Int. Agrophysics, 2000, 14, 279-289

MEASURING WIND GRADIENTS IN AGROFORESTRY SYSTEMS BY SHADED PICHE EVAPORIMETERS I. VALIDATION OF THE SQUARE-ROOT DEPENDENCE ON WIND SPEED

R.M.R. Kainkwa[1], *C.J. Stigter*[2]

[1]TTMI-Project, Agricultural Physics Research Group, Physics Department, University of Dar es Salaam
P.O. Box 35063, Dar es Salaam, Tanzania
[2]TTMI-Project, Department of Environmental Sciences, Wageningen University, Duivendaal 2, 6701 AP
Wageningen, Netherlands

Accepted January 3, 2000

Abstract. There is a general need for cheap and simple but physically well understood equipment for multi-point field use in quantifying and understanding the tropical agricultural environment. Performance of shaded Piche evaporimeters in agroforest environments was investigated. Piche atmometers shielded at the upper side from solar radiation closely followed a model of square root of wind speed dependence of their evaporation, provided that its sensitivity to temperature and humidity variations and to differences in turbulence is borne in mind. During periods when gradients of air temperature and air humidity are small, data sets for at least several hours are recommended at sites with very low wind speeds. Length of measuring periods is not a limitation at sites and times with high wind speeds, when wind speed ranges are not too small.

Keywords: agroforest systems, anemometry, cup anemometer, Piche evaporimeter, wind reduction

INTRODUCTION

Capacity building for agrometeorology in developing countries must grow jointly with a general increase of the application of physical sciences to agriculture and environment [13]. The use of physics in agricultural research requires a high degree of dexterity in experimental physics, not any less in outdoor experiments [18]. Quantification of the tropical agricultural environment necessary to understand growth conditions and yields, very often requires to be multi-point studies done under difficult heterogeneous conditions as experienced in agroforestry and other multiple on-farm cropping [2,3].

Examples from our work on studying the physics and field use of relatively simple instruments in outdoor conditions as well as on their calibrations may be found in [4-6,10-12, 17,19,23-26]. In this paper, consisting of two parts, we report, firstly on field tests in Tanzania carried out on the basic formula derived earlier indoors and in meteorological screens for the relation between evaporation as measured on the Piche evaporimeter, and wind speed. Subsequently, we present results of the field use of the shaded Piche for the interpolation and extrapolation of wind speed measured with electrical cup anemometers at a limited number of places in four African countries.

MATERIALS

Instrumentation

Twelve sensitive electrical cup anemometers with a solar powered data logger and an Epson portable computer for data processing (the full system designed with the Bottemanne Weather Instruments, Netherlands) were used as the main wind speed indicators. Mechanical

Woelfle anemographs (Lambrecht Measuring Instruments, Germany) were also used, basically to follow wind direction and as a backing up system. The anemometers were wind tunnels calibrated by the manufacturers but also compared in a homogeneous wind field at a near horizontal site on the shores of the Indian Ocean near Dar es Salaam. The electrical cup anemometers compared very well, within ± 2%, as was expected. Re-comparison was periodically done at the experimental sites before and after the measuring season. The instruments kept their accuracies throughout. The Woelfle anemographs read about 10% higher, with occasionally high standard deviations, which is largely due to the differences in their design, that made dynamic behaviour of the cups in turbulent wind very different [7]. Similar results were independently obtained in [9,14,15].

Piche evaporimeters from Casella (UK) and Lambrecht (Germany) were used. Their descriptions can be found in [7,26]. The lower end of the glass tube, holding a 3 cm diameter standard blotting paper, is in our design protected from rain and solar radiation by a circular plate of the 25 cm diameter. The plate is constructed of 2 cm of tempex sandwiched between two plates of 2.5 mm of wood, with a hole at the centre of 1.4 cm, through which the tube is protruding. The distance between blotting paper and plate was fixed as 7 cm, but may vary between 5 and 10 cm without any loss of accuracy [5]. The shade is fixed to an arm used to mount the shield system on a vertical mast. The upper surface of the plate is glued with highly reflective aluminized Mylar (polyester, with high long wave radiation emission coefficient) strips used for reaching the lowest temperature under direct radiation (e.g., [28]). The surface of the plate facing the soil was painted dully white, but differences in the performance with lower plates painted white or black were found to be negligible under high solar radiation [5]. All of the glass tubes protruding from the upper surface of the screen was protected by an aluminized Mylar covered insulating tube, but no performance differences were found when this protection was taken off [5].

