Revista Brasileira de Agrometeorologia, Santa Maria, v. 5, n. 1, p. 69-75, 1997.
Recebido para publicação em 14/02/97. Aprovado em 05/03/97.

ISSN 0104-1347

DEVELOPMENT OF AN EVAPORIMETRIC RADIOMETER TO ESTIMATE THE GLOBAL SOLAR RADIATION FLUX DENSITY

DESENVOLVIMENTO DE UM RADIÔMETRO EVAPORIMÉTRICO PARA ESTIMAR A DENSIDADE DE FLUXO DE RADIAÇÃO SOLAR GLOBAL

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SUMMARY

Based on measurements of evaporation through a black horizontal porous surface (Bellani capsules) supplied with pure water at zero potential, an instrument was developed to measure the incoming solar radiation (Qg), here called evaporimetric radiometer. Basically, it is composed of a set of two identical capsules; one completely exposed to the incoming solar radiation and the environment on the whole, and another covered to minimize the incidence of solar radiation. It was found that the difference of volumetric water evaporated (ΔVt) on both capsules is a good estimation of Qg. A linear regression showed that Qg ($MJ.m^{-2}.day^{-1}$) = 8.7028 + 0.2522 ΔVt (cm^3), (r^2 = 0.7237, n = 117) gives a reasonable fit to the data. Such relationship was tested against an indepedent set of data and the results show that the points fall around the 1:1 line.

Key words: solar radiometry, modelling.

RESUMO

Com base nas medidas de evaporação através de uma superfície horizontal porosa (cápsulas de Bellani) suprida com água pura a potencial zero, um instrumento foi desenvolvido para medir a

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absorção de radiação solar (Qg), aqui denominado de radiômetro evaporimétrico. Basicamente, o referido instrumento foi composto por um conjunto de duas cápsulas idênticas; uma completamente exposta a absorção de radiação solar e às condições atmosféricas locais e outra coberta para minimizar a incidência de radiação solar. Encontrou-se que a diferença entre o volume de água evaporada (ΔVt) em ambas cápsulas é uma boa estimativa de Qg. Uma regressão linear mostrou que Qg ($MJ.m^{-2}.dia^{-1}$) = 8,7028 + 0,2522 ΔVt (cm^3), (r^2 = 0,7237, n = 117) dá um ajuste razoável aos dados. Tal relação foi testada contra uma série de dados independentes e os resultados mostram que os pontos caem ao redor da linha 1:1.

Palavras-chave: radiometria solar, modelagem.

INTRODUCTION

It is a known fact that almost all physical or biological processes in the biosphere occur due to solar energy. In the description of any natural ecosystem, it is always very important to carry out the evaluation of radiant energy balance along a given period. So that the radiation balance is used to evaluate the energy availability to biosinthesis, evaporation, evapotranspiration, air and soil heating, and other minor processes.

The global solar radiation flux density is the source of energy for almost all phenomena that occur in nature. It has been for a long time a concern of agrometeorogists the development of equipments to measure this element, as well as mathematical models to make its estimation. The equipments to measure the global radiation flux density are not almost always available to farmers, because of their high cost and the use of models that lacks local adjustment in their coefficients.

According to KONDRATIEV (1969), different methods of energy measurement are based on the effects that radiant energy produces over the sensitive element of apparatus, resulting in other energy forms which are divided into two groups: with and without phase transformation.

In the instrumental group that uses phase transformation, usually with water or alcohol to measure and integrate the global solar radiation flux density are the works of PEREIRA (1959); CARDER (1960); GODOY (1961); PELTON (1964); DESJARDINS & HANSEN (1967); SMITH (1972); Carder (1960; 1966) quoted by GEDDES (1974) and REID & DESJARDINS (1976).

Facing the necessity of developing practical and simple solutions to agricultural meteorology measurements, the main aim of this work was to develop an integrator-measurer of the global solar radiation flux density, of easy handling and low cost, becoming acessible to farmers in general.

