Determination of the Total Precipitable Water by Varying the Intercept in Reitan's Relationship

CLAUDIO TOMASI

Laboratorio FISBAT, C.N.R., Bologna, Italy

(Manuscript received 11 July 1980, in final form 28 May 1981)

ABSTRACT

In the relationship proposed by Reitan (1963) between the total precipitable water and the dew-point temperature at ground level, the intercept is found to be a function of the scale height of the atmospheric water vapor and of the ground temperature. The scale height is closely related to the features of the vertical moisture profile in the low troposphere. The ground temperature is responsible for diurnal and seasonal variations of the intercept which are found to be of little importance. The slope coefficient is found to have a constant value of 0.068°C^{-1}.

On this basis, a method is proposed which determines the nocturnal time pattern of the intercept, by linear interpolation in time between the daytime estimates obtained from spectral hygrometer measurements. Thus, the nocturnal time pattern of the total precipitable water can be calculated from Reitan's relationship using these interpolated values of the intercept together with the nocturnal measurements of the dew-point temperature at ground level. Satisfactory results are found by applying this method to spectral hygrometer measurements made on several days.

Estimates of the total precipitable water at two stations of the Po Valley also have been obtained from Reitan's relationship by using local measurements of the dew-point temperature at ground level and suitable values of the intercept. These are determined by linear interpolation in time of the estimates of the intercept given by the radiosonde data taken from a remote station of the Po Valley. The comparison between calculated and measured values of the total precipitable water gives a satisfactory agreement for both autumn and winter periods, whereas considerable discrepancies are found on various summer days.

1. Introduction

The atmospheric transmission spectrum is characterized by a large number of water vapor absorption bands, from visible to centimeter wavelengths. The absorption bands centered at wavelengths from 0.54 to about 9 μm are associated with vibrational-rotational transitions of the water molecule. Those located at longer wavelengths are produced by purely rotational transitions. Since most of these bands present features of strong absorption, the atmospheric content of water vapor is an important parameter in the attenuation processes affecting both atmospheric and extraterrestrial radiation. Methods of determination of the amount of precipitable water in the atmosphere from ground level measurements of meteorological parameters are very useful not only for astronomical observations and studies on atmospheric radiation but also for various fields of meteorology, such as cloud physics, weather modification, weather forecasting, climatology and agricultural meteorology.

In order to obtain estimates of the total precipitable water from measurements of meteorological data at ground level, Reitan (1963) examined data taken over a period of three years, at 15 meteorological stations. On the basis of mean monthly data, he found a relationship of the form

$$\ln W = a + bT_d, \tag{1}$$

linking the total precipitable water W (cm STP or g cm^{-2}) to the dew-point temperature T_d at the ground. He obtained estimates of the slope coefficient b ranging between 0.0578 and 0.0857°C^{-1}, together with corresponding evaluations of the intercept a of 0.1492 and of 0.2192. The intercept a was found to vary between -0.1108 and 0.2192. Correlation coefficients $\geqslant +0.96$ were obtained for all stations. From these data, Reitan (1963) proposed the average values $b = 0.0614$°C^{-1} and $a = 0.1102$ for Eq. (1).

Average estimates of the parameters a and b also were made by Bolsenga (1965), who found $a = 0.1174$ and $b = 0.0769$°C^{-1} from mean daily data (with a correlation coefficient of +0.85) and $a = -0.0592$ together with $b = 0.0691$°C^{-1} from mean hourly data (correlation coefficient of +0.80).

Lowry and Glahn (1969) examined a large set of daily data taken over a period of two years at 56 meteorological stations. They found that ~83% of the variance of the logarithm of W can be explained

---

0021-8952/81/091058-12$07.00

by a linear function of the dew point T_d at the ground. About 86% of the variance of the logarithm of W was explained when surface dew point, weather and sky cover were taken into account. Examining the whole set of daily observations in terms of Eq. (1), they obtained the best-fit solution for $a = -0.917$ and $b = 0.0576°\mathrm{C}^{-1}$ with a correlation coefficient of $+0.91$. Moreover, from the examination of these data separately classified by month, by region and by season and region, they found that the average values of a and b present fairly gradual variations with the time parameters and discernable geographical patterns.

Radiosonde data taken over a period of two years at seven South African stations were analyzed by McGee (1974), who obtained very good values of the correlation coefficient for each station. Examining the complete set of mean monthly data, he found the average values $a = -0.038$ and $b = 0.066°\mathrm{C}^{-1}$.

A large set of measurements of total precipitable water obtained with an infrared hygrometer and of simultaneous measurements of the dew-point temperature at the ground was examined by Tomasi (1977) in terms of Reitan's relationship. The data taken in cloudless atmospheres on autumn and winter days were best fitted by the relationship of Eq. (1) with $a = -0.290$ and with $b = 0.061°\mathrm{C}^{-1}$, giving a correlation coefficient of $+0.95$.

The abovementioned investigations show that the relationship of Eq. (1), as proposed by Reitan (1963), is suitable for giving correct estimates of the total precipitable water, provided that appropriate values of the parameters a and b are used. These parameters present appreciable variations with time and region, as shown by Lowry and Glahn (1969). Moreover, they can be considerably influenced by the evolutionary features of the local meteorological conditions. These aspects are examined in the present paper.

2. Physical meaning of the intercept

Smith (1966, 1967) has shown that the intercept a is closely related to the vertical moisture profile. He proposed that the intercept be allowed to vary as a function of the parameter λ, which is used to model the decrease of moisture through the atmospheric column. Moreover, he suggested latitude and season corrections for the parameter λ. The validity of this modification of Reitan's relationship was discussed by Schwarz (1968), who found large discrepancies with respect to Smith's suggestions and concluded that surface moisture is a poor predictor of precipitable water in the warm season and that "even with a judiciously chosen estimation of mean vertical distribution of moisture, one should expect, for some areas and seasons at least, some large errors in trying to estimate liquid equivalent (precipitable water) in depth from surface dew points. At least this is shown to be the case for San Antonio in summer." Smith (1968) replied that these results are not surprising for particular seasonal and vertical moisture conditions of the atmosphere and that the parameter λ is used only to obtain estimates of the latitudinal average values of total precipitable water. Theoretical support to Smith's argument was given by Berkofsky (1967, 1968).