It is also important to give a short account of the earlier published results of the experiments that were set up to consider the possible influence of the circular shade plate on the air movement around the blotting paper [5]. Three shades were used in a long term field comparison in Sudan, one of 1m by 1 m, one of 50 cm by 50 cm and the 25 cm round shade. The larger distances of the two larger shades from the blotting paper were chosen in such a way that the shade cast on the blotting paper over the day was comparable to that of the 25 cm round shade at a distance between 5 and 10 cm from the blotting paper. Over long as well as short periods the differences in Piche evaporation from the differently shaded instruments were within the accuracy limits determined for the round shade. Because of the large distance between the 1 m by 1 m shade and the blotting paper, any influence of that shade on the air movement pattern around the evaporating surface can be ruled out. This showed that also the round 25 cm shade plate has no other influence on the evaporation of the Piche than through the provision of its shade, changing the energy balance of the blotting paper in such a way that it can be used as an ancillary isothermal anemometer [5].

Layout of the instruments

In the agroforest system with coffee with shade trees in Lyamungu, Tanzania, each electrical cup anemometer was twinned with a shaded Piche, on one mast in the opposite direction and perpendicular to the prevailing wind direction, making 12 such pairs. Distance between the centre of the blotting paper and the rotation centre of the cup was in the order of 0.5 m. Two pairs were installed over the open terrain as references, three pairs over grass land behind trees, and the remaining seven at different positions above the coffee plot, as in Fig. 1.

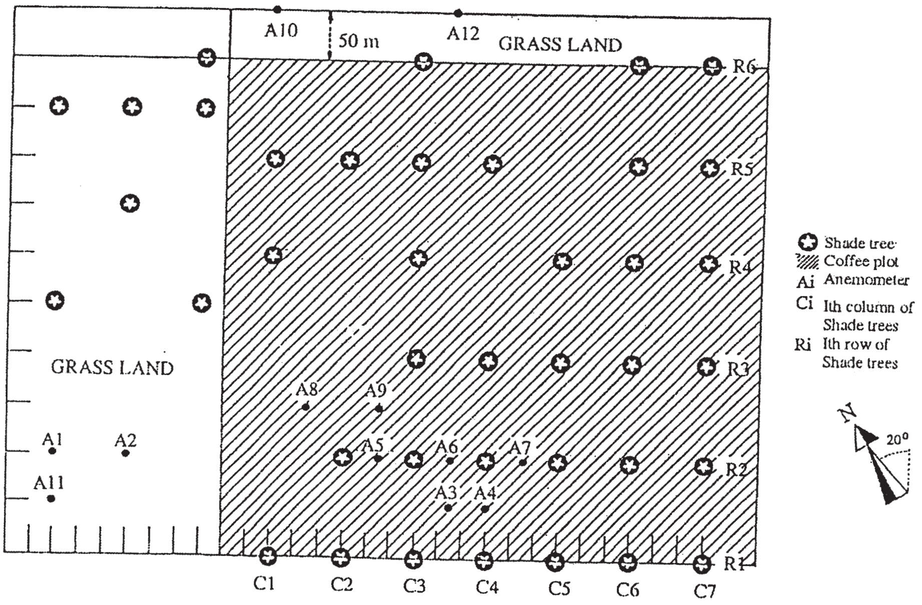

Fig. 1. Layout of the instrument positions in the north-west of the 4 ha experimental coffee cum shade trees agroforest system (shaded area) in Lyamungu, Tanzania [7]. Anemometers were at 20 cm above the highest coffee. The crown structure of the about 50 m tall trees (*Albizia schimperiana*) was of umbrella shape with an average crown diameter of 10 m and an average bare stem height of 10 m. The 50 m in the grass land are not to scale. The prevailing winds were from the north-east.

At the savanna woodland site in Setchet, Tanzania, six masts were used, while two pairs of the anemometers were installed on one mast. One was positioned at 2.5 m height, while the other pair was at 1.0 m. The anemometers were again mounted in the opposite directions from the mast and perpendicular to the prevailing wind field. One mast was installed in front of the woodland and the remaining five in turn on lines P1 till P8, in positions L1 till L5 perpendicular to the prevailing wind direction (Fig. 2). The masts forming these lines were at most 15 m apart. For a more detailed description of the woodland vegetation and other details, see [7,8,22].

Theory

From laminar drag considerations about flat discs, Thom *et al.* [29] suggested that Piche evaporation should be proportional to the square root of the wind speed. Simultaneously, a long series of experiments performed with fans indoors and in Stevenson screens outdoors in Tanzania [26,30] proved this to be true for such conditions, when wind directions were close to unilateral. The physics behind it supported the validity of this dependence of Piche evaporation on the square root of the wind speed [26,30]. Criticism could easily be redressed [27] and earlier findings of non-validity for the Stevenson's screens [29] could be understood from the changing wind directions and air flow patterns [26]. However, these conditions do not necessarily apply to the field conditions in crop or tree canopies with turbulent wind in the open and this was suggested as calling for an independent verification [26,30].

