12.8
8	14.4	14.9	16.7		15.3	16.8	14.3	16.8		16.0	15.7	17.1	15.0		15.9	10.2	16.0	14.5		13.6
9	15.4	13.7	17.1		15.4	16.8	14.6	16.9		16.1	13.5	15.5	15.0		14.7	13.5	15.1	14.1		14.2
10	14.7	14.4	17.3		15.5	16.7	17.4	15.9		16.7	13.2	13.8	15.2		14.1	12.4	13.2	14.1		13.2
11	15.0	16.0	17.6		16.2	15.3	17.1	14.5		15.6	14.4	12.9	15.5		14.3	11.3	13.7	15.3		13.4
12	14.7	14.8	17.3		15.6	16.5	16.8	13.7		15.7	16.1	14.5	16.4		15.7	11.2	14.2	15.6		13.7
13	15.2	15.4	16.2		15.6	17.2	17.0	14.2		16.1	16.6	16.0	16.7		16.4	11.1	14.4	15.6		13.7
14	15.0	15.9	17.1		16.0	17.1	14.8	16.5		16.1	16.7	13.3	16.8		15.6	11.2	14.7	14.2		13.4
15	14.6	16.1	16.7		15.8	17.5	11.2	16.6		15.1	16.8	12.6	16.4		15.3	10.9	13.1	13.6		12.5
16	14.3	15.8	16.3		15.5	17.2	13.4	13.2		14.6	15.7	13.0	16.3		15.0	10.4	13.1	13.5		12.3
17	15.4	15.9	17.5		16.3	17.4	16.7	11.9		15.3	14.3	12.2	16.5		14.3	10.7	13.4	13.2		12.4
18	16.5	16.6	17.6		16.9	17.6	16.9	12.4		15.6	14.2	12.3	16.7		14.4	10.9	12.1	12.0		11.7
19	16.6	16.2	17.9		16.9	17.1	16.9	13.6		15.9	15.3	11.5	16.9		14.6	11.5	11.7	12.1		11.8
20	16.6	17.0	16.0		16.5	16.9	16.8	14.7		16.1	15.7	11.8	16.4		14.6	10.9	10.4	12.4		11.2
:?I	16.1	17.1	16.5		16.6	15.2	16.0	14.9		15.4	15.0	10.5	16.1		13.9	12.3	10.7	13.3		12.1
22	16.2	16.3	17.7		16.7	15.3	16.4	15.4		15.7	15.2	10.6	16.3		14.0	13.8	13.0	11.9		12.9
23	16.5	15.5	16.7		16.2	16.8	17.0	15.6		16.5	15.4	10.9	16.0		14.1	12.5	13.0	12.7		12.7
24	16.1	16.3	17.6		16.7	16.7	16.3	15.8		16.3	16.5	13.9	14.3		14.9	11.1	12.3	13.7		12.4
25	16.9	17.2	16.7		16.9	17.2	16.6	15.8		16.5	16.7	15.4	14.4		15.5	10.4	14.7	12.6		12.6
26	17.5	18.1	16.9		17.5	16.7	16.4	15.3		16.1	16.7	14.7	16.1		15.8	10.9	15.8	12.7		13.1
27	16.8	16.8	15.6		16.4	16.8	16.3	16.2		16.4	17.0	14.4	16.7		16.0	9.8	15.7	11.4		12.3
28	17.3	16.9	16.1		16.8	13.9	16.2	16.4		15.5	16.4	13.0	15.1		14.8	10.9	15.1	10.6		12.2
29	16.8	17.1	15.9		16.6	11.6	16.1	15.6		14.4	15.8	12.4	14.9		14.4	10.3	15.1	11.6		12.3
30	16.7	16.7	16.7		16.7	12.9	16.6	14.6		14.7	14.3	12.2	15.6		14.0	11.0	14.9	11.6		12.5
31						13.9	16.4	14.2		14.8						13.1	14.6	10.1		12.6
MI apt	15.8	15.8	16.7		16.1	16.2	15.8	15.4		15.8	15.6	14.0	15.9		15.2	11.8	14.2	13.4		13.1

Table 2-1 contd.

DATE	JANUARY						FEBRUARY						MARCH						APRIL					
	1977	1978	1979	1980	1981	MEAN	1977	1978	1979	1980	1981	MEAN	1977	1978	1979	1980	1981	MEAN	1977	1978	1979	1980	1981	MEAN
1	-	11.3	10.7	7.4	8.7	9.5	-	10.3	10.4	7.1	4.7	8.1	-	7.0	9.1	9.6	4.7	7.6	-	9.7	10.0	-	11.7	9.8
2		10.3	10.5	8.7	10.6	10.0		10.0	10.5	10.0	7.0	9.4		6.1	7.5	10.6	4.9	7.3		10.0	6.2		10.8	9.0
3		10.1	10.5	8.5	10.4	9.9		11.0	12.1	11.2	5.6	10.0		5.8	11.2	8.9	4.3	7.6		9.2	5.8		11.4	8.8
4		10.9	8.7	8.9	7.9	9.1		10.9	11.1	10.8	6.3	9.8		4.3	11.4	7.2	5.6	7.1		6.3	9.4		10.5	8.7
5		10.3	8.0	10.1	7.5	9.0		11.4	10.3	10.5	7.2	9.9		8.1	12.3	6.8	-	-		8.2	9.9		11.9	10.0
6		9.4	9.0	10.2	6.7	8.8		11.0	11.9	9.2	7.3	9.9		7.3	11.4	7.6	6.0	8.1		9.0	8.1		10.2	9.1
7		10.8	9.8	10.7	5.2	9.1		12.0	11.6	8.3	9.4	10.3		9.7	10.6	7.3	5.6	8.3		12.5	7.8		9.4	9.9
8		10.4	9.1	11.1	4.9	8.9		11.3	12.3	7.4	8.3	9.8		11.5	11.0	10.1	5.9	9.6		12.1	6.4		10.1	9.5
9		9.7	9.1	10.5	8.4	9.4		12.4	13.0	6.2	10.6	10.6		9.0	8.7	7.5	7.3	8.1		12.0	6.2		5.3	7.8
10		8.8	8.8	9.5	10.6	9.4		10.4	12.4	6.7	9.6	9.8		7.1	9.2	8.5	10.0	8.7		11.6	7.5		5.4	8.2
11		10.9	9.1	8.0	10.4	9.6		9.5	13.0	7.9	9.5	10.0		8.3	6.2	12.5	13.0	10.0		9.8	10.1		6.9	8.9
12		12.0	9.3	10.1	10.6	10.5		8.5	13.3	7.1	9.3	9.6		8.7	4.3	11.8	12.3	9.3		9.1	10.6		10.2	10.0
13		10.7	8.5	9.3	11.3	10.0		8.7	13.0	8.1	9.3	9.8		11.5	7.4	8.9	11.8	9.9		7.7	11.5		8.2	9.1
14		9.2	9.2	10.0	11.4	10.0		5.0	12.4	6.5	9.7	8.4		9.6	7.5	7.4	11.1	8.9		13.0	11.4		11.3	11.9
15		5.3	9.9	9.8	11.6	9.2		7.6	12.4	6.6	4.6	7.8		11.4	8.4	7.0	10.7	9.4		10.0	13.9		13.4	12.4
16		8.8	9.6	9.7	12.1	10.1		9.7	10.1	9.1	4.4	8.3		11.7	7.8	7.4	8.7	8.9		12.8	12.6		11.1	12.2
17		6.3	10.1	9.8	11.0	9.3		11.8	8.2	7.7	4.1	8.0		8.7	7.8	5.8	6.9	7.8		10.6	13.3		11.1	11.7
18		4.8	11.2	9.6	10.9	9.1		13.1	12.8	6.9	2.7	8.9		10.1	7.7	3.8	10.9	8.1		10.8	12.6		13.2	12.2
19		6.2	13.0	9.4	11.6	10.1		12.1	14.1	6.8	3.6	9.2		10.7	9.8	3.3	9.7	8.4		9.2	9.8		11.2	10.1
20		5.7	12.8	8.9	10.8	9.6		10.9	14.3	6.5	5.0	9.2		10.9	7.9	5.1	10.6	8.6		9.2	9.9		10.2	9.8
21		8.9	10.6	7.1	10.0	9.2		10.9	11.3	16.6	5.2	8.5		10.5	6.6	5.8	11.6	8.6		9.5	11.6		9.6	10.2
22		9.9	10.7	7.5	9.4	9.4		13.0	13.5	6.4	5.7	9.7		9.2	9.7	6.2	12.7	9.5		11.6	9.7		10.2	10.5
23		8.4	12.2	7.8	10.6	9.8		12.4	12.6	6.2	3.6	8.7		9.8	10.5	5.7	9.1	8.8		12.8	10.2		8.6	10.5
24		9.5	12.2	6.5	10.3	9.6		11.0	13.3	6.0	2.0	8.1		9.4	7.7	6.2	8.1	7.9		10.8	9.5		12.0	10.8
25		10.1	11.6	7.1	11.6	10.1		7.1	10.7	5.7	3.3	6.7		10.5	9.9	4.8	11.4	9.2		12.1	8.9		9.1	10.0
26		10.0	10.7	6.5	10.6	9.5		6.5	12.4	5.9	3.1	7.0		11.4	9.3	7.1	12.6	10.1		11.5	8.7		12.2	10.8
27		8.0	8.8	6.9	9.5	8.3		6.4	11.8	6.5	3.8	7.1		11.8	8.0	5.6	12.0	9.4		12.0	10.5		11.2	11.2
28		6.6	9.5	6.8	8.4	7.8		6.8	12.3	7.8	4.3	7.8		8.9	8.7	7.2	12.6	9.4		9.6	11.8		10.2	10.5
29		7.6	9.2	7.8	8.5	8.3		-	-	9.3	-	9.3		8.9	9.0	11.9	9.0	9.7		10.8	12.9		12.6	12.1
30		6.4	11.6	8.4	7.6	8.5		-	-	-	-	-		7.0	10.1	13.8	8.9	10.0		9.7	11.8		13.7	11.7
31		7.9	10.6	8.0	5.2	7.9		-	-	-	-	-		7.0	9.7	12.8	10.3	10.0		-	-		-	-
MEAN		8.9	10.2	8.7	9.5	9.3		10.1	12.0	7.6	6.1	8.95		9.2	8.9	7.9	9.3	8.8		10.4	9.9		10.4	10.2