Evaluations of the intercept a were made by Tomasi (1977) as differences between the natural logarithm of W and the product bT_d, according to Eq. (1). The precipitable water W was measured with an infrared hygrometer (Tomasi and Guzzi, 1974) and the slope coefficient b was taken equal to $0.061°\mathrm{C}^{-1}$, according to Reitan (1963). These estimates of a were obtained for different seasonal periods including both some summer days presenting conditions of intense vertical mixing and several winter and autumn days characterized by the presence of a marked temperature inversion near the ground. From these data, the relationship

$$a = -0.725 - 0.971 \ln\beta \tag{2}$$

was found by Tomasi (1977), with a correlation coefficient of -0.98. The parameter β was taken proportional to the ratio between the absolute humidity ρ_0 at the ground and the total precipitable water W, so that it is equivalent to the inverse of the scale height of the atmospheric water vapor and can be expressed in kilometers^{-1}.

The relationship of Eq. (2) between a and β was confirmed by the examination of radiosonde data taken during autumn-winter periods for 88 cloudless days. From these data, the best-fit solution

$$a = -0.715 - 0.983 \ln\beta \tag{3}$$

was found with a correlation coefficient of -0.99.

The results of Eqs. (2) and (3) can be explained by representing the total precipitable water W (g cm^{-2}) as the product

$$W = 10^5 \rho_0 H, \tag{4}$$

where ρ_0 is the absolute humidity at the ground (g cm^{-3}) and the quantity H (km) is the vertical extent of the homogeneous atmosphere of water vapor, in which the absolute humidity is taken as being constant with height to give the total water vapor content W. More briefly, H is called the scale height of the atmospheric water vapor.

From the equation of state for water vapor, the absolute humidity at the ground can be expressed as a function of the water vapor partial pressure e_0 at the ground (bars) and of the ground temperature T_0 (°C), in the form

$$\rho_0 = \frac{e_0}{4.615(273.16 + T_0)} . \tag{5}$$

Thus, substituting Eq. (5) into (4) and taking the natural logarithm yields

$$\ln W = \ln(10^5/4.615) + \ln H + \ln e_0 - \ln(273.16 + T_0). \quad (6)$$

Making use of Magnus' empirical formula (see Tetens, 1930) which gives the saturation vapor pressure over water as a function of the temperature, the partial pressure e_0 of water vapor can be expressed as a function of the dew point T_d in the form

$$e_0 = 6.107\ 10^{-3}\ 10^{D(T_d)}, \quad (7)$$

with

$$D(T_d) = 7.5\ T_d/(237.3 + T_d). \quad (8)$$

Within the usual range of the dew-point temperature T_d at ground level, that is from −10 to +27°C, the term $D(T_d)$ is well approximated by the linear function of T_d having the form

$$D(T_d) = 0.02956\ T_d - 0.00639. \quad (9)$$

Thus, the expression

$$\ln W = 4.8705 - \ln(273.16 + T_0) + \ln H + 0.068\ T_d \quad (10)$$

can be found from Eqs. (6), (7) and (9).

Comparing Eq. (10) with Reitan's relationship in the form of Eq. (1), the slope coefficient b assumes the value of 0.068°C^{-1}. This result is in good agreement with the estimates made by several authors on the basis of radiosonde data and covering the range from 0.0576°C^{-1} (Lowry and Glahn, 1969) to 0.0769°C^{-1} (Bolsenga, 1965). Moreover, the comparison between Eqs. (1) and (10) gives a relationship of the form

$$a = 4.8705 - \ln(273.16 + T_0) + \ln H \quad (11)$$

between the intercept a and the scale height H and the temperature T_0 at ground level. For a temperature T_0 of 0°C, the expression

$$a = -0.740 + \ln H \quad (12)$$

is obtained from Eq. (11). Since H is the inverse of the parameter β and therefore

$$\ln H = -\ln\beta, \quad (13)$$

Eq. (12) assumes a form which is very similar to those of Eqs. (2) and (3), as found by Tomasi (1977) from hygrometer measurements and from radiosonde data, respectively.

In order to determine the usual range of the scale height H and at the same time to verify the reliability of the approximation of Eq. (9), a large set of soundings was examined. The radiosonde data were taken from five Italian stations, located at Udine (93 m MSL), Milan (107 m MSL), Rome (2 m MSL), Brindisi (15 m MSL) and Cagliari (4 m MSL). Among the soundings made during the last ten years, those of the year 1973 were taken. For each station and season, eight days characterized by anticyclonic conditions were chosen randomly. For each day, we considered the radiosonde data pertinent both to 0000 GMT (0100 LT) and to 1200 GMT (1300 LT). With this choice, a set of 320 soundings was collected, including four seasonal groups, each consisting of 40 daytime soundings and of 40 nocturnal soundings relative to five different sites of the Italian peninsula.

Each sounding gives data from the surface to 300 mb, corresponding to 10 standard levels and to other 8–14 significant levels. An 8% relative humidity was assumed for the levels presenting values of the relative humidity lower than the minimum of the sensor (~10%). For each sounding, calculations were made of (i) the total precipitable water W by summing the contents of the various atmospheric layers, (ii) the scale height H as the ratio between W and the absolute humidity at ground level, according to Eq. (4), and (iii) the intercept a by using the expression

$$a = \ln W - 0.068\ T_d, \quad (14)$$

as obtained from Eqs. (10) and (11).

These estimates of the intercept a are plotted in Fig. 1 as a function of the natural logarithm of H. The scatter of data is mainly due to the large differences of the temperature conditions at ground level. Only a few points lie outside of the two isopleths obtained from Eq. (11) for T_0 = −10°C and for T_0 = 35°C, showing that the expressions of Eqs. (10) and (11) can be considered as being reliable. As can be seen in Fig. 1, the scale height H ranges between 0.6 and 3.5 km. Correspondingly, the intercept a varies from −1.3 to about 0.6. Since the temperature T_0 ranges between −10 and 35°C, the temperature term in Eq. (11) can present, at the most, a variation of 0.16 when T_0 passes from one extreme value to the other. Therefore, the scale height H appears to be the variable of primary importance for the intercept a.