Wind speed U (m s^{-1}) under pure forced convection mass transfer conditions in the horizontal flow was proved to be related to the Piche evaporation rate, E_p, here in kg s^{-1}, by the expression [30]:

$$E_p = 6 \cdot 10^{-6} U^{0.5} (e_s/T_s - e_a/T_a) \qquad (1)$$

where e_s and e_a are saturated and partial water vapour pressures (hPa) averaged at the evaporating surface and in bulk air respectively,

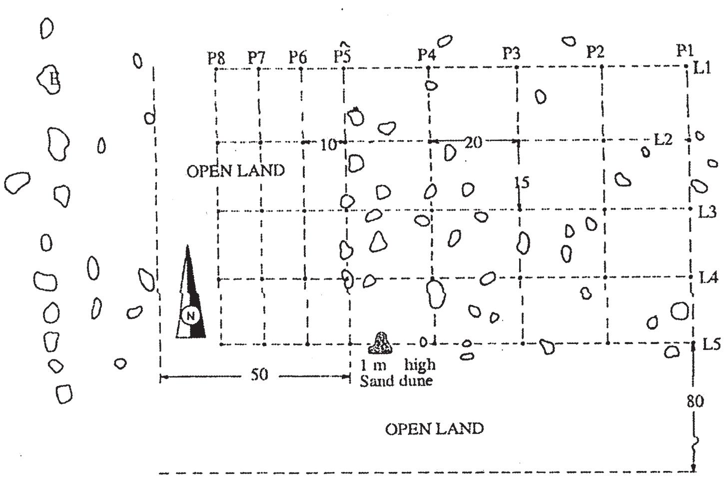

Fig. 2. Layout of the instrument positions in the edge area of a savanna woodland suffering from the tree falling at Setchet, Tanzania [7,8]. Measurements were taken at the heights of 1.0 and 2.5 m. The prevailing winds during the measurement taking were from the east. The projected tree crowns show density of this, now rather open woodland used for grazing. P1 to P8 give the measuring lines with the positions L1 to L5 for each measuring series in Table 3. The anemometer windward of the edge is not shown.

and T_s and T_a are temperatures (K) averaged at the evaporating surface and in the bulk air. Equation (1) shows that surface temperature (distribution) and related saturated vapour pressure (distribution) are involved. These facts are unknown but were proved to be related to air temperature and air saturation deficit in a certain way under the indoor and the Stevenson's screen experimental conditions [27], but these distributions may well be different under turbulence in canopies [26,30]. Its use in anemometry should therefore initially be limited to the conditions in which e_s/T_s - e_a/T_a is conservative. Under such restrictions, E_p can simply be related to U by the expression:

$$E_p = \mathrm{b}\, U^{0.5} + \mathrm{a} \qquad (2)$$

where b and a are correlation constants with a close to zero.

This simple model, the square root of mean wind speed relation, was now validated by the data from the two agroforest systems mentioned above, under conditions in which temperature and air humidity could be assumed to be fairly constant or to change rather simultaneously. Turbulence variation of wind between the (quite close) measuring points may also add some inaccuracy when correlating data collected from the two types of instruments. Air flow in canopies is characterised by gusts. Whether during or between gusts turbulence spectra differ much between the two places compared is difficult to say. We know that the turbulence structure depends explicitly on the roughness details of the surface arrays, because of the spatially distributed pattern of momentum absorption [20]. Moreover, the electric anemometer measures all the components at an angle with the horizontal ones of about 45 degrees or less and will have another time constant than the Piche that basically measures consequences of all components reaching it. Adding to this the influence of free convection components, below about 0.75 m s^{-1} wind speed [26,29], gives us enough reason to carry out field tests such as the tests in the two agroforest canopies. One example included below (Table 3(ii)) was recently given in a synopsis [21].

RESULTS

In Lyamungu 31 data sets were collected and 8 data sets in Setchet. Each set in Lyamungu had 12 data points corresponding to the 12 pairs of sensors installed. The 8 data sets at Setchet were further divided into those collected at 2.5 and 1.0 m height. For all these runs, regression parameters of Eq. (2) were calculated and the results are in Tables 1 and 2 for Lyamungu and in Table 3 for Setchet, respectively. Details are given in the legend for Table 1.

DISCUSSION

Lyamungu

Runs A, C, D and E (runs not mentioned were incomplete) in Table 1 were the runs for nearly a day or more. The minimum average half-hourly wind speed was well over 0.6 m s^{-1}, and in three cases even near or above 0.75 m s^{-1}. The maximum was higher than 1.1 m s^{-1}, and in three cases even over 1.3 m s^{-1}. Correlation coefficients for the linear regression between Piche evaporation and the square root of mean wind speed from the cup anemometers were 0.95 or higher in all these cases.

The inclusion of (0,0) as a measuring point increases this to 0.98 and higher. In this case, a virtual measuring point of zero evaporation at zero wind speed was added to the actual measuring points and the regression was calculated again. We argue in favour of inclusion of this point since even if there is only a temperature difference at the lower side of the blotting paper, it leads to free convection vapour losses at zero wind speed. However, in the conditions of Lyamungu, at actual zero wind speed also the relative humidity will have become so high that evaporation virtually stops.