MATERIAL AND METHODS

The present study was developed at the evaporimetric station of the Department of Physics and Meteorology at Escola Superior de Agricultura "Luiz de Queiroz" (College of Agriculture "Luiz de Queiroz"), in Piracicaba, São Paulo, Brazil, whose geographic coordenates are: latitude 22° 42' S, longitude 47° 38' W Greenwich and altitude 576 m.

Values of global solar radiation flux density were obtained by the following apparatus: Robitzsch bimetalic actinograph and evaporimetric radiometer. Two sets of the evaporimetric radiometer were installed, each one with two units: one covered and another uncovered. The covered unit had a porous plane surface with white blotter paper, whereas the uncovered unit had a black surface, as shown in Figure 1.

The beaker (A) graduated from 0 to 250 ml with divisions of 2 l allowed readings with approximation of 1 ml. There is a tube in its interior with an internal diameter of 0.4 cm with one extremity toward outside and another one at the level of 30 ml in order to keep the water internal pressure at this level equal to the atmosphere pressure. See details of each unit of the set on Figure 1.

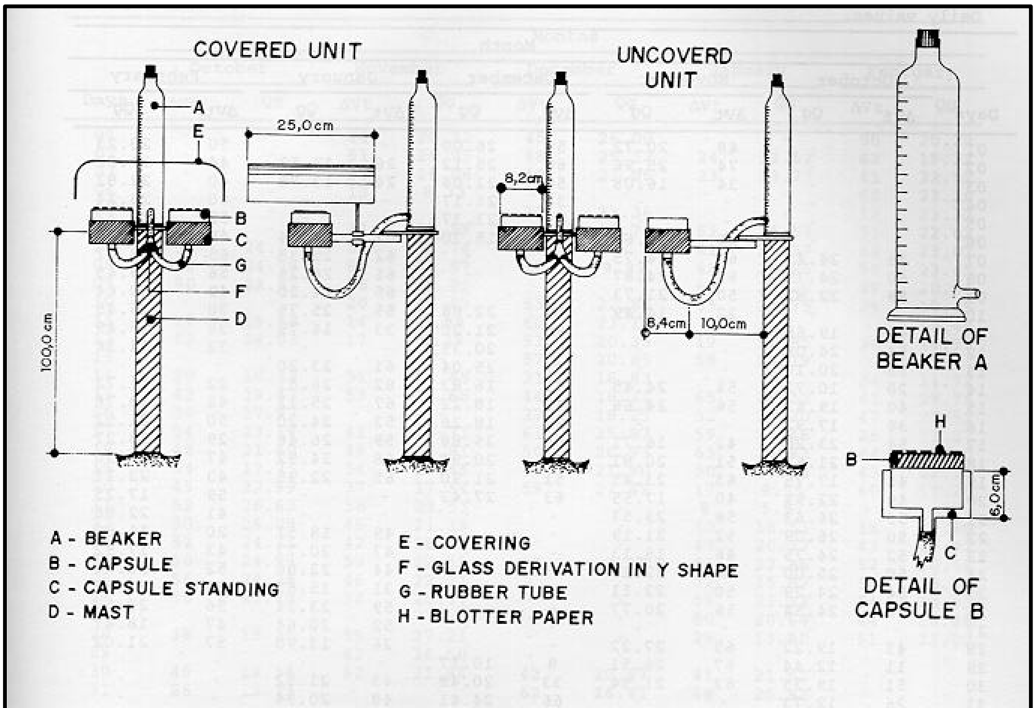

Figure 1. Evaporemetric radiometer assembly.

The clay capsule (B) did not suffer action of capillarity effect. There was a small hole in its middle whose main function was to expel the air out from the tank and allow the checking of the water level. The capsule standing (C) and the mast (D) were made by conduit tube and painted dim white.