TABLE 2.2: Daily mean values of absolute humidity (g m^{-3}) during the period 1977-81 for Nandi Hills.

DATE	MAY						JUNE						JULY						AUGUST					
	1977	1978	1979	1980	1981	MEAN	1977	1978	1979	1980	1981	MEAN	1977	1978	1979	1980	1981	MEAN	1977	1978	1979	1980	1981	MEAN
1	-	8.8	14.0	-	12.2	11.7	14.6	13.8	13		15.1	14.1	14.3	13.7	14		12.9	13.7	14.8	14.4	15	-	14.3	14.6
2	-	9.4	13	-	11.8	11.4	14.6	13.5	14		14.4	14.1	14.5	13.7	14		13.3	13.9	14.5	13.8	15	-	14.0	14.3
3	-	9.9	12	-	13.1	11.7	14.7	13.4	13		13.7	13.7	14.2	13.4	14		12.2	13.5	13.6	14.3	15	14.3	14.2	14.3
4	-	9.7	13	-	12.3	11.7	14.9	14.0	14		14.5	14.4	14.3	13.6	14		13.2	13.8	13.9	14.2	14	14.3	14.3	14.1
5	15.0	12.3	9	-	13.2	10.4	14.9	14.5	15		13.8	14.6	14.4	13.6	14		13.8	14.0	13.4	14.7	14	14.0	13.9	14.0
6	15.0	11.5	11	-	12.9	12.6	14.3	13.7	13		13.7	13.7	14.3	14.2	13		13.4	13.7	13.3	14.9	14	13.7	14.2	14.0
7	14.9	13.5	11	-	12.3	12.9	15.3	13.4	12		14.3	13.8	13.5	14.1	13		13.6	13.6	14.0	14.9	14	14.4	14.4	14.3
8	14.3	11.9	10	13.1	11.9	12.2	13.4	13.8	16		13.7	14.2	13.7	14.5	14		14.4	14.2	14.3	14.9	13	14.8	14.3	14.3
9	14.4	12.9	9	13.1	12.8	12.4	15.1	13.5	13		14.5	14.0	14.0	14.4	14		13.9	14.1	14.6	14.6	14	14.2	14.0	14.3
10	12.9	11.6	8	12.8	13.6	11.8	14.6	13.6	14		14.1	14.1	14.1	14.0	14		14.4	14.1	14.4	14.8	13	14.0	13.9	14.0
11	13.0	13.1	15	13.0	12.7	13.4	14.3	13.7	15		14.1	14.3	14.2	14.5	15		14.8	14.6	14.8	14.3	13	13.5	14.0	13.9
12	12.3	13.4	13	12.4	10.8	12.4	14.2	14.1	16		14.6	14.7	14.8	14.1	14		13.6	14.1	14.4	13.4	13	14.6	14.1	13.9
13	12.8	14.7	13	12.7	10.3	12.7	14.9	14.2	14		14.0	14.3	14.3	14.9	14		13.8	14.3	15.2	13.1	12	14.3	13.9	13.7
14	14.9	14.5	13	12.0	11.1	13.1	16.0	14.0	13		14.3	14.3	14.0	14.8	14		12.9	13.9	14.8	12.9	13	14.6	13.1	13.7
15	13.2	14.6	10	12.9	11.8	12.5	15.6	14.0	14		14.3	14.5	14.7	14.7	14		13.1	14.1	14.8	13.0	13	14.2	14.6	13.9
16	14.2	13.1	8	12.4	12.1	12.0	15.5	13.9	14		14.2	14.4	14.4	15.2	13		1222	13.7	15.1	14.1	13	14.6	14.4	14.2
17	13.8	11.0	9	12.6	13.1	11.9	15.5	14.0	14		14.0	14.4	14.3	14.6	13		12.6	13.6	14.5	14.2	12	14.0	14.7	13.9
18	12.7	13.1	9	13.3	13.4	12.3	15.6	13.8	13		13.8	14.1	14.2	14.4	13		12.0	13.4	13.9	14.4	14	13.4	14.4	14.0
19	14.7	12.8	10	14.0	12.0	12.7	14.4	14.0	14		14.0	14.1	15.0	13.7	13		12.3	13.5	14.4	14.4	14	13.2	14.7	14.1
20	13.2	13.3	11	14.8	9.6	12.4	15.1	13.9	14		14.0	14.3	15.6	14.3	14		13.4	14.3	14.2	14.5	13	14.0	14.0	13.9
21	12.0	14.4	11	13.8	11.1	12.5	14.8	14.4	15		14.2	14.6	14.8	14.1	14		14.0	14.2	13.4	14.4	13	14.1	14.5	13.9
22	13.6	14.5	11	14.6	11.8	13.1	14.5	13.9	14		14.3	14.2	14.8	15.0	15		15.0	15.0	13.6	14.5	12	13.9	14.6	13.7
23	14.7	14.3	9	13.8	11.3	12.6	14.2	14.0	14		14.3	14.1	14.8	14.7	15		14.5	14.8	14.1	14.5	12	14.5	14.3	13.9
24	12.7	13.7	11	13.9	9.8	12.2	14.8	14.8	14		14.3	14.5	15.0	15.0	15		14.4	14.9	14.1	14.5	12	13.9	14.2	13.7
25	14.1	15.4	10	14.4	11.6	13.1	15.3	15.4	13		13.9	14.4	14.8	14.9	15		14.3	14.8	14.1	13.9	13	13.4	14.2	13.7
26	14.3	13.7	10	14.4	13.2	13.1	15.4	14.9	14		14.2	14.6	15.1	15.0	14		15.0	14.8	14.2	14.2	14	13.7	13.5	13.9
27	15.2	15.1	10	13.8	12.2	13.3	-	13.7	14		14.4	14.0	15.0	14.6	14		14.3	14.5	14.7	14.2	14	13.4	14.7	14.2
28	14.0	14.1	11	13.8	12.6	13.1	14.4	13.4	14		12.8	13.7	14.8	14.7	14		13.8	14.3	14.4	14.1	15	14.0	13.6	14.2
29	15.4	14.6	12	13.9	13.8	13.9	14.8	13.5	13		13.0	13.6	14.5	14.3	14		14.4	14.3	13.9	13.7	14	13.7	14.0	13.9
30	15.2	14.5	13	14.4	14.5	14.3	15.0	13.4	13		12.3	13.6	14.8	13.8	15		14.4	14.5	14.0	13.8	15	14.6	14.2	14.3
31	15.0	14.1	13	-	14.1	-	-	-	-		-	-	14.2	13.7	15		14.5	14.4	13.7	13.5	15	13.7	14.0	14.0
MEAN	14.0	13.0	11	13.5	12.2	12.7	14.8	13.9	14		14.0	14.2	14.5	14.3	14		13.7	14.1	14.2	14.2	14	14.0	14.2	14.1

