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A model for the estimation of precipitable water

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ABSTRACT

A model has been developed for the estimation of precipitable water on clear days based on the daily and hourly measurements of global I.R. solar radiation and on humidity data taken at ground level. The model takes into account the attenuation processes of radiation by water vapour. The results concerning precipitable water are compared with those obtained with radiosondes both for daily and hourly intervals, obtaining correlation coefficients higher than those achieved with the equations proposed by Reitan and Smith in which only humidity parameters are used. The model has been applied to three periods: cold (October–March), warm (April–September) and annual (January–December) over 3 years in Salamanca (central N–W Spain).

1. Introduction

In many studies on solar radiation and in several different fields of meteorology such as weather prediction, climatology and agricultural meteorology, knowledge of the global atmospheric water vapour content is of greater interest than humidity parameters taken at ground level. Precipitable water (PW) is the term most commonly used to refer to the overall water vapour content above any given meteorological station. The last generation of operational satellites (TIROS-N) has attempted estimation of PW (Manna, 1985). The scarcity of stations able to carry out radiosondes, however, has contributed to the development of methods which relate PW with some humidity parameters taken at ground level (Revuelta et al., 1984) as well as with radiometric parameters.

Reitan (1963), Smith (1966) and Karalis (1974) studied the relationship between the logarithm of precipitable water (W) and dew point temperature (T_d) at the surface of the earth. Reitan was led to propose the equation:

$$\ln W = a + bT_d$$

and Smith introduced a modification in this expression such that the independent term would be a function a parameter λ which represents the variation in humidity in a vertical column of atmosphere. Smith's equation is:

$$\ln W = \exp(0.1183 - \ln(\lambda + 1) + 0{\cdot}0707T_d),$$

The correlation coefficient between the log of precipitable water and dew point temperature at ground level ranges from 0.33 to 0.99. As expected, the correlations also decrease when the period of time analyzed is reduced, since a relationship of mean values between PW and humidity over longer periods of time (months and years) gives rise to uniformity in the vertical humidity profile.

Tuller (1977) examined the correlation between the log of PW and three humidity parameters (dew point temperature, mixing ratio and water vapour pressure) at six New Zealand stations. The differences that this author noted between the correlation coefficients at each station are small: 0.05, whereas for the different climatic seasons the values obtained ranged between 0.47 and 0.90 in spite of the fact that New Zealand has a climate in which the vertical mixing of the atmosphere is good. According to Reber and Swope (1972), when stratification stability increases, and thus the vertical mixing mechanisms decrease, this correlation deteriorates. A correlation between the log of PW and humidity parameters may therefore be valid when the mean values of such variables are considered over longer periods of time and when atmospheric convection processes are present.

The present work proposes a new method for evaluating PW. It is based on the measurement of global solar radiation in the 300–3000 nm wavelength range since in that part of the solar spectrum, the only atmospheric component which affects radiation significantly is water vapour. A study is also made in which the log of PW is plotted as a linear function of the absorption of the global I.R. solar radiation and humidity parameters. It is then possible to estimate atmospheric water vapour regardless of the actual distribution of humidity since the radiative variable introduced into the correlation depends on the water vapour present throughout the vertical atmospheric column.

2. Data

This section is devoted to a description of the variables, the apparatus used and the working conditions for obtaining the data employed.

2.1. Global solar radiation (280–2800 nm) G, and global I.R. solar radiation (710–2800 nm) G_R

These were recorded at the actinometric station of the Department of Air Physics, Facultad de Ciencias, University of Salamanca (40°56′N, 5°57′W) at 814 m a.s.l. Global solar radiation (G) was measured with a Kipp-Zonen pyranometer equipped with a Schott WG-7 filter; Global I.R. Solar Radiation (G_R) was measured with an Eppley precision spectral pyranometer fitted with a Schott RG-8 filter. The interpretation of both readings was performed with a Haff-317 planimeter and an electronic integrator.

2.2. Precipitable water W

Because atmospheric sondes for the calculation of PW are not carried out in Salamanca, data were taken from the radiosonde station at Barajas (Madrid) at 210 km to the E of Salamanca in view of the similarity in climate of both geographic zones. The sondes employed were taken at 00.00 and 12.00 GMT. The value of PW was calculated from a vertical profile extending from the ground to 500 hPa, overlooking the water vapour above that level because values are very reduced.

2.3. Other variables

The remaining variables involved, water vapour pressure, dew point temperature (T_d), cloudiness N and sunshine S, were provided by the meteorological station at Matacán (Salamanca) and correspond to measurements taken at ground level. Daily values were means of the observations made at 07.00, 13.00 and 18.00 GMT.