3. Features of the intercept

From the results discussed above, realistic estimates of the scale height H of the atmospheric water vapor can give useful estimates of the intercept a using Eq. (11), from which reliable values of W can be obtained by simply measuring the dew-point temperature at ground level. The first purpose of the present paper is to examine the behavior of the intercept a for different seasonal conditions and its variations with time (Sections 3 and 4). The second purpose is to propose techniques suited to determining precipitable water from local measurements of dew point and from estimates of the inter-

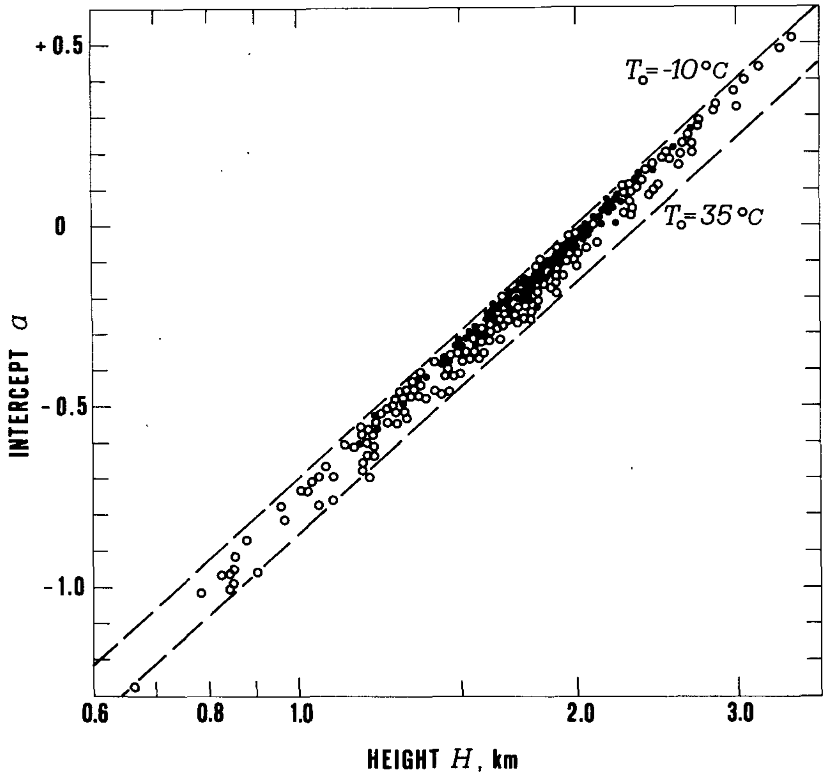

FIG. 1. Measurements of the intercept a, as obtained from 320 soundings, versus the logarithm of the scale height H. Open circles represent single points. Solid circles are double points. The two dashed curves are given by Eq. (11) for $T_0 = -10°C$ and $T_0 = 35°C$.

cept a made by using reliable procedures (Sections 5 and 6).

The scale height H is proportional to the ratio between the total precipitable water W and the absolute humidity at the ground. Since W is given by the integral of the absolute humidity along the vertical column of the atmosphere, the height H is closely related to the features of the vertical distribution curve of the absolute humidity. Considering that the larger fraction of W is given in the first few kilometers of the troposphere, the features of the moisture profile in this altitude region appear to be of the greatest importance. The radiosonde data show that large values of H are associated with moisture profiles which are almost constant or slowly decreasing with the altitude through the first few kilometers of the atmosphere. These conditions are typical of cold atmospheres, in which a marked ground inversion of the temperature is associated with a subsidence inversion to give rather high values of moisture up to an altitude of 1–2 km. Large values of H also can be found in summer days when the strong heating of the ground by the sun can cause extensive convective motions through the low atmosphere.

Low values of H are found when the relative humidity assumes rather large values in the ground layer and decreases quickly with altitude at the upper levels. These features can be frequently observed in winter atmospheres characterized by ground inversions of the temperature as well as in summer atmospheres having isothermal conditions near the ground.

To illustrate these remarks, the water vapor content W_1 of the first 0.5 km depth of the atmosphere, above the station, was calculated from the abovementioned radiosonde data. The ratio between W_1 and W gives the percentage of the total precipitable water within the ground layer of 0.5 km depth. The estimates of W_1/W are plotted in Fig. 2 as a function of the intercept a. Although the data are widely scattered, the ratio W_1/W shows the general tendency to decrease as the parameter a increases from -1.3 to 0.6. About 68% of the examples present values of a between -0.6 and 0.0 which correspond to values of the scale height H from 1.2 km to about 2.0 km. About 22% present positive values of a which are associated with values of $H > 2$ km. The remaining 10% refer to values of a smaller than -0.6 and so to values of $H < 1.2$ km. The results of Fig. 2 show that comparable features of the vertical profile of absolute humidity can be found in

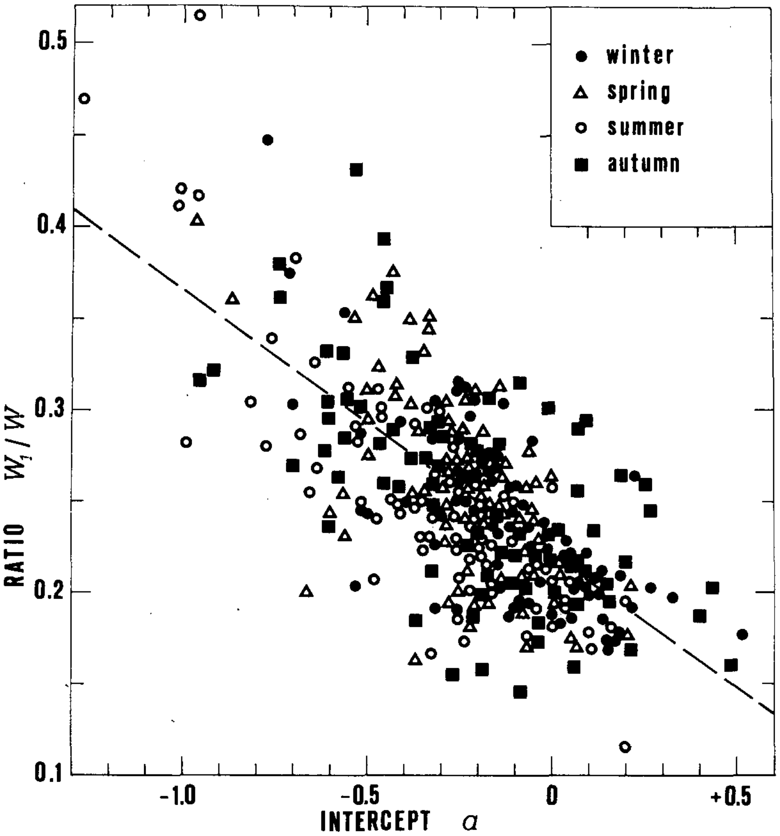

FIG. 2. Estimates of the ratio W_1/W plotted as a function of the intercept a. The data are obtained from 320 soundings made at five Italian stations. The regression line is given by $W_1/W = 0.219 - 0.145a$, with a correlation coefficient of -0.71.