Table 2.2 contd.

IL	SEPTEMBER						OCTOBER						NOVEMBER						DECEMBER					
	1977	1978	1979	1980	1981	MEAN	1977	1978	1979	1980	1981	MEAN	1977	1978	1979	1980	1981	MEAN	1977	1978	1979	1980	1981	MEAN
1	14.0	13.4	14.0		15.1	14.1	15.2	14.0	14.4		15.4	14.8	14.5	14.0	12.4	5	13.8	12.8	12.7	12.3	13.9	9.0	14.0	12.4
-	14.0	12.9	13.0		14.7	13.7	14.9	12.6	14.8		15.2	14.4	12.9	1 .7	14.7	7	14.2	12.6	13.6	12.5	12.1	10.8	13.5	12.5
3	14.2	13.3	13.9		15.6	14.3	13.8	11.7	14.8		14.5	13.7	13.4	15.0	15.3		13.7	13.6	12.2	12.2	12.8	10.4	1≷5	12.2
4	14.3	12.7	14.4		14.6	14.0	14.6	12.4	15.0		15.5	14.4	13.8	14.9	14.6	1 0	13.7	13.6	13.1	11.8	13.5	11.1	2.3	12.4
	14.1	13.3	13.6		15.4	14.1	13.8	11.8	14.4	7.1	14.5	12.3	13.0	14.9	14.1	1 3	14.1	13.9	12.3	12.7	13.6	11.5	9.5	1.9
	13.3	13.2	13.2		14.9	13.7	15Z	13.2	14.8	8.7	14.4	13.3	14.6	15.4	13.5	1 03	14.2	13.6	11.6	12.3	12.4	11.5	5.9	0.7
	12.9	13.2	14.2		15.0	13.8	14.5	14.1	13.1	10.8	14.6	13.4	14.7	15.7	13.9	●5	15.7	13.3	7.4	12.9	13.6	7.8	7.2	9.8
-	12.9	13.1	14.5		14.9	13.9	15.1	11.0	11.7	11.0	14.9	12.7	13.1	15.1	13.9	9.0	15.8	13.4	9.2	13.9	12.8	8.3	66	10.2
9	13.3	12.0	14.8		15.1	13.8	14.3	12.5	10.2	12.4	14.5	12.8	11.3	13.5	13.4	8.8	14.4	12.3	11.0	13.7	12.0	8.6	62	10.3
10	12.5	12.5	15.1		15.4	13.9	14.8	14.4	11.8	14.8	13.4	13.8	11.3	11.2	13.1	12.4	14.0	12.4	10.8	11.6	12.8	8.8	39	9.6
11	12.4	14.3	15.4		14.9	14.3	11.6	14.8	14.2	15.1	12.8	13.7	12.6	10.2	14.1	14.4	12.2	12.0	9.7	12.0	13.9	10.8	47	10.2
12	13.1	13.3	14.7		15.3	14.1	14.0	13.8	14.5	12.4	12.5	13.4	14.3	12.7	14.5	14.7	10.8	13.4	8.9	12.7	13.8	11.3	79	10.9
1▪	13.3	13.6	15.0		15.5	14.4	15.5	14.8	9.2	10.3	10.9	12.1	14.7	13.9	14.6	14.6	10.5	13.7	8.9	12.9	13.5	10.6	10.7	11.3
14	13.1	13.9	15.3		15.3	14.4	15.1	12.3	14.2	10.8	11.1	12.7	14.6	11.1	14.[illegible]	14.8	11.4	13.3	9.4	12.9	12.7	9.7	11.2	11.2
15	12.8	13.6	14.9		14.7	14.0	15.0	8.7	14.5	11.9	12.4	12.5	14.4	11.0	14.6	14.6	12.3	3.4	9.6	12.0	12.2	7.7	12.3	10.8
16	12.7	13.7	14.4		14.2	13.8	15.1	11.5	9.2	12.4	11.5	11.9	13.9	12.1	15.0	14.5	10.4	3.2	9.2	11.8	11.5	8.4	12.3	10.6
17	14.1	13.7	15.4		14.9	14.5	15.0	14.5	9.4	8.5	14.0	12.3	12.1	10.0	14.7	14.5	11.4	2.5	9.0	11.9	11.4	8.7	11.5	10.5
18	14.3	14.4	15.6		15.2	14.9	15.1	14.9	10.8	8.8	12.0	12.3	12.3	10.5	14.6	14.8	9.6	2.4	9. .	10.7	9.4	12.0	11.8	10.6
19	14.8	14.7	15.5		15.2	15.1	15.2	14.1	12.5	11.6	12.9	13.3	13.5	9.5	14.5	14.4	6.8	11.7	9.3	10.5	9.4	10.6	11.8	10.3
20	14.3	14.8	13.6		15.6	14.6	14.2	14.5	11.3	13.0	10.9	12.8	13.8	9.9	14.4	14.0	6.6	1.7	9.5	9.4	10.5	8.0	11.6	9.8
21	13.4	14.6	14.4		15.4	14.5	13.4	14.7	13.8	13.6	9.2	12.9	13.3	9.4	14.5	12.	6.3	1.1	10.7	10.1	11.1	7.8	12.4	10.4
22	12.8	14.3	15.2		14.6	14.2	13.2	14.4	13.5	15.1	11.0	13.4	13.3	9.0	14.2	11.5	7.4	1.1.	12.3	12.0	9.9	10.1	12.0	11.3
23	13.8	13.5	14.8		14.2	14.1	14.4	14.5	13.8	13.9	14.4	14.2	12.5	9.1	13.4	11.5	9.2	11.1	11.0	11.8	11.3	12.6	11.3	11.6
24	3.8	14.7	15.1		13.5	14.3	14.5	14.6	14.5	14.8	14.7	14.6	14.5	12.8	12.7	10.6	8.4	11.8	8.2	10.2	12.0	11.9	10.3	10.5
25	14.7	15.0	14.6		13.8	14.5	14.6	14.8	13.6	10.2	14.5	1≥5	14.6	13.7	12.4	10.6	6.4	11.5	9.3	13.2	10.4	10.7	8.3	1●4
	14.3	15.5	14.8		14.2	14.7	13.8	14.7	14.6	9.3	14.5	13.4	14.5	13.4	14.4	11.3	5.5	11.8	9.2	1≥ 5	10.5	12.2	9.9	11.1
	14.1	15.0	14.0		13.5	14.2	14.1	13.2	14.6	8.9	14.4	13.0	14.8	12.7	15.3	11.1	9.7	12.7	8.2	13.4	9.3	11.7	9.6	10.4
	15.2	14.7	14.3		13.8	14.5	11.0	14.4	13.5	6.3	15.0	12.0	15.0	11.5	13.5	9.0	9.8	11.8	8.4	13.6	8.1	11.5	9.3	10.2
9	14.7	14.8	14.2		14.2	14.5	9.3	14.5	13.2	6.8	15.1	11.7	13.4	10.7	13.0	9.9	13.0	12.0	8.2	13.6	9.3	10.3	6.5	9.6
	14.8	14.3	14.6		13.4	14.3	10.3	14.8	11.6	9.3	13.7	11.9	12.3	10.8	13.	10.1	14.3	12.2	9.7	13.3	> 1	10.9	9.8	10.6
	-	-	-		-	-	12.7	14.8	—	9.6	14.4	12.9	-	-	-	-	-	-	11.3	13.2	E.6	9.0	10.4	10.5
	13.7	13.9	14.5		14.7	14.2	14.0	13.6	13.6	11.0	13.5	13.1	13.6	12.2	14.	11.8	11.2	12.6	10.1	12.3	11.5	10.1	9.9	10.8