The data employed correspond to a 3-year period, 1979, 1980 and 1981. Some authors, such as Karalis (1974), Tuller (1977) and Viswanadham (1981) obtained widely varying correlation coefficients between PW and the humidity parameters, depending on the weather station at which the measurements were taken. Accordingly, we have grouped the days analysed into three periods: a first period which we have named "cold", from October to March, a second period called "warm", from April to September and third one "annual" which comprises the whole year.

3. Description of proposed method

Analysis of the solar absorption spectrum reveals that the components involved in the absorption process of solar radiation do not act continually; rather, particular spectral lines or bands ranging from U.V. to far I.R. wavelengths are associated with each atmospheric component. Even though the absorption processes of solar radiation by water vapour take place across the whole spectrum, it is in the I.R. solar spectrum (710–2800 nm) where absorption becomes really important and, moreover, in that wavelength interval, the absorption phenomena due to the remaining atmospheric components may be considered negligible.

The G_R registered at ground level depends on the amount of water vapour present in the atmosphere. Fig. 1 shows the mean monthly values of precipitable water W and I.R. solar radiation G_R for the three years studied. There is a lag between curves of PW and radiation. This is a climatological feature and will thus not affect the study. In general, an increase (or decrease) in W may be seen to be accompanied by a decrease (or increase) in I.R. radiation. This is more patent in the cold period than in the warm one. However, there are monthly means of I.R. solar radiation whose trend reflects the variations in monthly means of W. In

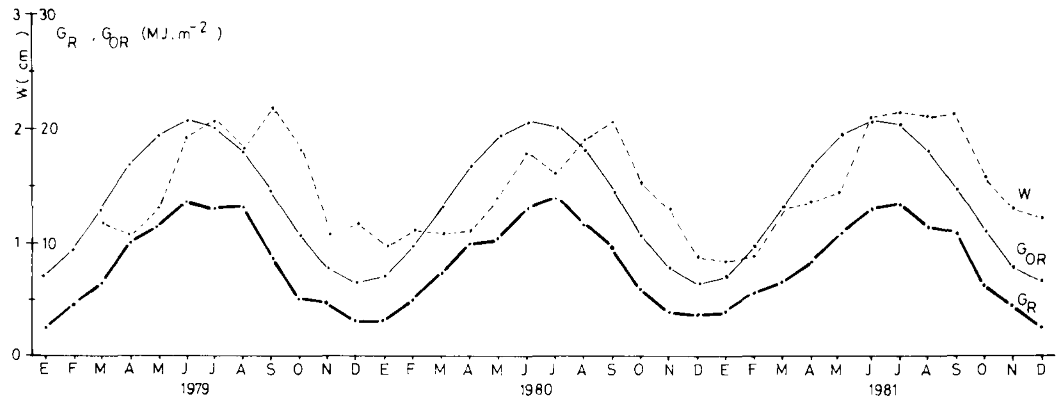

Fig. 1. Evolution of monthly means of global solar rdiation and precipitable water. W is the precipitable water; G_{OR} is the extraterrestrial I.R. global solar radiation and G_R is the I.R. global solar radiation at the ground.

the first part of the year, this was accounted for by a greater relative increase shown by G_R compared with that undergone by W, whereas from July to December, radiation decreases and such a decrease is favored by the presence of water vapour.

Precipitable water indicates the amount of water vapour in a vertical column of the atmosphere and it is known that water vapour is not distributed homogeneously within such a column. The humidity parameters at ground level will be estimated variables of the precipitable water when the vapour is concentrated in the layers close to ground level. We believe that because global I.R. solar radiation crosses the whole atmosphere, its estimation is the best manner of determining PW in that its measurement depends on the total amount of water vapour, regardless of whether it is found in the upper or lower strata of the atmosphere. The first relationship which we analyzed was the I.R. global solar radiation G_{OR}, calculated at the top of the atmosphere from the equation proposed by Kondratyev (1969) with the solar constant obtained from the extraterrestrial solar spectrum of Thekaekara (1974), and its corresponding value G_R recorded at ground level at the station. A simple calculation shows that the difference between these two variables will be linked to the energy absorbed by the water vapour present:

$$W = aG_W + b, \tag{1}$$

where $G_W = (G_{OR} - G_R)$, represents the I.R. global radiation absorbed throughout the day.

From the analysis of the recording of I.R. radiation and of the precipitable water values obtained by radiosonde, it may be seen that the small variations in PW during the day do not correlate with the greater alterations in G_W appreciable in the same period. In order to approximate both variations and to include this aspect in eq (1), we normalized the fluctuations of G_W by dividing it by the true daily sunshine S, such that: CGS $= (G_W/S)$, which would account for the hourly attenuation of the I.R. component. In view of this, a new equation is proposed:

$$W = a\,\mathrm{CGS} + b, \tag{2}$$

whose results substantially improve those of the first equation.