The capsule covering (E) was made using plastic material with the following dimensions: 40 x 20 x 10 m. Its external face was painted white and the internal one dim black.

The glass derivation in Y shape (F) had the function to join the beaker to the tanks through flexible rubber tubes (G).

The blotter paper (H) worked as an evaporant surface. It was boiled to eliminate the gum of manufacturing before its use. The paper to the uncovered set was painted black.

The measurements of global solar radiation flux density were calculated daily by diagram area integration.

The global solar radiation flux density was estimated by evaporimetric radiometer, as a function of water evaporation from evaporant units, according to the following considerations:

The evaporation from the uncovered unit occurred according to the following function:

$$\Delta Vd = f\ (Qg;\ \Delta e;\ v;\ p) \qquad (1)$$

where: ΔVd = evaporated water volume on the uncovered unit; Qg = global solar radiation flux density; Δe = saturation deficit; v = wind; p = capsule geometry, reflection coefficient, water temperature, aerodynamic conditions and other minor factors.

For the covered unit, the climatic elements that ruled the evaporation process, excepting for Qg, were the same ones from the uncovered unit plus the diffuse radiation flux density. Then:

$$\Delta Vc = f\ (qd;\ \Delta e;\ v;\ p) \qquad (2)$$

where: ΔVc = evaporated water volume on the covered unit; qd = diffuse radiation flux density.

qd is contemptible due to the covering geometry, considering that $\Delta Vd = f(Qg, \Delta e, v, p)$ and $\Delta Vc = f(\Delta e, v, p)$, it is possible to formulate the following hypothesis:

$$\Delta Vt = \Delta Vd - \Delta Vc = f(Qg) \qquad (3)$$

which suggests that the observed evapored water volume difference between both sets (ΔVt) is function of the incident global solar radiation flux density (Qg). To test this hypothesis, daily values of ΔVt were compared to daily values of Qg, obtained by the Robitzsch bimetalic actinograph.

The values of global solar radiation flux density estimated from the evaporation difference observed in both units of the evaporimetric radiometer were correlated with the values measured by Robitzsch bimetalic actinograph for the select days. Thus, it was obtained simple linear regression equations and its respective correlation coefficients for such daily values as well as for the averages of five readings.

As the values of correlation (r) and determination (r^2) coefficients analysed insulately can carry inadequate interpretation about the performance of the studied model, it was also used the agreement index d proposed by WILLMOTT et al (1985), given by:

$$d = 1 - [\Sigma(Pi - Oi)^2 / \Sigma(|Pi - O| + |Oi - O|)^2] \quad (4)$$

where: Pi is the estimated value, Oi is the observed value and O is the average of the observed values.

RESULTS AND DISCUSSION

The values of evaporation obtained on the sets 1 and 2 and global solar radiation flux densities measured through actinograph are presented in Tables 1 and 2 (daily values) and in Table 3 (five readings average values).

By the analysis of simple linear regression applied to these data, we could check that the measured data and the calculated values of global solar radiation flux density are closely correlated, showing that around 80% of the evaporated volume variations on the units of the evaporimetric radiometer can be explained by the presented regression equations.

Table 1. Evaporation values from the evaporimetric radiometer (ΔVt_1, in $cm^3.day^{-1}$) and global solar radiation values measured by Robitzsh actinograph (Qg, in $MJ.m^{-2}.day^{-1}$) - Daily values.