TABLE Z.2 contd.

Attempts were made to see if any rigorous relationship existed between absolute humidity at the surface and precipitable water in the atmosphere computed from radiosonde measurements made at Bangalore and Nandi Hills during 1977-80. During 1979-81 radiosonde ascents were made on 275 days, on 247 days at Bangalore and on 28 days at Nandi Hills. 84 of these radiosonde ascents were made during 1979-80, 56 at the Raman Research Institute, Bangalore and 28 on Nandi Hills, by the Meteorological Unit of the Institute to provide basic data for the computation of precipitable water W and for the calibration of the infrared spectral hygrometers and the microwave radiometer. The remaining ascents were taken at the Central Observatory by the staff of the India Meteorological Department at Bangalore. Tables 2.3 and 2.4 give the values of precipitable water W at the two stations for the period 1979-80. The technique of computing W from radiosonde data is described in Section 2.3.

In Fig 2.1 the measured values of absolute humidity and the values of precipitable water computed from radiosonde data are plotted at Bangalore for the years 1979-80. Fig 2.2 gives similar values of W and d_v for Nandi Hills. The measurements of precipitable water were confined to cloud-free days during the period October to May

Table 2.3: Daily values of precipitable water (mm) comwted from radiosonde ascents made at the RRI, Bangalore, during 1979-80

	1979		1980			1979		1980	
Months	Date	W	Date	W	Months	Date	W	Date	W
Dec	18	15.9			March	2	14.6	2	30.8
	19	11.2				3	22.3	18	6.9
	29	7.5				7	18.7		
	30	7.1				19	18.6		
	31	4.4				31	25.5		
Jan	30	26.6	5	8.5	April	5	20.9	12	17
			8	12.2		11	24.8	21	21.8
			14	14.7		16	34.8		
			15	8e6		19	25.1		
			16	7.5		20	32.5		
			17	10.5		24	24.3		
			18	10.3		25	19.7		
			19	9.1					
			22	13.1	May	13	14.8	8	25.2
						16	19.0	25	16.3
Feb	5	14.2	1	10.3		17	21.7		
	7	27.2	6	13.5		19	21.2		
			7	14.6		21	24.9		
			7	14.1		22	24.4		
			9	8.2		24	22.2		
			11	13.4		25	26.2		
			22	12.5		28	11.8		
			22	12.4					
			23	10.2					
			24	13.4					
			25	17.6					

Table 2.4: Daily values of precipitable water W at Nandi Hills computed from radiosonde data during 1979-80

31. No.	Date	Time IST	W mm
1	27.4.79	1250	22.6
2	28.4.79	1010	18.5
3	29.4.79	0935	18.0
4	30.4.79	0925	21.9
5	1.1.80	1610	9.0
6	1.1.80	2200	6.1
7	2.1.80	1030	4.6
8	2.1.80	1235	6.7
9	2.1.80	1435	4.3
10	5.3.80	1645	20.3
11	5.3.80	2150	17.6
12	6.3.80	1015	9.9
13	6.3.80	2150	14.6
14	7.3.80	1015	15.3
15	7.3.80	1325	13.4
16	7.3.80	2008	13.5
17	9.3.80	1450	14.4
18	9.3.80	2355	14.7
19	10.3.80	1420	12.7
20	12.3.80	1515	25.1
21	13.3.80	2230	10.6
22	14.3.80	1125	9.2
23	14.3.80	1550	10.4
24	15.3.80	1650	11.1
25	15.3.80	2200	14.8
26	16.3.80	1055	9.9
27	16.3.80	1320	14.3
28	16.3.80	1555	11.6