However, there is one aspect which is not considered in our previous equations. In the atmospheric strata close to the ground, owing to a greater concentration of water vapour water, molecules must exist in the condensed phase which do not exhibit absorption of the I.R. global solar radiation (Kondratyev, 1969; Mateos, 1976; Hänel, 1976). The presence of this condensed water vapour at levels close to the observation point is measured by T_d or by the water vapour pressure. In this way, we obtain new equations for the calculation of precipitable water:

$$W = a\,\mathrm{CGS} + bT_d + c, \tag{3}$$

$$W = a\,\mathrm{CGS} + be + c, \tag{4}$$

where the coefficients a, b and c are different in both equations.

4. Instantaneous or hourly determinations

By using eqs. (3) and (4), it is possible to calculate the mean PW on one day fairly satisfactorily, though it is necessary to have all the information of that day previously available. The idea of being able to carry out this evaluation of PW at different times of the day prompted us to assay the validity of these equations at hourly intervals. The hour chosen was noon (12.00 GMT). The equation assayed was number (4), which would take the form:

$$W_h = s\,\mathrm{CGS}_h + be_h + c, \qquad (5)$$

where CGS_h represents the decrease of I.R. global solar radiation upon passing through the atmosphere for one hour. The water vapour pressure e_h is obtained from the 11.00, 12.00 and 13.00 GMT observations. Since this equation is applicable at any time of the day, it is then possible to follow the time course undergone by PW with a degree of simplicity which is not characteristic of atmospheric sounding and thus to obtain better results than with the equations of Reitan and Smith for hourly periods.

Table 1. *Distribution of the days according to the periods analysed*

Period	Cold	Warm	Total
no. of days	51	80	131

5. Results

In the present work, the method proposed was applied to 131 clear days from a total of 1096 days analysed corresponding to the recording of global I.R. solar radiation of 3 years. In order to do this, we selected the criterion that the cloudiness index, the sum of observations at 07.00, 13.00 and 18.00, should not exceed 4 octas; this generally ranges between 0 and 2 octas. We also excluded those days on which, without overt cloudiness, the degree of opaqueness due to haze or mist might have masked the attenuation effect we were trying to measure. The number of clear days for the cold, warm and annual periods are shown in Table 1.

The results obtained with the method proposed are compared with those obtained with the Reitan and Smith equations. The parameter λ which appears in Smith's equations was calculated from the expression:

$$\frac{q}{q_0} = \left(\frac{p}{p_0}\right)^{\lambda},$$

where q and q_0 represent specific humidity, and p and p_0 the atmospheric pressure of the upper and lower limits of each atmospheric layer (surface—850 hPa, 850–700 hPa and 700–500 hPa) into which the atmosphere is divided. The humidity and pressure data were taken from the radio soundings conducted at Barajas. The annual value of the λ parameter for the Madrid-Salamanca zone was 3.534, slightly greater than that reported by Smith (1966) for this latitude. For each of the three periods analysed, using both eqs. (3) and (4) and those of Reitan and Smith, Tables 2, 3 and 4 plot

Table 2. *Values of the correlation coefficients, the regresion equation, degree of significance and % of variance explained by daily measurements for the cold period*

Equation	Regression equation	Correlation coefficient	Degree of significance	Variance 1st variable	2nd variable	total
Reitan	$\ln W = 0.065t_d - 0.148$	0.668	99.5	46.49	—	46.49
Smith	$W = \exp(0.1133 - \ln(\lambda + 1) + 0.0393t_d)$	0.658	99.5	43.29	—	43.29
$W = a\mathrm{CGS} + bt_d + c$	$W = 4.844\mathrm{CGS} + 0.037t_d - 0.208$	0.823	99.5	57.37	10.39	67.76
$W = a\mathrm{CGS} + be + c$	$W = 4.449\mathrm{CGS} + 0.081e - 0.636$	0.836	99.5	57.37	12.36	69.83

Table 3. *As in Table 2 except for the warm period*

Equation	Regression equation	Correlation coefficient	Degree of significance	Variance 1st variable	Variance 2nd variable	Variance total
Reitan	$\ln W = 0.064t_d - 0.138$	0.712	99.5	50.69	—	50.69
Smith	$W = \exp(0.1133 - \ln(\lambda + 1) + 0.0393t_d)$	0.640	99.5	40.96	—	40.96
$W = a\mathrm{CGS} + bt_d + c$	$W = 3.767\mathrm{CGS} + 0.060t_d - 0.143$	0.736	99.5	37.51	16.70	54.21
$W = a\mathrm{CGS} + be + c$	$W = 3.950\mathrm{CGS} + 0.088e - 0.699$	0.740	99.5	37.51	18.09	55.60