	Month									
	October		November		December		January		February	
Days	ΔVt_1	Qg	ΔVt_1	Qg	ΔVt_1	Qg	ΔVt_1	Qg	ΔVt_1	Qg
01	-	-	48	20.72	59	26.00	-	-	50	20.23
02	-	-	74	25.96	60	25.12	26	13.52	44	19.22
03	-	-	34	16.08	50	21.06	24	13.78	40	22.82
04	-	-	-	-	36	25.17	-	-	60	23.24
05	-	-	-	-	65	23.37	-	-	52	23.32
06	-	-	26	19.60	28	15.70	62	24.54	49	22.03
07	55	24.41	60	24.75	-	-	62	25.38	65	23.07
08	60	24.79	62	24.87	-	-	66	26.26	56	23.45
09	59	22.82	50	21.73	-	-	65	24.20	49	20.64
10	-	-	22	14.49	59	22.86	55	25.75	30	15.45
11	49	19.68	-	-	60	21.20	33	16.79	38	15.49
12	54	24.04	-	-	53	20.35	-	-	32	14.36
13	55	20.10	-	-	57	25.04	61	23.20	-	-
14	20	10.72	54	24.45	33	16.83	82	26.51	22	11.72
15	40	19.47	56	24.66	48	18.22	67	25.12	46	18.76
16	34	17.92	-	-	27	18.26	52	24.20	50	21.52
17	54	23.20	42	16.71	64	25.88	59	26.46	29	13.27
18	54	21.61	51	20.81	53	20.94	68	24.92	47	19.30
19	46	17.75	63	23.45	51	21.90	65	22.95	43	22.11
20	49	22.99	40	17.55	63	27.43	-	-	59	17.25
21	53	26.63	58	23.53	-	-	-	-	41	22.86
22	50	26.09	52	21.19	-	-	49	18.51	20	11.60
23	52	24.75	46	18.13	-	-	47	20.77	43	17.92
24	50	25.00	58	22.15	-	-	44	22.86	52	20.56
25	54	24.29	50	22.11	-	-	31	15.87	53	23.32
26	52	24.54	56	20.77	-	-	59	23.24	56	20.52
27	-	-	-	-	-	-	52	20.64	47	18.47
28	43	19.22	65	27.22	-	-	26	13.90	57	21.02
29	11	12.44	67	26.51	8	10.17	-	-	-	-
30	51	19.35	62	21.94	33	20.48	43	21.52	-	-
31	26	12.73	-	-	66	24.41	48	20.94	-	-

Table 2. Evaporation values from the evaporimetric radiometer (ΔVt_2, in $cm^3.day^{-1}$) and global solar radiation values measured by Robitzsh actinograph (Qg, in $MJ.m^{-2}.day^{-1}$) - Daily values.

	Months									
	October		November		December		January		February	
Days	ΔVt_2	Qg	ΔVt_2	Qg	ΔVt_2	Qg	ΔVt_2	Qg	ΔVt_2	Qg
01	-	-	44	20.72	45	26.00	-	-	50	20.22
02	-	-	61	25.95	58	25.12	24	13.52	42	19.22
03	-	-	33	16.08	48	21.06	23	13.77	41	22.82
04	-	-	12	8.33	-	-	-	-	60	23.24
05	-	-	-	-	70	23.36	-	-	52	23.32
06	-	-	37	19.59	25	15.70	59	24.53	51	22.02
07	58	24.40	53	24.74	-	-	61	25.37	64	23.07
08	59	24.79	64	24.87	15	9.92	68	26.25	56	23.45
09	60	22.82	38	21.73	-	-	63	24.20	49	20.64
10	-	-	20	14.49	53	22.86	55	25.75	26	15.45
11	59	19.68	14	9.88	60	23.19	-	-	-	15.49
12	52	24.03	17	9.29	51	20.35	19	11.85	30	14.36
13	-	-	-	-	57	20.85	58	23.19	-	-
14	20	10.72	51	24.45	31	16.83	-	-	24	11.72
15	42	19.47	53	24.66	44	18.21	65	25.12	41	18.76
16	36	17.92	-	-	27	18.25	52	24.20	47	21.52
17	54	23.19	41	16.71	61	25.87	59	26.46	26	13.27
18	48	21.60	49	20.81	50	20.93	63	24.91	44	19.30
19	44	17.75	54	23.45	48	21.90	50	22.94	43	22.11
20	45	22.99	37	17.54	59	27.42	17	9.55	60	17.25
21	52	26.63	58	23.53	-	-	8	5.57	-	-
22	50	26.08	46	21.19	-	-	50	18.51	18	11.60
23	52	24.74	42	18.13	-	-	47	20.77	43	17.92
24	50	24.99	53	22.15	62	22.15	43	22.86	52	20.56
25	56	24.28	46	22.11	-	-	32	15.87	54	23.32
26	50	23.78	54	20.77	-	-	59	23.24	54	20.52
27	-				-	-	50	20.64	44	18.46
28	38	19.21	59	27.21	-	-	25	13.90	51	21.02
29	-	-	62	26.50	-	-	-	-	-	-
30	46	19.34	62	21.94	42	20.47	41	21.52	-	-
31	26	12.73	-	-	62	24.41	48	20.93	-	-