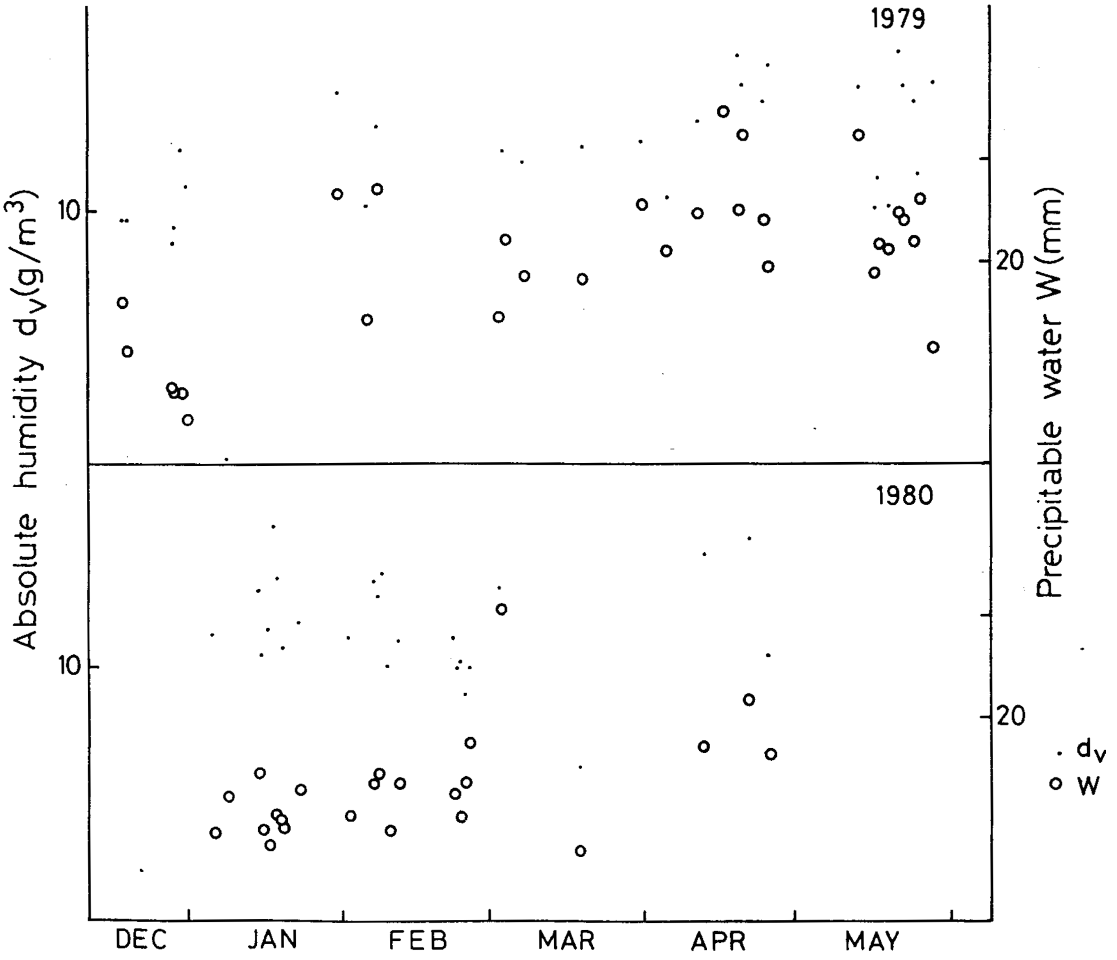

Fig 2.1 Absolute humidity d_v and precipitable water W values at Bangalore during the period 1979-80

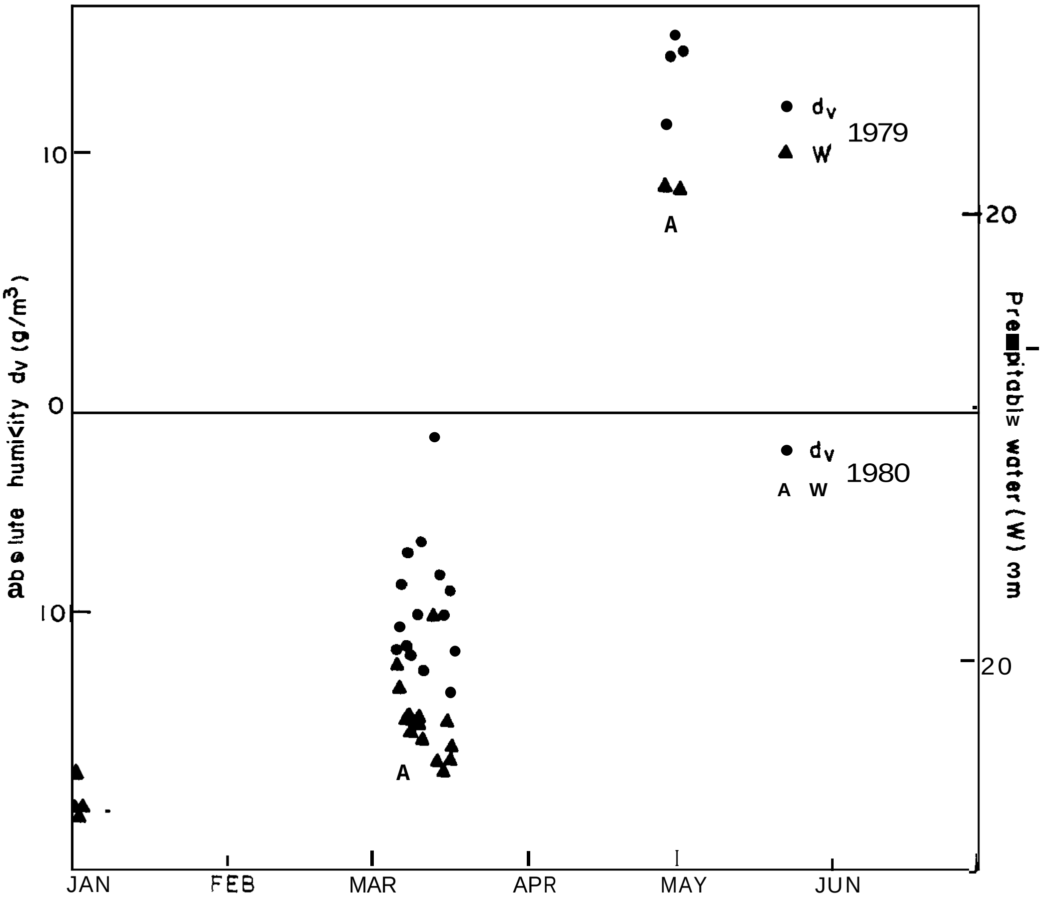

Fig. 2.2 Absolute humidity d_v and precipitable water W at Nandi Hills during 1979-80

for the years 1979-80. W and d_v are both generally low during the months December to February, with higher values after March. During the dry season, water vapour is confined to a thin layer near the ground and variations in the surface water vapour density and the precipitable water may be expected to be similar.

Figs 2.3 and 2.4 show the correlation between the surface absolute humidity d_v and the zenith precipitable water W computed from radiosonde data obtained at Bangalore and Nandi Hills for the years 1979-81. While a roughly linear relationship exists between the absolute humidity d_v and the precipitable water W, for values of W in the range of 5 to 35mm at Bangalore and 5 to 25mm at Nandi Hills, the scatter is so large that attempts to obtain a rigorous relationship between d_v and W appeared to be meaningless. Such a close correlation between the two will exist only if the water vapour density in the atmosphere has always the same relative distribution with height.