Table 4. *As in Table 2 except for the annual period*

Equation	Regression equation	Correlation coefficient	Degree of significance	Variance 1st variable	Variance 2nd variable	Variance total
Reitan	$\ln W = 0.065t_d - 0.141$	0.783	99.5	60.49	—	60.49
Smith	$W = \exp(0.1133 - \ln(\lambda + 1) + 0.0393t_d)$	0.778	99.5	59.43	—	59.43
$W = a\mathrm{CGS} + bt_d + c$	$W = 3.711\mathrm{CGS} + 0.046t_d - 0.146$	0.838	99.5	60.88	9.43	70.31
$W = a\mathrm{CGS} + be + c$	$W = 3.678\mathrm{CGS} + 0.077e - 0.460$	0.844	99.5	60.88	10.37	71.25

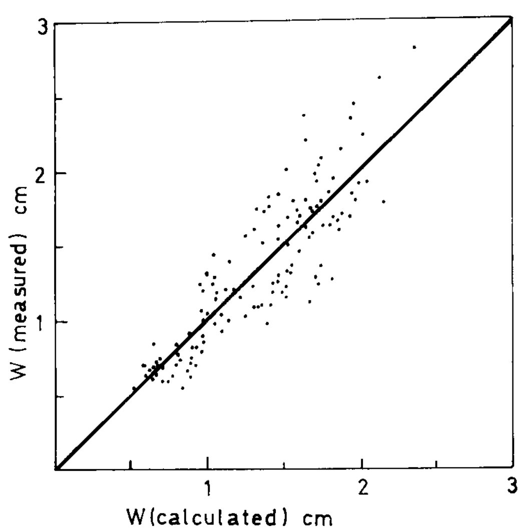

Fig. 2. Scatter diagrams and regression lines showing the relationship between radiosonde data and values calculated with the expression $W = a\,\mathrm{CGS} + be + c$ of precipitable water during the annual period.

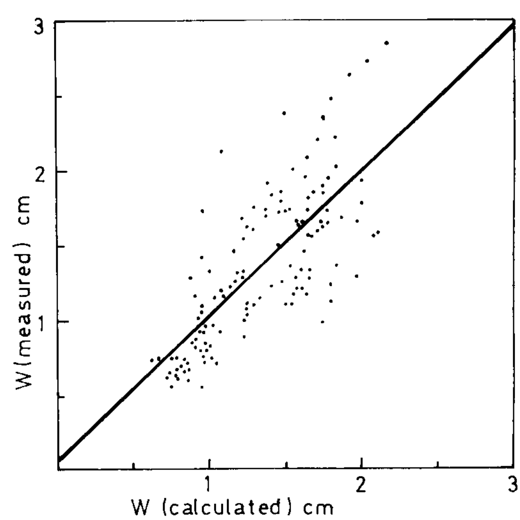

Fig. 3. Scatter diagrams and regression lines showing the relationship between radiosonde data and values calculated with Reitan's equation of precipitable water during the annual period.

Table 5. *Values of the correlation coefficients for the cold, warm and annual periods obtained from the data of the hourly measurements*

Equation	Period		
	Cold	Warm	Total
Reitan	0.385	0.431	0.783
Smith	0.552	0.550	0.701
$W_h = a\text{CGS}_h + be_h + c$	0.621	0.633	0.821

the regression equation, the correlation coefficients, the degree of significance and the variance of each of the variables used in the estimation of the mean PW of one day. The dispersion diagrams between the PW obtained by radio sounding and the values calculated from eq. (4) and from Reitan's equation are shown in Figs. 2 and 3.

The correlation coefficients obtained with eqs. (3) and (4), calculated with the S.P.S.S. (Statistical Package for the Social Sciences) using a Univac 1100 computer, are slightly higher than those obtained with equations in which only humidity parameters (Reitan, 1963; Smith, 1966) are included in any of the three periods analysed. In the warmest period of the year, the correlation coefficients are more similar and lower than in the other two periods, and, as pointed out by Karalis (1974) and Bolsenga (1965), this is due to the lack of vertical mixing in the absence of convection.

When the same periods are analysed but calculating the PW over one hour at noon (12.00 GMT), the differences in the correlation coefficients between eq. (4) and those of Reitan and Smith become more marked than when the mean PW of the whole day is used (Table 5).

6. Conclusions

The inclusion of radiation variables together with humidity parameters improves the evaluation of precipitable water compared with the equations which only use humidity data. The difference between these kinds of equations may also be seen in the determination of the hourly values of PW. This allows a continual estimation of PW during the day which may not be obtained with radiosonde techniques.

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