Table 3.Evaporation values of the evaporimetric radiometer (ΔVt) and the global solar radiation flux measured by Robitzsch actinograph (Qg, in $MJ.m^{-2}.day^{-1}$) - averages of five readings.

October			November			December			January			February		
$\Delta Vt1$	$\Delta Vt2$	Qg	ΔVt_1	ΔVt_2	Qg	ΔVt_1	ΔVt_2	Qg	ΔVt_1	ΔVt_2	Qg	ΔVt_1	ΔVt_2	Qg
46.2	49.0	19.57	39.8	37.4	18.14	54.0	53.6	24.4	29.4	27.8	15.58	49.2	49.0	21.77
40.6	41.4	18.45	41.4	37.8	19.14	42.2	40.8	18.41	56.2	55.8	23.68	49.8	49.2	20.93
51.2	48.6	22.44	44.8	42.2	19.19	45.8	44.0	20.84	56.8	55.2	22.17	28.0	27.0	14.10
51.6	51.6	24.78	51.8	47.4	20.77	46.6	44.0	23.03	43.0	39.4	17.89	45.6	44.0	18.69
32.8	30.2	15.93	59.7	56.0	23.45	38.6	40.0	19.85	46.0	46.2	20.25	41.8	41.8	19.25
									42.2	41.0	19.25	47.2	44.8	18.30

ΔVt_1 = Evaporation of the set 1 - $mm.day^{-1}$
ΔVt_2 = Evaporation of the set 2 - $mm.day^{-1}$

Thus, the regression models for evaluation of the solar radiation flux density obtained from daily values and averages of five readings were the followings:

-In daily basis: $Qg = 0.2522 * \Delta Vt_1 + 8.7028$

-In basis of five days: $Qg = 0,3044 * \Delta Vt_1 + 6.2196$

where ΔVt_1 is expressed by in $cm^3.day^{-1}$ and Qg in $MJ.m^{-2}.day^{-1}$.

The determination coefficients of correlation (r^2), considering the same sequence of proposed models were: 0.7237 and 0.7908, for n (number of observations) correspondent to 117 and 27, respectively.

On Figures 2a and 2b, we can verify that the volume differences observed between the covered and uncovered units of one of sets which composed the evaporimetric radiometer in study (ΔVt_1) are clearly correlated with the global solar radiation flux density values measured by Robitzsch bimetalic actinograph (Qg).

For validation of the proposed regression models, values of solar radiation estimated from the evaporation difference observed in another equipment set (ΔVt_2) were plotted 1:1 line, revealing a good similarity between the compared values (Figures 3a and 3b). Such figures show that the dispersal of global radiation flux density (Qg) measured and estimated values around 1:1 line, considering an independent serie of data, is relatively small, being however confirmed statistically through the calculation of Willmott's agreement index (d).

The Figures 3a and 3b bring information concerning the accuracy of analysis (given by the tendence lines presented), as well as its exactness (visualized by the dispersal of the data around 1:1 line). So, we could verify that Qg estimatives obtained from ΔVt_2 were very good, presenting d values greater than 0.92, exceeding hence values considered as satisfactory, whose inferior limit recommended by ROBINSON & HUBBARD (1990) is 0.75.