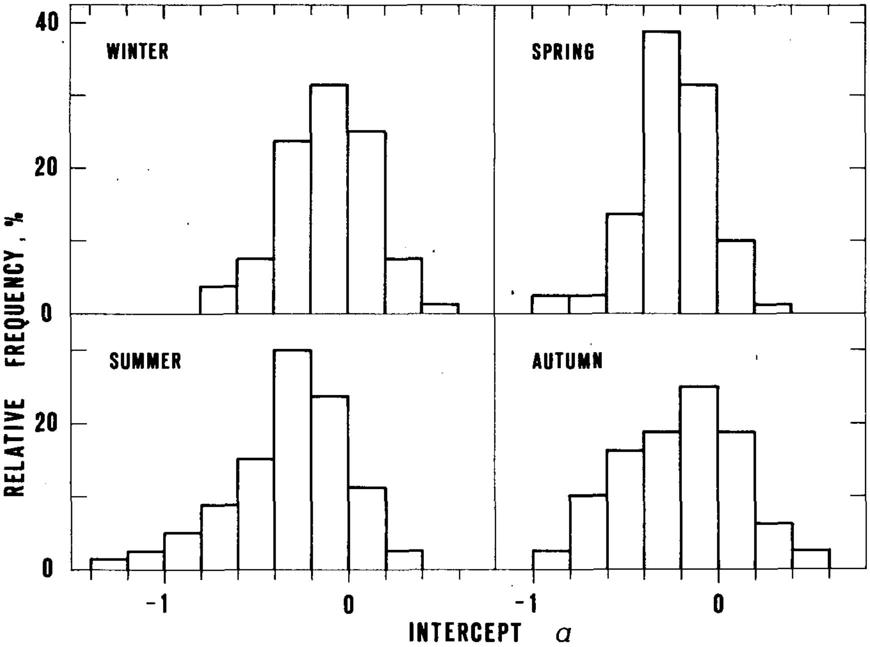

FIG. 3. Seasonal percentage histograms of the intercept a calculated from Eq. (14) using radiosonde data.

TABLE 1. Average values and standard deviations of the intercept a, of the ground temperature T_0 and of the height H, as obtained for the seasonal classes of radiosonde data.

Class	Intercept a	Ground temperature T_0 (°C)	Height H (km)
Winter	-0.11 ± 0.25	1.6 ± 2.8	1.92 ± 0.47
Spring	-0.24 ± 0.21	9.2 ± 5.4	1.69 ± 0.35
Summer	-0.32 ± 0.31	20.7 ± 4.8	1.68 ± 0.47
Autumn	-0.21 ± 0.31	5.3 ± 5.4	1.79 ± 0.54

different seasonal periods giving similar values of both the scale height H and the intercept a. However, the diverse features of the thermal structure of the atmosphere from one season to another could give different seasonal spectra of frequency of the quantities H and a. In order to examine these aspects, the estimates of the intercept a obtained from the sample of 320 soundings were classified by season. The diagrams of relative frequency for the intercept a are given in Fig. 3, showing that the median is located at -0.12 for winter, at -0.22 for spring, at -0.25 for summer and at -0.19 for autumn. The average values of the intercept a, of the ground temperature T_0 and of the height H are given in Table 1 for the four classes. These evaluations show that the seasonal variations of the intercept are considerably larger than those produced by the ground-temperature dependence term of Eq. (11) for the usual variations of T_0 from one season to another. A large part of the seasonal modifications of the intercept appears to be due to changes of the scale height H. However, considering the large standard deviations found for the seasonal mean values of the intercept a, it should be pointed out that a definite dependence on season of the intercept does not exist.

According to Eq. (11), variations of the intercept a also can be due to changes of the ground temperature during the day. In order to give a measure of this effect, the winter and summer estimates of the intercept were examined separately for the two soundings at 0000 and 1200 GMT. The diagrams of relative frequency of the parameter a are shown in Fig. 4. Values of the median of -0.10 and of -0.14 are found for the two winter histograms pertinent to night and day soundings, respectively. The corresponding values of the average temperature at the ground are of 1.3 and of 1.9°C, while the average values of H are found to be of 1.97 and 1.87 km, respectively. These similar results are consistent with atmospheric conditions of marked stability near the ground, such as those observed during winter days when strong temperature inversions are only slightly altered by radiative processes.

Considerable discrepancies can be observed between the two summer histograms of the intercept, as shown on the right side of Fig. 4. The nocturnal median of a is located at -0.20, while that given by the daytime data is at -0.35. Since the average value of T_0 varies correspondingly from