Only set G, which was a run for a period of about 4 days, had a poorer correlation. This is very likely due to long periods with low wind speeds, with the maximum below 1.0 m s^{-1} and the minimum close to only 0.5 m s^{-1}. The limit for influence of free convection, for which the square root of wind speed dependence does not hold [19], is usually taken at 0.75 m s^{-1}, as explained earlier. There was also a day with 23 mm of rainfall, the highest within these sets of data, and this may also have spoiled the correlation.

Table 2a collects 11 short periods, of 3 to 4 h, with the minimum half hourly wind speed of above 0.5 m s^{-1}. For 9 of these runs the correlation is 0.92 or higher, improving to 0.97 or higher with the zero point (0,0) included. Run C26 has for no obvious reasons a rather high EX value and a lower correlation, of 0.81, that improves to 0.93 when including the zero. For run C4, EX and EY are exceptionally large,

Table 1. Linear regressions of the comparisons between the wind speed determined by the electrical cup anemometers and Piche evaporation. For each of the runs, a is the Y-intercept, b is the slope of the line, r is the correlation coefficient, *h* is the run period in hours, U_{ma} and U_{mi} are the maximum and minimum half hourly average wind speeds for the total run period, E_p(av) is the average Piche evaporation in mm h^{-1} over that period, n is the number of data points, EY is the standard error of the Y estimate and EX is the standard error of X. Values in the second line are regression data where the point (0,0) was added as a measuring point. Anemometer positions are in Fig. 1 and (for runs P1 till P8) in Fig. 2. The Table is for Lyamungu in January and for periods of nearly a day or more. In this period there were 6.6, 1.5, 1.0, 14 and 23 mm of rain in the respective periods A, C, D, E and G

Run	a	b	U_{ma}	U_{mi}	E_p(av)	r	*h*	n	EX	EY
A	-1.53	3.97	1.36	0.87	2.58	0.99	44.0	10	0.20	0.06
	-0.13	2.60				0.98			0.15	0.06
C	-0.29	2.03	1.32	0.74	1.69	0.95	47.5	12	0.21	0.08
	-0.04	1.78				0.99			0.08	0.08
D	-0.62	2.50	1.36	0.79	1.91	0.98	23.5	12	0.17	0.07
	-0.09	1.98				0.99			0.09	0.10
E	-0.21	1.71	1.11	0.64	1.35	0.96	95.5	12	0.15	0.05
	-0.03	1.52				0.99			0.06	0.06
G	-0.13	1.14	0.95	0.53	0.83	0.84	95.5	12	0.23	0.08
	-0.02	1.01				0.96			0.09	0.08

T a b l e 2. Linear regressions as in Table 1, for Lyamungu but in November, for the two series of runs, with the minimum average wind speed of above (Table 2a) and below (Table 2b) 0.5 ms^{-1}, respectively. Runs C4, C7, C11, C15, C19, C23, C27, C31 and C35 were taken from 15-18 h; C5, C9, C21, C25 and C33 from 07-11 h; C3, C6, C10, C14, C22, C26, C30 and C34 from 11-15 h and C1, C28 and C32 from 18-07 h

(2a)

Run	a	b	U_{ma}	U_{mi}	E_p(av)	r	h	n	EX	EY
C3	-0.97	4.54	1.62	0.64	3.82	0.98	4	11	0.29	0.17
	-0.23	3.86				0.99			0.19	0.22
C4	-0.84	2.80	1.71	0.66	2.22	0.64	3	11	1.11	0.71
	-0.21	2.24				0.78			0.56	0.69
C6	-0.34	3.55	1.94	0.85	3.71	0.93	4	12	0.46	0.20
	-0.21	3.36				0.98			0.18	0.22
C7	-0.84	4.03	1.78	0.73	3.58	0.98	3	12	0.29	0.18
	-0.19	3.46				0.99			0.17	0.21
C10	-0.67	2.93	1.38	0.54	2.17	0.98	4	12	0.20	0.11
	-0.17	2.43				0.98			0.14	0.15
C14	-0.23	2.70	1.65	0.54	2.54	0.96	4	12	0.25	0.17
	-0.07	2.55				0.99			0.14	0.17
C15	0.24	2.57	1.88	0.56	3.03	0.92	3	12	0.35	0.27
	0.08	2.71				0.97			0.20	0.26
C22	-0.06	3.19	1.73	0.52	3.25	0.99	4	11	0.19	0.11
	-0.01	3.15				1.00			0.09	0.11
C26	-0.41	2.44	1.68	0.75	2.29	0.81	4	12	0.56	0.31
	-0.08	2.15				0.93			0.25	0.30
C27	0.57	3.47	1.72	0.52	4.25	0.94	3	12	0.39	0.24
	0.14	3.86				0.98			0.21	0.24
C30	-0.10	3.72	1.46	0.55	3.65	0.93	4	12	0.48	0.26
	-0.02	3.64				0.98			0.22	0.25