The correlation between daily values of Qg measured and estimated by the proposed regression equation, indicated by Figure 3a, evidences the obtainment of the following correlation (r) and agreement (d) coefficient values: 0.8920 and 0.9267, respectively. For the grouping of five days, presented on Figure 3b, r and d values found were equal to 0.8994 and 0.9376, respectively.

Performance indexes c, defined by the multiplication between r and d, preconized by CAMARGO & SENTELHAS (1995), were calculated and the values obtained in daily basis and in grouping of five days basis were, respectively: 0.8266 and 0.8433. Such values revealed however very good performance, according to interpretation criterion of the models performance presented by the forerunners of this index.

It is important to mention that the dispersal of Qg estimated values obtained by regression equation, showed on Figure 3a and 3b, can be checked partially because of the difficulty in the integration of the actinograph diagrams in cloudy and partially cloudy day conditions, being worth hence to add that the utilization of present methodology in future studies developed with accuratest equipments will be able to improve the analysis precision and contribute for the proposition of much more reliable models.

CONCLUSIONS

From the results obtained in this research paper, we can make the following inferences:

1. The global solar radiation flux density can be estimated through a regression equation adjusted to local conditions, in function of the differential evaporation observed by the evaporimetric radiometer with measurement accuracy comparable to the ones recorded by Robitzsch actinograph.
2. The evaporimetric radiometer is a low cost equipment that can be calibrated to local climatic condictions. For this reason, it can substitute the actinograph use.

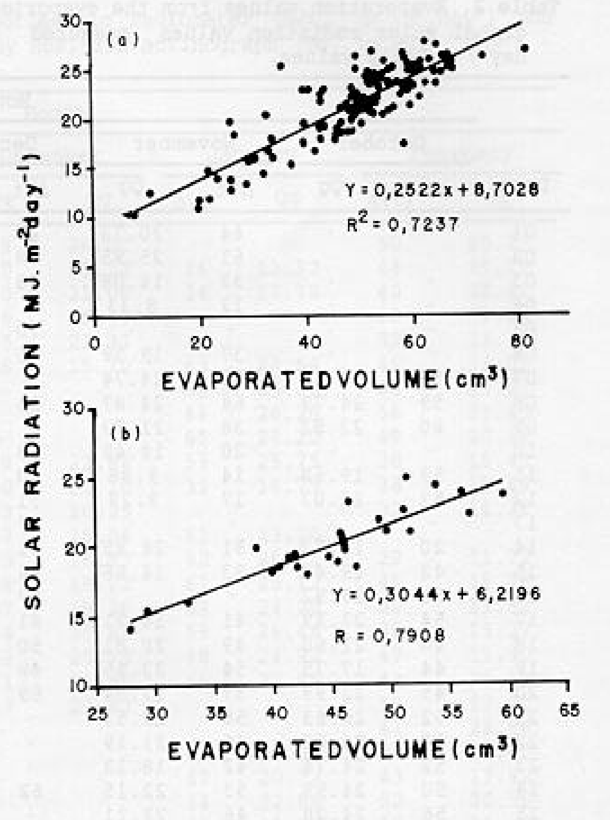

Figure 2. Relationship between global solar radiation (Qg) measured by actinograph and observed volume difference between both units of the radiometer evaporimetric (ΔVt,) from daily values (a), and from the averages of five radings (b).