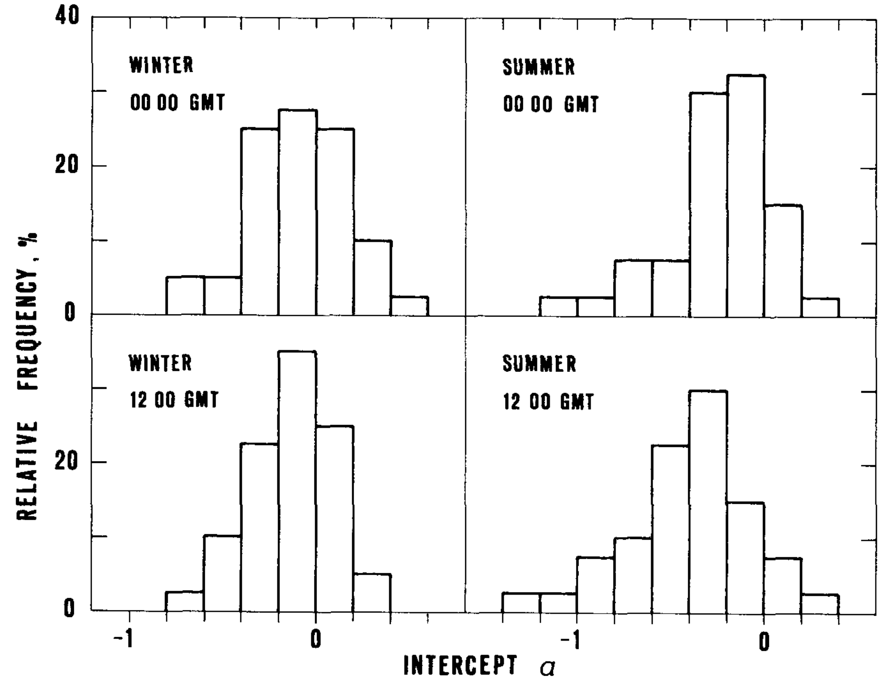

FIG. 4. Percentage histograms of the intercept a for winter and summer classes of radiosonde data separately examined for the sounding time at 0000 GMT and for that at 1200 GMT.

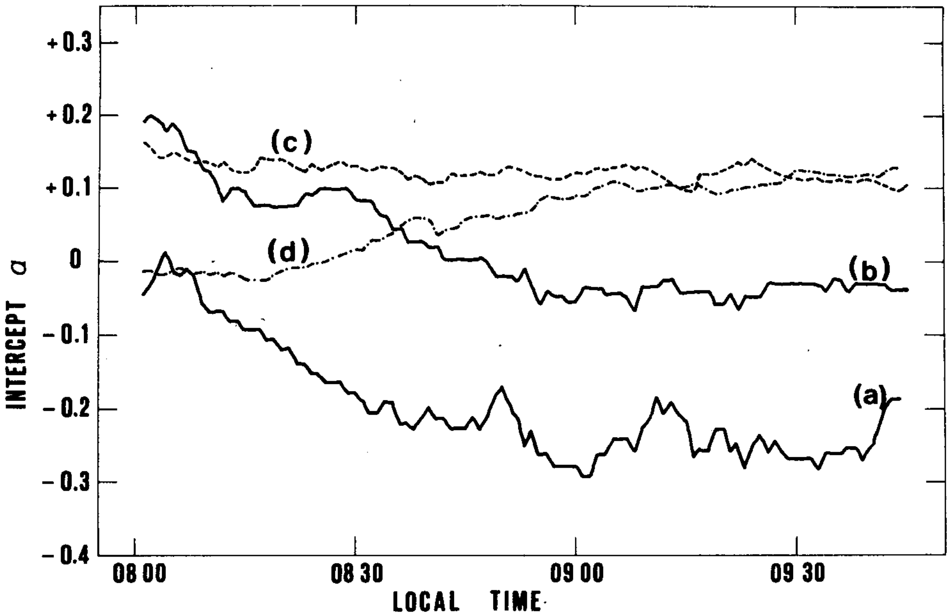

FIG. 5. Time patterns of the intercept *a* with a time interval of 90 minutes for four days: (a) 26 January 1974; (b) 30 January 1974; (c) 24 May 1974; (d) 26 June 1974. The readings were taken every 20 s.

18.1 to 23.3°C, the temperature dependence term of Eq. (11) accounts for a small part of the overall decrease. On the other hand, the average value of H varies correspondingly from 1.78 to 1.58 km, so that the greater part of the decrease of the median of a can be ascribed to the variations of the scale height H.

These results indicate that the intercept a depends mainly on the features of the vertical moisture profile, which are strongly influenced by the thermal structure conditions of the low troposphere. The diurnal and seasonal variations of the ground temperature can by itself cause very limited modifications of the intercept.

4. Time variations of the intercept

Continuous measurements of the total precipitable water made with spectral hygrometers (King and Parry, 1965; Tomasi and Guzzi, 1974) have shown that W presents generally steady time patterns during days characterized by calm conditions of the low atmosphere. The diurnal trend of W is to increase gradually during the morning as a result of water evaporation from the ground and to decrease slightly during the afternoon. The temperature and the relative humidity at the ground are subject to considerable variations during the day and show fre-

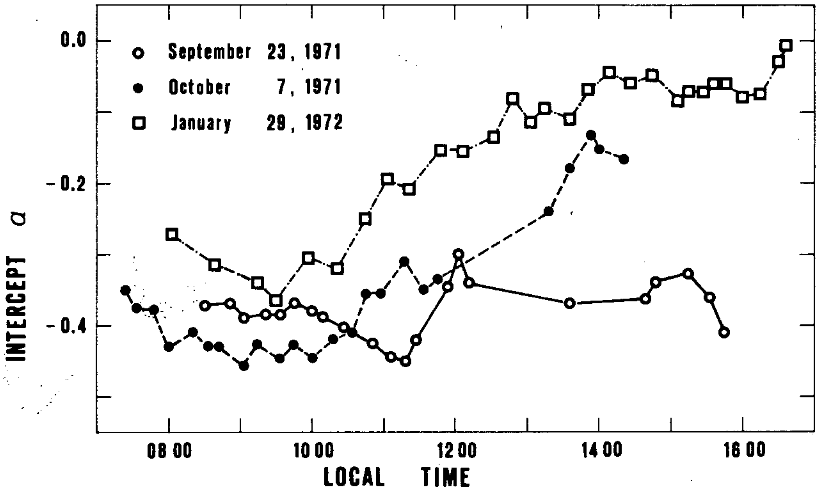

FIG. 6. Time patterns of the intercept *a*, as obtained from spectral hygrometer measurements of the total precipitable water on three days with clear sky.

quent nearly periodical features with opposite rates so that the absolute humidity at the ground turns out to be a rather stable quantity with time. Considering that the temperature dependence term of Eq. (11) does not cause appreciable effects for the usual changes of T_0, the intercept a depends mainly on H and, hence, should present rather stable time patterns during the day when W and ρ_0 vary slowly with time.

Some examples of the time pattern of the intercept a are shown in Fig. 5 for a short period of 90 min during the morning. The measurements of W were made with a spectral hygrometer every 20 s, while temperature and relative humidity were measured continuously by a thermo-hygrograph. From these data, the intercept a was evaluated according to Eq. (14). As can be seen in Fig. 5, the parameter a does not present sudden and wide fluctuations but varies with rather stable features although the measurements refer to a daytime period which is characterized by atmospheric conditions of intense vertical mixing due to the strong heating of the ground by the sun.