(2b)

C1	0.28	0.64	0.89	0.17	0.72	0.67	13	12	0.22	0.13
	0.12	0.86				0.86			0.15	0.14
C5	0.23	0.56	1.16	0.36	0.69	0.65	4	12	0.20	0.12
	0.08	0.73				0.87			0.12	0.12
C9	-1.06	2.24	1.00	0.29	0.71	0.92	3.5	12	0.31	0.16
	-0.32	1.35				0.85			0.25	0.23
C11	0.00	2.73	1.31	0.37	2.47	0.97	3	12	0.21	0.15
	0.00	2.73				0.99			0.13	0.14
C18	-0.19	3.43	1.02	0.38	2.73	0.91	4	11	0.52	0.23
	-0.04	3.26				0.97			0.24	0.22
C19	0.45	2.56	0.93	0.24	2.39	0.92	3	12	0.34	0.20
	0.16	2.92				0.97			0.22	0.20
C21	0.12	1.86	1.31	0.36	1.78	0.86	3	12	0.36	0.24
	0.04	1.94				0.94			0.21	0.23
C23	0.20	3.68	1.67	0.48	4.06	0.95	3	12	0.40	0.23
	0.05	3.82				0.99			0.19	0.22
C25	-0.20	0.95	0.76	0.15	0.43	0.84	4	11	0.20	0.11
	-0.08	0.78				0.88			0.14	0.11
C28	-0.01	0.89	0.80	0.23	0.61	0.71	13	12	0.28	0.15
	0.00	0.88				0.84			0.17	0.15

Table 2. Continuation

Run	a	b	U_{ma}	U_{mi}	E_p(av)	r	*h*	n	EX	EY
C31	0.97	3.83	1.32	0.40	4.50	0.88	3	12	0.65	0.37
	0.26	4.57				0.97			0.37	0.38
C32	0.21	0.82	0.85	0.22	0.80	0.94	13	12	0.10	0.06
	0.08	1.00				0.97			0.07	0.07
C33	-0.02	1.24	0.84	0.20	0.92	0.87	4	12	0.23	0.12
	-0.01	1.23				0.95			0.13	0.11
C34	0.66	3.49	1.40	0.44	4.04	0.93	3	12	0.43	0.24
	0.16	3.98				0.98			0.23	0.25
C35	1.13	2.74	1.27	0.37	3.61	0.85	3	12	0.53	0.33
	0.35	3.57				0.95			0.35	0.37

which is most likely due to an error in data collection.

The 15 remaining runs of short duration, now also including three runs of 13 h, have all the minimum half hourly wind speeds below 0.5 m s^{-1}, but this does not necessarily lead to low correlations (Table 2b). Almost half (7) of these periods give a correlation above 0.9 and 5 more between 0.84 and 0.88, while only 3 have a really bad correlation, between 0.65 and 0.71. Two of those latter 3 periods are of 13 h, have the maximum wind speed of hardly above 0.75 m s^{-1} and were taken at night. The tird one and three of the five other relatively low correlations were obtained between 7 and 11 h. In half of these cases wind speeds were extremely low. Low windspeeds in daytime as such are not always a sufficient reason for bad correlations, pointing to favourable wind speeds distributions and other mechanisms at work around both types of anemometers that influence the data. All the correlations but one (C28) improve to 0.85 or higher with the zero included, with 10 of 0.94 or higher. Also these results are in favour of the validity of the square root of the wind speed dependence of Piche evaporation.

It appears that b in Eq. (2) is indeed far from conservative under our experimental conditions of Lyamungu. From the comparison of the January and November data, it may also be observed that on the average longer periods, not only night periods, have higher correlations. This confirms our earlier results [26] and our results obtained with the use of the Piche to replace the aerodynamic term of the Penman evaporation equation [1,5].

Setchet

The data obtained in Setchet, as shown in Tables 3(i)-3(iii), are characterised by an extreme scatter of a-values and by inequality of b-values simultaneously found at different heights. This is extreme for the worst measuring series, P2/P21/P22, after the first interaction of the wind with the tree biomass took place. A general (but not overall) improvement in the correlations is obtained by separating the data for the two heights (Tables 3(ii) and 3(iii)). In general, the wind structure of the horizontal winds must be different at the two heights, due to tunnelling at 1.0 m height (higher wind speeds than at 2.5 m height) and differences in turbulence, due to the differences in accumulating interaction with the biomass of the tree crowns/canopy. It is shown by the Setchet data that the correlation is 0.9 or higher in the first row, P1/P11/P12, when little or no interaction with the trees took place (Fig. 2). It worsens for P2/P21/P22, improves for P3 at 2.5 m (P32) but worsens for P3 at 1.0 m (P31), then is better for P41 (0.93) than for P42 (0.81). It becomes very high (0.96 and higher) for the remaining lines P5, P6, P7 and P8 for 2.5 m height, when the wind reduction saturated [8], but is lower (0.85 for P81 but more than 0.9 for the others) at 1.0 m, where saturation occured deeper into the woodland [8].