2.3 Computation of precipitable water from radiosonde measurements

2.3.1 General

With the introduction of worldwide radiosonde

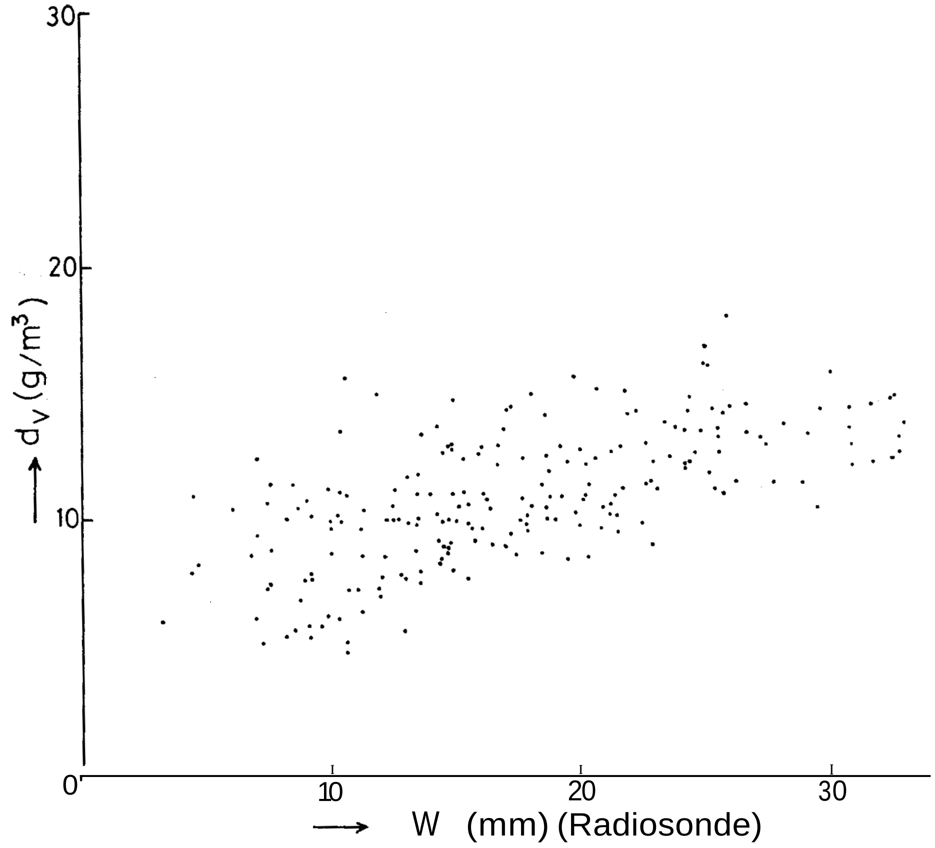

Fig.2.3 Correlation between precipitable water W (from radiosonde ascents) and absolute humidity d_V at Bangalore based on data during 1979-81

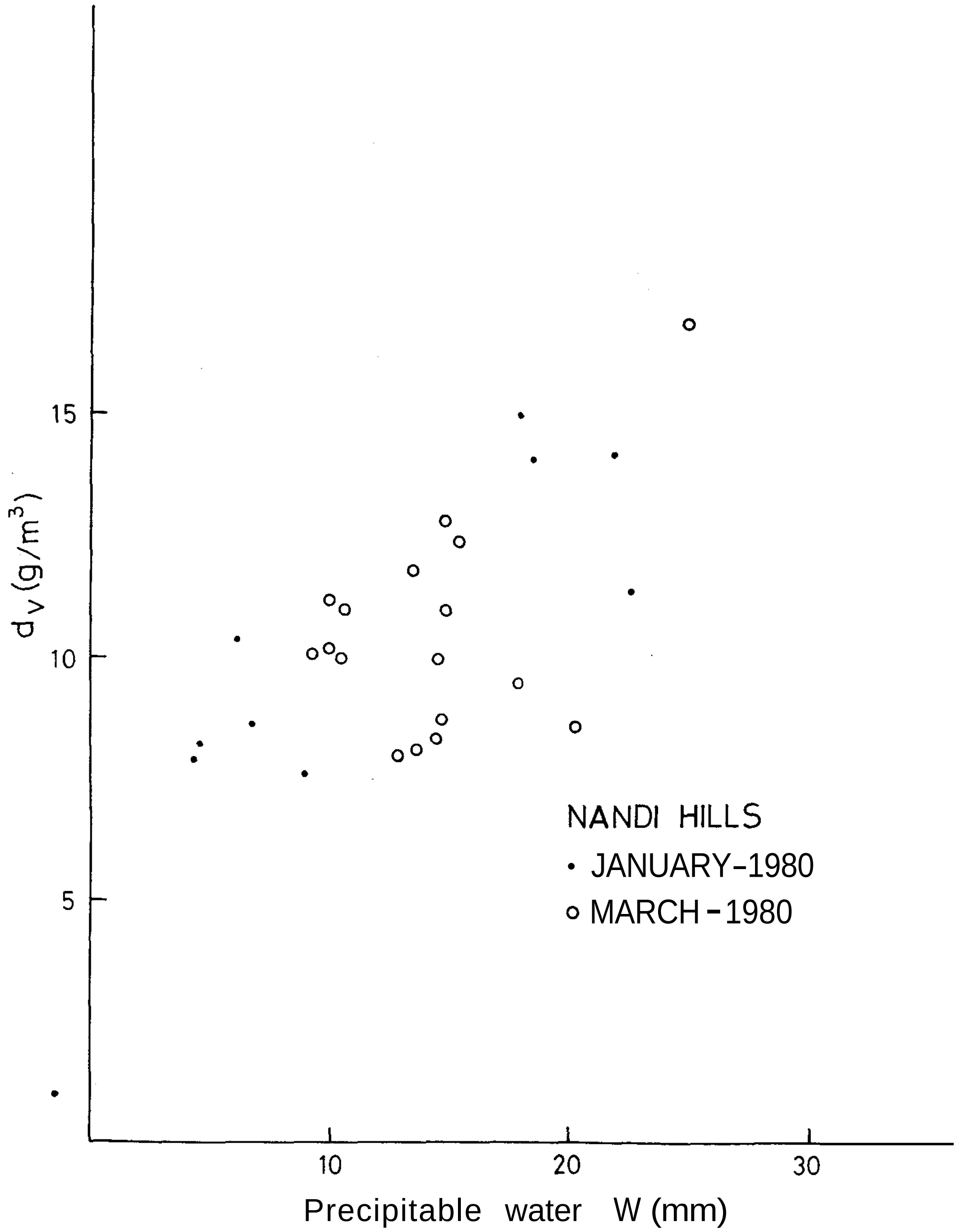

Fig 2.4 Correlation between precipitable water W (from radiosonde ascents) and absolute humidity d_V at Nandi Hills during' the period 1979-80

ascents in the forties, it became possible to obtain in-situ measurements of atmospheric humidity from the ground to 30 km heights and to compute precipitable water by integrating over specified layers of the atmosphere the precipitable water contained in them. Solot (1939) was the first to do so. Shands (1949) prepared maps showing the distribution of mean precipitable water in the atmosphere over the United States based on about four years' data at 29 stations. He found that above 8 km, "the contribution is of the order of hundredths of an inch in summer and thousandths of an inch in winter". At locations near sea level he found the maximum concentration of water vapour in the lowest 2 km. Benton et al (1953) computed similar precipitable water data for the USA for one year, 1949.

Showalter (1954) prepared a transparent template for computing total precipitable water from dew point values plotted against pressure in mb, obtained from radiosonde ascents. The total precipitable water was obtained by adding the increments of precipitable water for indiczted intervals. He assessed the errors to be largest when W is less than 1.2 cm and quite small with W exceeding 3.7 cm.

Elabroate tables for the computation of precipitable water were published by the Hydrometeorological Section of the U.S. Weather Bureau and published as Weather Bureau Technical Paper No. 14, in which precipitable water increments for each mb interval and for each degree Fahrenheit were given. It was using these data that Showalter (1954) prepared his template for computing total precipitable water from plotted dew points. Peterson (1961) has also published a nomogram for precipitable water using standard radiosonde evaluation techniques.

Reitan (1960) made computations of mean monthly values of precipitable water from the surface to 325 mb for about 50 radiosonde stations in the USA, for the 11-year period 1946-1956, the longest period for which such data have been computed for such a large network. In an earlier paper, Reitan (1959) had given the individual monthly values, an elementary statistical description of the precipitable water values at each station and a general discussion of the computational process.