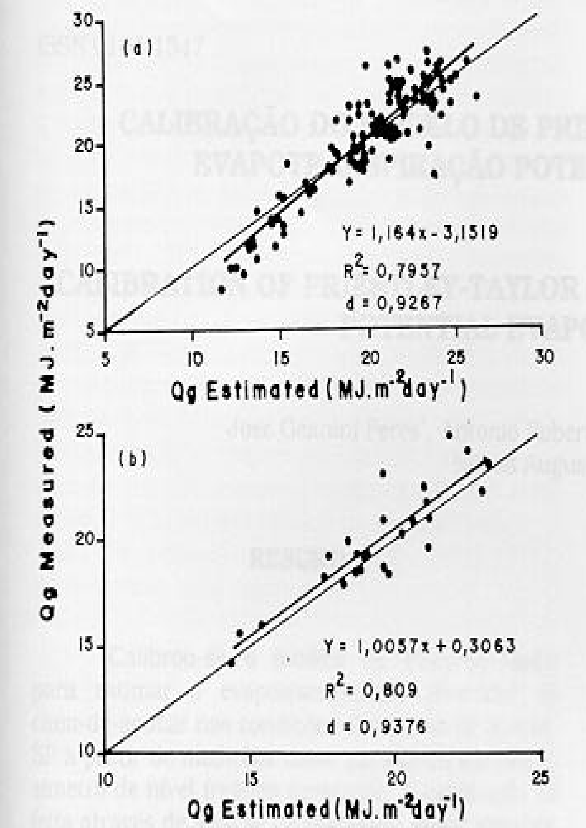

Figure 3. 1:1 line graphic between solar radiation measured by actinograph and solar radiation estimated by proposed regression equation from daily values (a), and form the averages of five readings (b)

ACKNOWLEDGEMENTS

The authors are very grateful to Prof. Fernanda Bacellar from the University of São Paulo, Brazil, who revised the version in English of this paper.

REFERENCES

CAMARGO, A .P., SENTELHAS, P.C. Avaliação de modelos para estimativa da evapotranspiração potencial mensal, em base diária para Campinas e Ribeirão Preto, SP. In: CONGRESSO BRASILEIRO DE AGROMETEOROLOGIA, 7, 1995, Campina Grande. **Resumos...** Campina Grande, 1995. p. 415-417.

CARDER, A.C. Atmometer assemblies, a comparison. **Can. J. Pl. Sci**., Ottawa, v. 40, p. 700-706, 1960.

DESJARDINS, R. L., HANSEN, R.O. Wind response of black porous disc and Bellani plate atmometer. **Can. J. Pl. Sci**., Ottawa, v. 47, p. 498-498, 1967.

GEDDES, H.B. A model, for a modified carburundum block atmometer. **Can . J. Pl. Sci**., Ottawa, v. 4, p. 703-711, 1974.

GODOY, R**. Modificação do radiômetro de Gunn Bellani para medidas da radiação solar e da evapotranspiração**. Piracicaba, 1961, 71 p.

(Tese de Doutorado), Escola Superior de Agricultura "Luíz de Queiroz", 1961.

KONDRATIEV, K.Y. **Radiation in the atmosphere**. Academic Press. New York, 1969, 912 p.

PELTON, W.L. Evaporation from atmometers and pans**. Can . J. Pl. Sci**., Ottawa, v. 44, p. 397-404, 1964.

PEREIRA, H.C. Pratical field instruments for estimation of radiation and evaporation. **Q. J. R. Meteorological Society**, London, v. 85, p. 253-261, 1959.

REID, W.S., DESJARDINS, R. L. A continuous recording black porous disc atmometer - Capacitance Method**. J. Agric. Eng. Res.,** v. 21, p. 443-446, 1976.

ROBINSON, J.M.; HUBBARD, K.G. Soil water assessment model for several crops in high plains. **Agronomy Journal, Madison,** v. 82, n. 6, p. 1141-1148, 1990.

SMITH, G. W. Inexpensive instruments for the measurement of solar radiation. **Q. J. R. Meteorological Society**, London, v. 98, p. 855-859, 1972.

WILLMOTT, C.J., ACKLESON, S.G., DAVIES, R.E. *et al.* Statistics for the evaluation and comparison of models. **Journal of Geophysical Research**, v. 90, n. 5, p. 8995-9005, 1985.