T a b l e 3. Linear regressions as in Table 1, but for Setchet, in October. The longer runs (h>13) were taken overnight while the other runs were in daytime. In this Table, the first part (i) is for data points at the two heights together, while in the parts (ii) and (iii) the two heights were separated

Run	a	b	U_{ma}	U_{mi}	E_p(av)	r	h	n	EX	EY
(i) All twelve data points										
P1	2.06	2.16	7.45	4.44	7.16	0.91	16	12	0.31	0.18
	0.12	2.97				0.99			0.10	0.23
P2	10.34	-0.20	9.20	6.68	9.76	0.06	3.5	11	1.07	0.55
	0.33	3.29				0.97			0.28	0.78
P3	3.77	4.00	7.38	5.02	13.62	0.66	5	12	1.41	0.87
	0.22	5.43				0.98			0.36	0.87
P4	0.23	1.44	6.93	2.38	3.45	0.81	13.5	12	0.33	0.37
	0.05	1.52				0.95			0.15	0.35
P5	3.41	4.35	7.71	2.90	12.68	0.89	8	12	0.70	0.73
	0.65	5.62				0.98			0.36	0.82
P6	-0.46	2.24	5.98	2.06	4.09	0.95	13.5	12	0.23	0.27
	-0.11	2.08				0.98			0.12	0.27
P7	4.86	2.90	8.63	3.09	11.60	0.88	5	12	0.49	0.62
	1.10	4.47				0.97			0.36	0.92
P8	6.06	2.89	8.68	3.76	12.86	0.87	6.5	12	0.52	0.55
	1.00	5.00				0.97			0.36	0.91
(ii) Groups of six data points for 2.5 m height										
P12	0.25	2.95	6.29	5.40	7.44	0.90	16	6	0.73	0.12
	0.00	3.05				1.00			0.05	0.11
P22	-13.90	7.88	9.20	8.33	9.57	0.76	3.5	6	3.34	0.43
	-0.03	3.22				0.99			0.17	0.47
P32	-0.29	5.39	7.38	4.60	13.27	0.85	5	6	1.64	0.84
	-0.01	5.28				0.99			0.32	0.76
P42	0.23	1.36	6.93	2.38	3.21	0.81	13.5	6	0.49	0.46
	0.04	1.45				0.96			0.18	0.41
P52	-0.93	6.26	6.22	2.90	12.46	0.99	8	4	0.53	0.36
	-0.08	5.87				1.00			0.16	0.34
P62	-1.13	2.57	5.96	2.51	4.20	0.98	13.5	6	0.24	0.19
	-0.14	2.11				0.99			0.12	0.24
P72	0.98	4.46	7.76	3.85	11.60	0.98	5	6	0.49	0.37
	0.09	4.83				1.00			0.15	0.36
P82	2.96	4.22	7.59	4.43	13.08	0.96	6.5	6	0.63	0.38
	0.18	5.36				1.00			0.20	0.47
(iii) Groups of six data points for 1.0 m height										
P11	3.08	1.66	7.45	4.44	6.89	0.99	16	6	0.10	0.05
	0.14	2.93				0.99			0.14	0.30
P21	5.09	1.81	8.33	6.68	9.95	0.67	3.5	5	1.17	0.30
	0.05	3.66				1.00			0.14	0.35
P31	-0.89	1.90	6.82	5.02	13.97	0.59	5	6	1.31	0.37
	0.07	5.75				1.00			0.19	0.42
P41	0.50	1.41	6.79	4.35	3.69	0.93	13.5	6	0.28	0.17
	0.03	1.61				0.99			0.08	0.16

Table 3. Continuation

Run	a	b	U_{ma}	U_{mi}	E_p(av)	r	*h*	n	EX	EY
P51	6.37	3.08	7.71	3.15	12.90	0.91	8	6	0.71	0.57
	0.78	5.65				0.98			0.53	1.12
P61	0.06	1.41	5.98	2.06	3.98	0.93	13.5	6	0.28	0.34
	0.01	2.00				0.99			0.15	0.31
P71	6.85	2.09	8.63	3.09	11.60	0.91	5	6	0.48	0.48
	1.09	4.54				0.96			0.56	1.30
P81	7.68	2.15	8.68	3.76	12.64	0.85	6.5	6	0.66	0.56
	0.90	5.02				0.97			0.56	1.28

Narrow wind speed ranges contribute to the bad correlations for P21, P22 and P31. At the highest wind speeds, over about 7.5 m s^{-1}, also Piche vibrations were noted, which negatively influenced the correlations at P21, P22, P71 and P81. When including the (0,0) as a measuring point, correlations improve tremendously everywhere. The scatter in a-values decreases and a much better similarity in b-values is now found for the two heights. Even when the data at these heights are not separated, the lowest r is 0.95. Inclusion of the zero (0,0) is allowed for the Setchet data because with minimum half hourly average wind speed of over 2 m s^{-1}, only forced convection occurred. This would contribute nothing to the Piche evaporation when it becomes zero at zero wind speed.