Although climatic humidity data are relatively plentiful for the lowest km of the atmosphere, dew point and mixing ratio maps showing the average distribution in time and space are not available. World maps of the mean precipitable water above the surface and above the 850, 700 and 500 mb levels (above, in practice, is from the particular level to a pressure altitude of 300 mb) were prepared by Bannon and Steele (1960).

Maps showing the distribution of precipitable water over India using radiosonde data were prepared by Ananthakrishnan et al (1965) and Mokashi (1971) who published total precipitable water values for 19 stations in India using dew point data from the old fan type and clock type radiosondes in use at the time. Rangarajan and Mani (1982) have computed total precipitable water for 124 stations in the country based on data from audiofrequency modulated radiosondes introduced about 1970, and published 12 maps showing the detailed month-by-month distribution of precipitable water over India.

2.3.2 Radiosonde measurements at Bangalore and Nandi Hills

2.3.2.1 The computation of precipitable water from radiosonde data is the most objective of the methods available and is used to calibrate or verify all the other methods normally used for the estimation, computation or measurement of precipitable water.

Therefore, a number of radiosonde ascents were specially made during 1979–80 at the Baman Research Institute, Bangalore and at Nandi Hills (i) to compute the precipitable water at the two stations both during the day and night, (ii) to calibrate the infrared spectral hygrometer and microwave radiometer designed and constructed by the author. The ascents were made only at times when the sky was free from clouds. The soundings were made by the Meteorological Unit of the Raman Research Institute. The radiosonde ground equipment was obtained on loan from the India Meteorological Department and the balloons, radiosondes and accessories used were supplied on payment by the Department. With the establishment in 1981 of a regular radiosonde observational station, making two ascents a day, at 00 and 12 GMT, at the Central Observatory, Bangalore, 5 km southeast of the Raman Research Institute, the special radiosonde observations at the Raman Research Institute were discontinued.

The radiosonde used is the audiofrequency modulated type, transmitting signals on 401 MHz, with a baroswitch to switch in electrical temperature (thermistor) and humidity (hygristor) elements in flight.

Using the calibration curve supplied with each instrument, the records of temperature and humidity against height were evaluated and the computed values of temperature T and dew point temperature T_d plotted on a tephigram. T and T_d for every 50 or 25 mb could be obtained from this diagram.

2.3.2.2 computation of precipitable water radiosonde measurements

The method adopted is the same as that used by Ananthakrishnan et al (1965), the principle of which is as follows:

Consider a vertical column of the atmosphere of unit cross-sectional area. If q is the specific humidity of the air in this column at a height z, where the air pressure and density are p and ρ respectively, the precipitable water W in the air column is given by:

$$W = \int q . \rho . dz. \qquad (2.6)$$

It follows from equation (1.14) that

$$W = \frac{1}{g} . \int q \, dp \qquad (2.7)$$

Since $q = \frac{r}{1+r}$

where r is the humidity mixing ratio, we can write

$$W = \frac{1}{g} \cdot \int \frac{r}{1+r} dp \qquad (2.8)$$

Since g is nearly equal to 980 cm/sec^2, and r is of the order of 0.1 to 0.2 near the ground, g(1+r) is nearly equal to 1000. At higher levels, although the value of g(1+r) is slightly less than 1000, the error introduced in constituting it equal to 1000 is quite small in the computation of W. Hence we can write with sufficient accuracy

$$W \doteq \int \frac{r}{1000} \cdot dp. \tag{2.9}$$

If pressure is expressed in millibars, we have

$$W = \int r.\ dp. \tag{2.10}$$

The atmosphere can be divided into layers of 25 mb thickness and the mean r for each layer obtained from radiosonde data and W can be calculated by finite integration in steps of 25 mb each.

The values of r for the surface, 900, 875, 850 etc. mb levels were calculated from the corresponding dew point temperature T_d, using the definition of vapour pressure e in terms of the mixing ratio r and atmospheric pressure p,

$$r = \frac{0.622\ e}{p-e} \quad g/g \tag{2.11}$$

and using Teten's empirical formula (1930) based on laboratory measurements, expressing the variation of e_m the saturation vapour pressure with dew point temperature T_d (°C),

$$e_m = 6.11 \times 10^{\frac{7.5\,T_d}{237.3 + T_d}} \qquad (2.12)$$

A similar theoretical formula can be easily derived from the equation of Clauaius-Clapeyron for the heat of condensation (Haurwitz, 1941). The mixing ratio r for the corresponding T_d for the surface, 900, 875, 850 mb was calculated and the precipitable water W from

$$W = 25\ r + 10\ r_s \qquad (2.13)$$

where the surface pressure is assumed to be 910 mb and r_s is the mixing ratio corresponding to the surface*

2.3.2.5 Accuracy and sources of error

Three types of error can occur in radiosonde measurements:

a) systematic errors characteristics of the type of sonde.

b) instrumental errors which persist throughout the sounding but may vary from one sounding to another.

c) random errors in observation occuring during the sounding.

It is not easy to assess the absolute accuracy of a radiosonde, since no convenient standards are readily available for flight comparisons. But an assessment of the errors of the types (a) and (b) can be obtained by twin ascents, i.e. sending up on the same balloon two radiosondes of the same type and comparing the results obtained or by comparing the sonde with one of the reference radiosondes so designated by the World Meteorological Organization. The readings can also be independently checked by aircraft observations and radar determinations of heights.

The audiofrequency modulated sonde of the type used in the present study, if properly made and correctly calibrated, is said to be capable of measuring pressure correct to 5 mb, temperature to 1°C relative humidity to 10 percent and the height to 1 perqent at a: given: pressure level. The systematic errors increase with height and are greater by day than by night. Random errors can average about 7 mb and 1°C.

While pressure and temperature errors can be estimated with some certainty, despite the inherent lag and radiation errors, the accuracy of humidity sensors leaves much to be desired. These errors mainly arise from their low rate,of response at low temperatures and their insensitivity near the extremes of humidity. Since the variation of humidity with height is generally much more irregular than that of temperature, it is not practicable to apply lag corrections on a routine basis. With the type of lithium chloride hygristor element used in the present work, an accuracy of the order of ± 10 per cent only can be expected under the most favourable circumstances at temperatures above 0°C. From about -20° to -40°C the indications are only useful for qualitative information, especially since at -40°C, the typical lag of the hygristor is about 10 minutes and at still lower temperatures, where the concentration of water vapour is minute, the element has to be regarded as useless. Lithium chloride sensors are adversely affected by exposure to very wet fog or if wetted by rain and are also liable to errors due to polarisation. Since only the ascents at Bangalore and Nandi Hills on clear days and nights are considered, the latter error is not likely to occur.

With an uncertainty in T of the order of ± 1°C and in relative humidity of ± 5 per cent, T_d can typically be obtained only to an accuracy of ± 3°C. Since the partial pressure of water vapour e is given by equation (2.12) we have:

$$\frac{\delta e}{e} = \pm\ 17{\cdot}3\ \delta T_d \left[\frac{237{\cdot}3}{(T_d + 237{\cdot}3)^2} \right]$$

$$= \pm\ 0{\cdot}073\ \delta T_d$$

An uncertainty of ± $3^{o}C$ in T_d will result in an error of ± 20 per cent in e. From equation (2.11)

$$\frac{\delta r}{r} = \pm \frac{\delta e}{e} \pm \frac{\delta p + \delta e}{p - e}$$

From the above it can be seen that an error in e of ± 20 per cent will result in a similar error in r. From equation (2.13) we find the error in determining W will be about ± 20 per cent. This error will be larger when relative humidity values are below 15 per cent, when additional uncertainties arise as a result of the erratic behaviour of the lithium chloride hygristor at very low humidities. Such low humidities are observed in all seasons at high levels and during the dry season even at low levels.