Fig. 6 shows some time-patterns of the intercept a for a daytime period of ~8 h. They were obtained from measurements of W taken with a spectral hygrometer every 15 min and from measurements of the dew point T_d made with the thermo-hygrograph. These measurements show that the intercept a can vary largely during the day through features which vary gradually. The increase of a during the morning is due to the increment of W by evaporation combined with rather stable conditions of the absolute humidity at the ground.

The time-patterns of a and of the total precipitable water are shown in Fig. 7 for a period of eighteen days. The evaluations of W were obtained from the radiosonde data taken from the Milan station at 0000 and at 1200 GMT, during the period from 10 December 1972 to 27 December 1972. The corresponding estimates of the intercept a were made using Eq. (14). During the days characterized by conditions of marked thermal inversion in which the absolute humidity assumes rather stable values at the ground, the time patterns of a and of W present similar features. For most of these days, the intercept a is subjected to modifications smaller than 0.15 from one sounding to the next. Only in a few cases, does the intercept vary by more than 0.30 over a time interval of 12 h.

5. A method for determining the total precipitable water by night

Correct measurements of the total precipitable water can be obtained with a spectral hygrometer using the infrared spectrum of the sun, for solar elevations ⩾10°. A spectral hygrometer can then be used only for a limited period of the day. On the other hand, the determination of the total precipitable water is of great usefulness during the night when measurements of atmospheric and extraterrestrial radiation are made in the infrared and/or in the centimeter wavelength range. Moreover, nocturnal estimates of precipitable water can be very useful for meteorological and climatological studies.

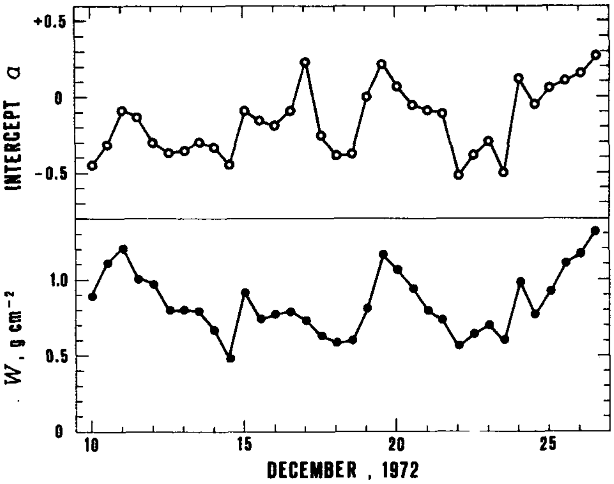

FIG. 7. Time patterns of the intercept a and of the total precipitable water W, as obtained from radiosonde data taken from the Milan station at 0000 and at 1200 GMT, over the period of 18 days from 10 December to 27 December 1972.

As pointed out in a previous section, the intercept a of Reitan's relationship is closely related to the thermal and moisture features of the low atmosphere. We can note that measurements, such as those shown in Fig. 6, indicate that the intercept varies rather regularly during the day and does not produce sudden fluctuations during the periods of strong vertical mixing through the lower layers of the atmosphere. Considering that the nocturnal evolution of the thermal structure of the low atmosphere is mainly regulated by the gradual processes of radiative cooling, it appears realistic to assume that the intercept varies slowly with time, with a nearly constant rate from sunset to sunrise. In this view, the nocturnal time pattern of the intercept can be described, with a good approximation, by the linear interpolation in time between a certain value of the intercept measured using a spectral hygrometer in the afternoon before the sunset and another value appropriately measured early next morning.

This simple procedure should give realistic estimates of the intercept during the night. Thus, reliable evaluations of the total precipitable water can be obtained during the night, at any time, from the equation

$$\ln W = a + 0.068\, T_d, \qquad (15)$$

using the interpolated values of the intercept a

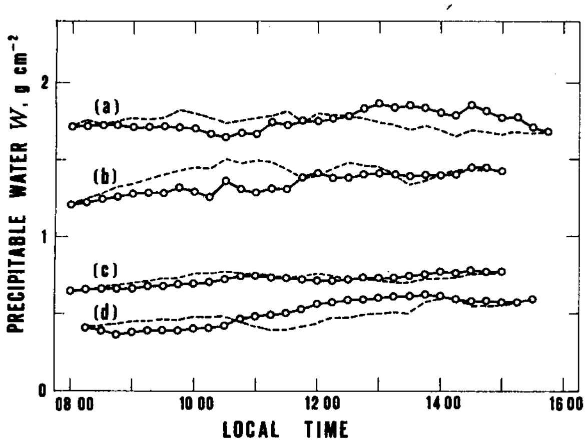

FIG. 8. Time patterns of the total precipitable water W for four days characterized by clear-sky conditions: (a) 22 September 1971; (b) 2 October 1971; (c) 7 October 1971; (d) 19 December 1972. Open circles are measurements of W made with an infrared hygrometer. The dashed curves represent the time-patterns of W, as obtained with the procedure based on the interpolation in time of the intercept a for periods of several hours.

together with the contemporaneous measurements of the dew point T_d at the ground. This procedure is very similar to that proposed by Tomasi (1978) based on the use of the inverse of H or of the absolute humidity at the ground as basic parameters. Since the daytime time patterns of the intercept show generally regular features, the present procedure can be applied also to time intervals of several hours when the spectral hygrometer is employed to give occasional readings of the total precipitable water.

Spectral hygrometer measurements of W were used to verify the reliability of the present method interpolating the intercept in time. The time patterns of the total precipitable water for four days are shown in Fig. 8, as obtained from spectral hygrometer measurements taken every 15 minutes. Measurements of precipitable water W also were calculated using the above procedure. The data were analyzed as follows: (i) for each day, the first and the last reading of W given by the spectral hygrometer and the contemporary dew-point temperatures obtained from the thermo-hygrograph data were used in Eq. (14) to evaluate the intercept a; (ii) the time pattern of the intercept a was determined for each day by linear interpolation in time between the two estimates of a, as found in (i); (iii) the interpolated values of the intercept were used in Eq. (15) together with simultaneous evaluations of the dew point T_d, as obtained from the thermo-hygrograph data, to determine the total precipitable water.