CONCLUSIONS

The results obtained for the two experimental sites discussed above lead to the conclusion that the square root of wind speed dependence of Piche evaporation is a valid approximation also outdoors in the open. High turbulence negatively influences such correlations, but including the (0,0) as a measuring point reduces this influence. Strictly speaking, this has only been proved here for the cases of pure forced convection mass transfer in all the measuring points (Setchet data) and for the cases of mixed free and forced convection mass transfer under high humidity conditions (Lyamungu data), in which at zero wind speed evaporation may be expected to be very low. Results indoors and in Stevenson screens [16,26], where simple additions of the mass transfer contributions of free and forced convection processes improved the correlations, suggest that the relation might still hold outdoors under such “added” conditions as well. During the periods when the gradients of air temperature and air humidity are small, data sets for at least several hours are recommended at sites with very low wind speeds. Length of measuring periods is not a limitation at the sites and times with high wind speeds, when wind speed ranges are not too small. The actual accuracy levels in using Piche evaporation and its square root of the wind speed dependence for interpolation and/or extrapolation of wind speeds in several agroforest systems was separately dealt with elsewhere [22].

ACKNOWLEDGMENTS

The authors thank Setchet Wheat Company Limited, Hanang, Tanzania, and the leaders of the Agricultural Research Station, Lyamungu, Tanzania, for their collaboration during the years of our experiments. The Traditional Techniques of Microclimate Improvement (TTMI) -Project, in which context the Ph.D. research, part of which we report here, took place, was mainly founded by the Directorate General of International Co-operation (then DGIS/DPO/OT) in the Ministry of Foreign Affairs, The Netherlands.