An additional source of error is the drift of the balloon in strong winds when the computed precipitable water W may not represent the true zenith value.

Tables 2.3 and 2.4 give the values of precipitable water computed from radiosonde measurements made at Bangalore and Nandi Hills during 1979-1981. The variation of W with time is plotted in Figs 2.1 and Fig 2.2 for both stations for the period 1979-81. The diurnal and seasonal variations of W are discussed in Chapter 5.

2.4 Computation of scale height of precipitable water

The scale height H for precipitable water W is defined as the altitude at which W reduces to $\frac{1}{e}$ times the value at the surface. If W_z is the precipitable water at altitude z,

$$W_z = \int_z^\infty d_{v,z}\,dz \qquad (2.14)$$

where $d_{v,z}$ is the density of water vapour at altitude z and is given by:

$$d_{v,z} = d_{v,o}\,e^{-\frac{z}{H}} \qquad (2.15)$$

Substituting (2.15) in (2.14), we have

$$W_z = \int_z^{\infty} d_{v,0}\, e^{-\frac{z}{H}}\, dz \qquad (2.16)$$

$$= d_v \left[e^{-\frac{z}{H}} \Big/ \tfrac{-1}{H} \right]_z^{\infty}$$

$$= d_v \cdot H \cdot e^{-\frac{z}{H}} \qquad (2.17)$$

When $z = 0$, precipitable water W is given by

$$W = d_v \cdot H \qquad (2.18)$$

This is valid if the decrease with height of d_v is exponential. From measured values of d_v at the surface of the earth and values of W computed from radiosonde data, it is therefore possible to obtain values of H for a given time and place.

H can also be calculated if the fractional precipitable water δW in the layer from the surface to the height corresponding to H is known.

$$\overset{H}{\underset{\text{Surface}}{\delta W}} = \left(1 - \frac{1}{e}\right) W \qquad (2.19)$$

From equation 2.15 we have

$$\ln. d_{v,z} = \ln(d_v) - \frac{z}{H}$$

If the assumption of an exponential decrease of d_v with height is again valid, then a plot of ln. $d_{v,z}$ against z will be a straight line, the slope of which will give H i.e. the value of z which corresponds to

$$\ln.\ d_{v,z} = \ln.\ d_v - 1$$

This gives a third method of computing H. The values of d_v at different levels are computed from radiosonde data using formula given in equation (1.8).

Using all three methods the scale height H was calculated for Bangalore for individual days for the period 1979-81. The scale height values calculated from radiosonde ascents at Bangalore using the second method are plotted against precipitable water in Fig 2.5.

It was observed that the scale height changes from day to day and from season to season and varies with W. There appears to be no unique value of H for either of the two stations. On the other hand, there is a general tendency for H to increase with W.

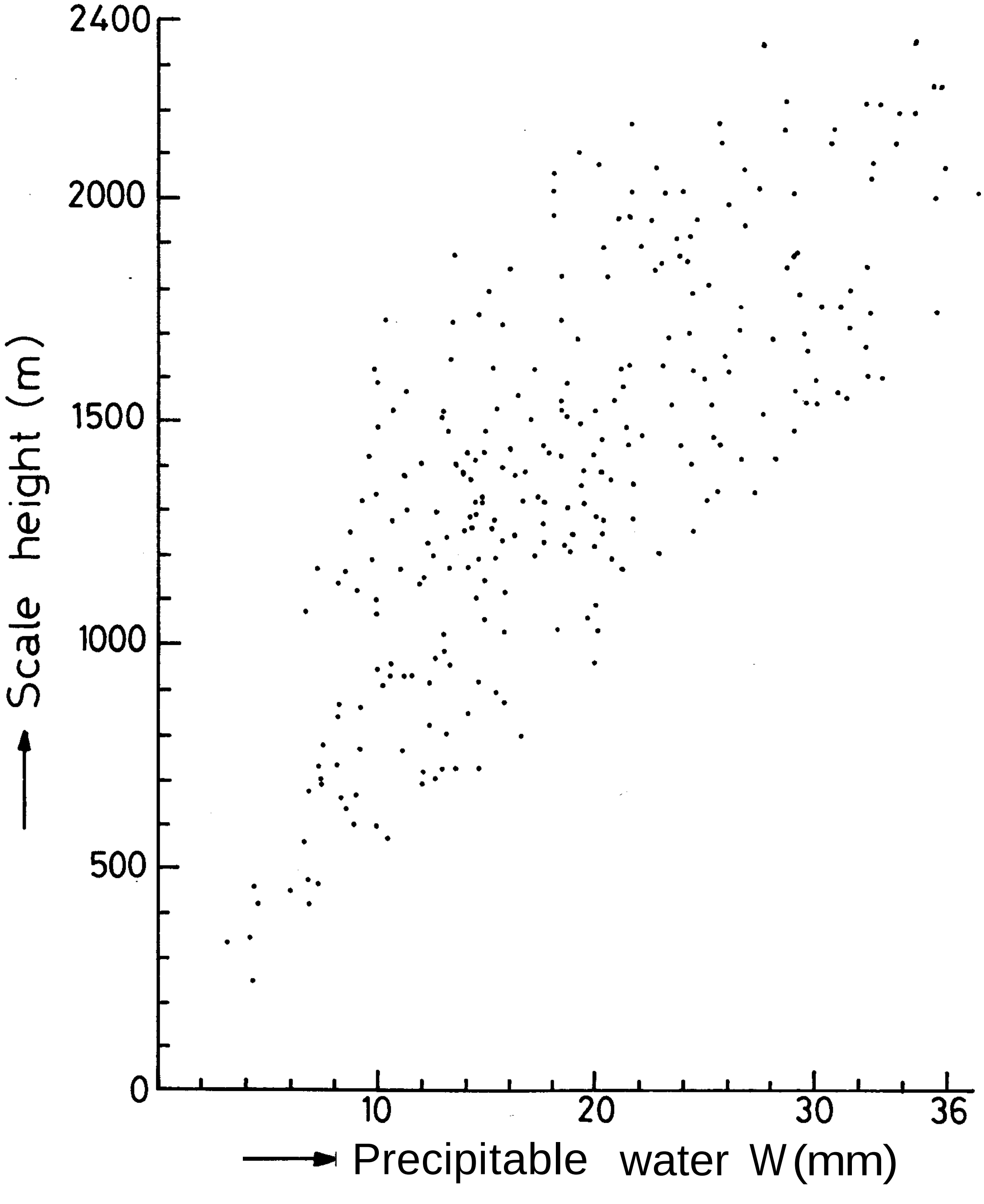

Fig. 2.5 Correlation between scale height H and precipitable water W computed from radiasonde data

2.5 Summary

An examination of the results obtained from the two methods shows that no simple linear relationship exists between precipitable water W and the absolute humidity d_v at the surface and precipitable water cannot be computed, except qualitatively from the surface humidity values.

On the other hand, computation of precipitable water from humidity measurements obtained with a radiosonde provides the most reliable method of deriving W, with an accuracy of ± 20%.

LIST OF FIGURES

LIST OF TABLES

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