These time patterns of W are compared in Fig. 8 with those measured with the spectral hygrometer. As can be seen, the calculated values of W differ from those simultaneously measured by the infrared hygrometer by no more than 24%. For half of the cases, the relative differences between calculated and measured values of W vary between -6 and $+4\%$.

This test is necessarily made for daytime time intervals in which the ground heating by the sun causes more rapid and unstable changes of the moisture features of the low atmosphere than those produced by the slow processes of nocturnal radiative cooling. Since the agreement between measured and calculated values of W is satisfactory, the present procedure appears to be suitable for giving realistic and correct results when applied to night periods.

6. Determination of *W* from distant measurements of the intercept

Similar extensive meteorological and climatological conditions often involve the whole area of the Po Valley, in various periods of the year. Strong ground inversions of the temperature take place during winter and autumn periods when the region is characterized by anticyclonic conditions. They are frequently associated with marked subsidence inversions at altitudes ranging between 1 and 2 km which give stable conditions of the low troposphere which can last for many days. In other periods of the year, stable conditions are formed in the lower layers of the atmosphere by night and vanish gradually during the morning, as a consequence of the ground heating by the sun. In these cases, common features of the vertical moisture profile of the low atmosphere can be present over a wide region so that similar values of the total precipitable water, absolute humidity and temperature at the ground can be found at the different sites. For these extensive and uniform conditions, nearly equal values of Reitan's intercept should be found in any locality of the Po Valley. In this view, the intercept a evaluated from the radiosonde data taken from the Milan station can be assumed representative of the whole area.

Therefore, estimates of the total precipitable water can be made from Eq. (15) using local measurements of the dew point T_d and contemporary estimates of the intercept obtained from the radiosonde data taken from the Milan station. This procedure was applied to three sets of thermo-hygrograph measurements at the ground and the results were compared with the simultaneous measurements of the total precipitable water made with an infrared hygrometer (Tomasi and Guzzi, 1974):

1) Set A consists of data taken in autumn 1971 at Buda (10 m MSL) which is 25 km northeast of Bologna. Three measurements of W (made at 0800, 1200 and 1600 LT) were taken for each day. Only

for a few days, was a single measurement used for the comparison.

2) Set B concerns measurements taken during the winter periods of the years 1973 and 1974, at Bologna (35 m MSL), which is about 200 km southeast of the Milan station.

3)Set C refers to measurements made during the summer of 1973 at Bologna, at 1200 and 1600 LT of each day.

The data were analyzed as follows: (i) simultaneously to each measurement of W made with the infrared hygrometer, the dew point T_d was calculated from the data of temperature and of relative humidity recorded by the thermo-hygrograph at ground level; (ii) the radiosonde data taken from Milan station were used to evaluate the total precipitable water and the surface dew point at 0000, 1200 and 2400 GMT of each measurement day; from these data, the corresponding estimates of the intercept a were obtained through Eq. (14); (iii) for each spectral hygrometer measurement of W, the simultaneous value of the intercept a was evaluated by linear interpolation in time between the estimates of the intercept found in (ii); (iv) for each measured value of W, the simultaneous estimate of the intercept a made in (iii) and the simultaneous value of T_d, as obtained in (i), were used to calculate the total precipitable water from Eq. (15).

The comparison between the measured values of W and those calculated with the procedure described above based on remote estimates of the intercept is shown in Fig. 9 for the set A of data and in Fig. 10 for sets B and C. The agreement is very good for sets A and B. In fact, the average value of the differences between calculated and measured values of W turns out to be of 0.06 and 0.08 g cm^{-2} for sets A and B, respectively, whereas the corresponding standard deviations are of 0.18 and of 0.14 g cm^{-2}. Sets A and B consist of data taken mostly in atmospheres characterized by marked temperature inversion near the ground. For most of these days the temperature and relative humidity conditions observed at Milan are very similar to those measured at the stations of Buda (set A) and of Bologna (set B). This means that the values of the height H and of the intercept a do not present large variations between the two remote stations of the Po Valley as a result of similar or equivalent features of the vertical distribution curve of water vapor.

Large differences between calculated and measured values of W are found for the set C which involve data taken on summer days frequently characterized by sultry weather conditions at the ground. The temperature at Bologna generally exceeded that observed simultaneously at the Milan station by a few degrees Celsius. The relative humidity conditions were very similar so that smaller values of the absolute humidity were measured at the Milan station. Appreciably smaller values of the scale height H and of the total precipitable water W were found at the Milan station during these observations. These discrepancies suggest that a thicker layer of warm and humid air was present above the Bologna station probably as a result of the stronger heating of the ground by the sun. In this regard, it can be noticed that the effects produced by insolation on the vertical distribution of water vapor are often cited as important causes of the wider variability of Reitan's parameters during the summer months (Schwarz, 1968; Lowry and Glahn, 1969; Glahn, 1973).

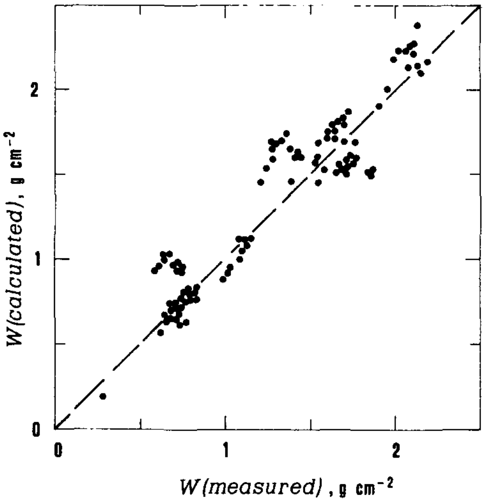

FIG. 9. Comparison between measured and calculated values of the total precipitable water W pertinent to set A. The measured values were taken with an infrared hygrometer on several days in autumn 1971, at Buda near Bologna (Po Valley). The calculated values are obtained from Eq. (15) using the values of T_d measured simultaneously at Buda together with the contemporaneous estimates of the intercept a made on the basis of the radiosonde data taken from the Milan station. The differences between calculated and measured values of W give the average value of 0.06 g cm^{-2} with the standard deviation of 0.18 g cm^{-2}.