REFERENCES

1. **Abdulai B.I., Stigter C.J., Ibrahim A.A., Adeeb A.M., Adam H. S.:** Evaporation calculations for lake Sennar (Sudan): search for a meteorological minimum input approach for shallow lakes. A synopsis. Neth. J. Agric. Sc., 38, 725-730, 1990.
2. **Baldy C., Stigter C.J.:** Agrometeorology of Multiple Cropping in Warm Climates. Translated from the French edition (INRA, 1993). INRA, Paris, France + Oxford & IBH Publ.Co., New Delhi, India + Science Publ. Inc., Enfield, USA, 1997.
3. **Coulson C.L., Stigter C.J.:** Appropriateness of instrumentation in agroforestry/agricultural research in developing countries. In: Meteorology and Agroforestry (Eds W.E. Reifsnyder, T.O. Darnhofer). ICRAF, Nairobi, Kenya, 305-314, 1989.
4. **Coulson C.L., Stigter C.J., Akunda A., Floor-Drees E.:** Instrument based distortions of leaf/air temperature differences and interpretations of bean drought stress resistance. J. Trop. Agric., 65, 352-354, 1988.
5. **Ibrahim A.A., Stigter C.J., Adeeb A.M., Adam H.S., Jansen A.E.:** Development and validation of a shaded Piche evaporimeter for the tropics to replace humidity and wind speed data in the aerodynamic term of the Penman equation. Instruments and Observing Methods Report No. 25, WMO/TD-No. 303, WMO, Geneva, 147-152, 1989.
6. **Ibrahim A.A., Stigter C.J., Adeeb A.M., Adam H.S., Van Rheenen W.:** On-farm sampling density and correction requirements for soil moisture determination in irrigated heavy clay soils in the Gezira, central Sudan. Agric. Water Managm., 91-113, 1999.
7. **Kainkwa R.M.R.:** Shelter efficiency of some traditional wind breaks in Tanzania. Ph.D. thesis, University of Dar es Salaam, Tanzania, 1992.
8. **Kainkwa R.M.R., Stigter C.J.:** Wind reduction downwind from a savanna woodland edge. Neth. J. Agric. Sc., 42, 145-157, 1994.
9. **Mohammed A. El-Tayeb:** The influence of a Eucalyptus shelter-belt on sand movement in North-West Gezira (Sudan). Ph.D. thesis, University of Gezira, Wad Medani, Sudan, 1991.
10. **Mohammed A.E., van de Veer O.D., Oldenziel H.J., Stigter C.J.:** Wind tunnel and field testing of a simple sand catcher for sampling inhomogeneously saltating sand in desertified environments. Sedimentology, 43, 497-503, 1996.
11. **Mungai D.N., Stigter C.J., Coulson C.L., Ng'etich W.K., Muniafu M.M., Kainkwa R.M.R.:** Measuring solar radiation transmission in tropical agriculture using tube solarimeters. A warning. Agric. For. Meteorol., 86, 235-243, 1997.
12. **Mungai D.N., Stigter C.J., Coulson C.L., Ng'ang'a J.K.:** Simply obtained global radiation, soil temperature and soil moisture in an alley cropping system in semi-arid Kenya. Theor. Appl. Climat., 65, 63-78, 2000.
13. **Olufayo A.A., Stigter C.J., Baldy C.:** On needs and deeds in agrometeorology in tropical Africa. Agr. For. Meteorol., 92, 227-240, 1998.
14. **Onyewotu L.O.Z.:** The effects of multiple shelterbelts on microclimate and agricultural use of a desertified semi-arid environment near Kano, Nigeria. Ph.D. thesis, Ahmadu Bello University, Zaria, Nigeria, 1996.
15. **Oteng'i S.B.B.:** An investigation of the influence of mulching and agroforestry systems on the microclimatic conditions affecting soil moisture and a maize/bean intercrop in semi-arid areas of Laikipia district, Kenya. Ph.D. thesis, University of Nairobi, Nairobi, Kenya, 1996.
16. **Rashidi A.G.M.:** Further experiments with the Piche evaporimeter: its use within a meteorological screen and in the open. M.Sc. thesis, Agricultural Physics Section, Physics Department, University of Dar es Salaam, 139, 1981.
17. **Spaan W.P., Stigter C.J.:** Measuring wind erosion with simple devices: a synopsis. Mitt. Deut. Bodenk. Gesells., 65, 51-56, 1991.
18. **Stigter C.J.:** The use of physics in agricultural research. Int. J. Env. Stud., 19, 269-271, 1982.
19. **Stigter C.J., Jiwaji N.T., Makonda M.M.:** A calibration plate to determine the performance of infrared thermometers in field use. Agric. Meteorol, 26, 279-283, 1982.
20. **Stigter C.J., Kainkwa R.M.R., Mohammed A.E., Onyewotu L.O.Z.:** Essentials and cases of wind protection from scattered trees and shelterbelts (in French). Opening paper in: Parkland Agroforestry of the Semi-arid Areas of West Africa. (Eds E.G. Bonkongou, E.T. Ayuk, I. Zoungrana). SALWA Network, Ouagadougou, ICRAF, Nairobi, 1-22, 1997.
21. **Stigter C.J., Kainkwa R.M.R., Oteng'i S.B.B., Ibrahim A.A., Mohammed A.E., Onyewotu L.O.Z.:** The shaded Piche evaporimeter as an ancillary isothermal anemometer. Instruments and Observing Methods, Report No. 77, WMO/TD-No. 877, WMO, Geneva, 377-380, 1998.
22. **Stigter C.J., Kainkwa R.M.R., Oteng'i S.B.B., Onyewotu L.O.Z., Mohammed A.E., Ibrahim A.A., Rashidi A.G.M.:** Measuring wind gradients in agroforestry systems by shaded Piche evaporimeters. II. Accuracies obtained in some African case studies. Int. Agrophysics, 14, 2000 (in print).
23. **Stigter C.J., Makonda M.M., Jiwaji N.T.:** On the sensitivity of simple infrared field thermometers. J. Phys. E. (Sci. Instr.), 16, 613-614, 1983.
24. **Stigter C.J., Mjungu Y.B., Lutege P.M.B., Waryoba J.M., Othieno C.O., Mwampaja A.R.:** Relationships between soil albedos and soil and air temperatures. Neth. J. Agric. Sc., 32, 33-42, 1984.
25. **Stigter C.J., Mjungu Y.B., Waryoba J.M.:** An outdoor demonstration experiment on the effect of soil albedo on soil surface temperature. Amer. J. Phys., 52, 742-744, 1984.

26. **Stigter C.J., Uiso C.B.S.:** Understanding the Piche evaporimeter as a simple integrating mass transfer meter. Appl. Scient. Res., 37, 213-224, 1981.
27. **Stigter C.J., Uiso C.B.S., Rashidi A.G.M.:** Evaporation data from a Piche evaporimeter - a comment using Tanzanian results. J. Hydrol., 73, 193-198, 1984.
28. **Stigter C.J., Welgraven A.D.:** An improved radiation protected differential thermocouple psychrometer for crop environment. Arch. Meteorol. Geoph. Biocl. B, 24, 177-188, 1976.
29. **Thom A.S., Thony J.L., Vauclin M.:** On the proper employment of evaporation pans and atmometers in estimating potential evaporation. Quart. J.R. Meteorol. Soc., 107, 711-736, 1981.
30. **Uiso C.B.S., Stigter C.J.:** A physical interpretation of evaporation rates of the screened Piche evaporimeter. Univ. Sc. J. (Dar Univ.), 6, 131-150, 1980.