7. Conclusions

Doubts have been expressed by Reber and Swope (1972) on the reliable use of relationships of Reitan's type for determining the total precipitable water on an individual observational basis, at any time of day or night, as required when conducting scientific measurements. There can be no question, as pointed out by Glahn (1973), that the study of the absorption processes due to the atmospheric water vapor needs accurate measurements of the total precipitable water performed at the same time as the attenuation

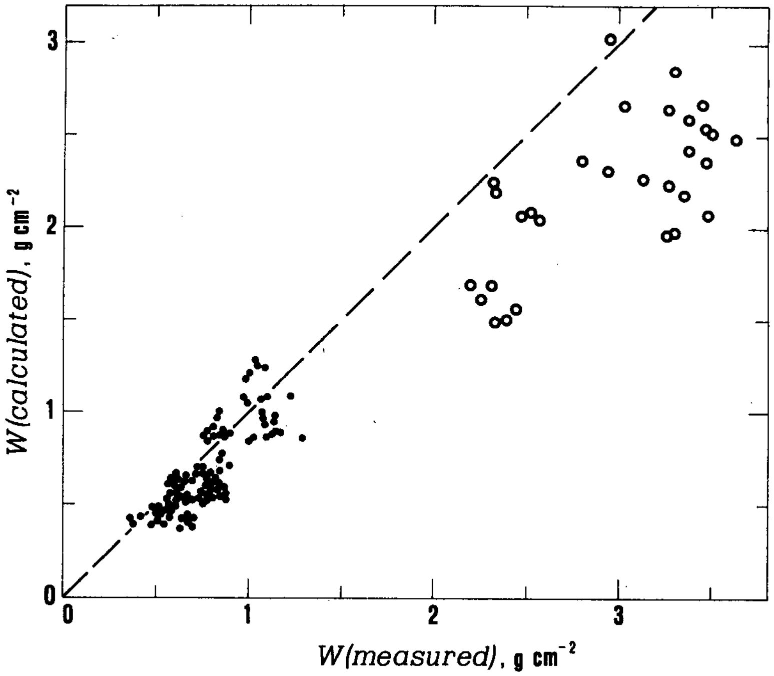

FIG. 10. As in Fig. 9 for sets B and C. Solid circles refer to set B of measurements performed in winter 1973, at Bologna (Po Valley). The average value of the differences between calculated and measured values of W is of -0.08 g cm^{-2} with the standard deviation of 0.14 g cm^{-2}. Open circles concern set C which consists of data taken in summer 1973 at Bologna. The average value of the differences between calculated and measured values of W is of -0.74 g cm^{-2} with the standard deviation of 0.37 g cm^{-2}.

measurements. For this purpose, an infrared hygrometer, such as that designed in our laboratory, gives excellent results. This instrument is based on measurements of direct radiation from the sun so that it can be used only during a limited period of the day. On the other hand, many astronomical observations are performed during the night. Based on the linear interpolation in time of the intercept, the present procedure can give precise evaluations of the total precipitable water with an accuracy comparable with that provided by the radiosonde data. Therefore, Reitan's relationship can be of great usefulness in scientific observations.

The other application of Reitan's relationship is based on measurements of the intercept taken in a remote site. This procedure can be conveniently adopted for areas characterized by uniform features of the meteorological parameters and by homogeneous geographical conditions. Thus, the linear interpolation of the intercept, both in time and in the geographical coordinates, could be applied to the estimates of the intercept given by the radiosonde data of remote stations for describing the evolutionary features of the total precipitable water in a certain region. This procedure could be very useful for meteorological and climatological studies.

Acknowledgments. This research has been carried out in the frame of the Programma Finalizzato "Promozione della Qualità dell'Ambiente" (Subprogetto Aria) sponsored by the Consiglio Nazionale delle Ricerche.

REFERENCES

Berkofsky, L., 1967: Comments on "Note on the relationship between total precipitable water and surface dew point." *J. Appl. Meteor.*, **6**, 959–960.

——, 1968: Further comments on "Note on the relationship between total precipitable water and surface dew point." *J. Appl. Meteor.*, **7**, 719.

Bolsenga, S. J., 1965: The relationship between total atmospheric water vapor and surface dew point on a mean daily and hourly basis. *J. Appl. Meteor.*, **4**, 430–432.

Glahn, H. R., 1973: Comments "On the correlation of the total precipitable water in a vertical column and absolute humidity at the surface." *J. Appl. Meteor.*, **12**, 1411–1414.

King, R. L., and H. D. Parry, 1965: Field tests and calibration of the total atmospheric water vapor hygrometer. *Humidity and Moisture, Applications*, A. Wexler, Ed., Reinhold, 450–457.

Lowry, D. A., and H. R. Glahn, 1969: Relationship between integrated atmospheric moisture and surface weather. *J. Appl. Meteor.*, **8**, 762–768.

McGee, O. S., 1974: Surface dewpoint: precipitable water vapour relationship for South Africa. *S. Afr. J. Sci.*, **70**, 119–120.

Reber, E. E., and J. R. Swope, 1972: On the correlation of the total precipitable water in a vertical column and absolute humidity at the surface. *J. Appl. Meteor.*, **11**, 1322–1325.

Reitan, C. H., 1963: Surface dew point and water vapor aloft. *J. Appl. Meteor.*, **2**, 776–779.

Schwarz, F. K., 1968: Comments on "Note on the relationship between total precipitable water and surface dew point, *J. Appl. Meteor.*, **7**, 509–510.

Smith, W. L., 1966: Note on the relationship between total precipitable water and surface dew point. *J. Appl. Meteor.*, **5**, 726–727.

——, 1967: Reply. *J. Appl. Meteor.*, **6**, 960–961.

——, 1968: Reply. *J. Appl. Meteor.*, **7**, 510.

Tetens, O., 1930: Über einige meteorologische Begriffe. *Z. Geophys.*, **6**, 297–309.

Tomasi, C., 1977: Precipitable water vapor in atmospheres characterized by temperature inversions. *J. Appl. Meteor.*, **16**, 237–243.

——, 1978: Interpolation methods for estimating atmospheric precipitable water vapour during the night from surface meteorological data and using diurnal infrared hygrometer measurements. *Mem. Soc. Astron. Ital.*, **49**, 119–125.

——, and R. Guzzi, 1974: High precision atmospheric hygrometry using the solar infrared spectrum. *J. Sci. Instrum.*, **7**, 647–649.