On the Estimation of Potential Evaporation and Evapotranspiration in Central Mexico

by

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1. Introduction

In large areas of Central and Northern Mexico evaporation exceeds precipitation on an annual basis. Consequently, the study of the regime of evaporation is of vital importance for a better understanding of the climate. Furthermore a more precise estimation of the evaporation is fundamental in order to determine the water needs of crops and natural vegetation that grow in the valleys of Central Mexico, where a large proportion of the population of the country is settled.

Systematic observation of evaporation by means of Class A type Pans of the U.S. Weather Bureau (four feet in diameter, ten inches deep and elevated from the ground) have been made in Mexico for several decades. The Meteorological Service as well as the Secretariat for Hydraulic Resources have tanks of this type in operation and in the central region of the country there is now an acceptable network of evaporimetric stations.

Since up to the present time there have been few attempts to compare the Class A type Pan values with evaporation estimations obtained from meteorological data, it was thought that it would be of interest to attempt such a comparison in this tropical region. The evaporation from pans can give an acceptable indication of the evaporation in Mexico, at least during months when evaporation is less than precipitation.

Since the PENMAN's formula (1948) can also be used to calculate from meteorological factors the evaporation of a waterfilled pan, the results may be compared with the evaporation values measured in Class A Pans. Due to the lower albedo of water in similar conditions of exposure, the 'potential' evaporation Ep, (that is, the one originating from a free limited water surface), must be greater than the potential evapotranspiration of crops or natural vegetation; but the greater aerodynamic roughness of natural vegetation tends to reduce the difference between the tank evaporation and evapotranspiration. If a good relation is found between the evaporation observed in Class A type Pans and the estimation from meteorological data, then PENMAN's model can be applied (using appropriate albedo values) to estimate potential evapotranspiration of vegetation growing in this region.

Since the rate of potential evaporation depends on evaporative power of air, as defined by humidity content, wind, radiation, and temperature, the existing diverse empirical evaporation formulas are usually expressed by these variables. In this study, the degree of correlation between the evaporation of Class A Pan and the above mentioned meteorological factors is examined. Then the potential evaporation of an open pan of water is calculated using PENMAN's formula and the results compared with the evaporation observations of Class A Pans. Finally some estimates of evapotranspiration are made.

Once lysimetric observations begin to be made on a routine basis (a lysimeter has just been recently installed in Chapingo), it will be feasable to compare them with those of the evaporimeters as well as with the estimates obtained by the different evapotranspiration models.

2. The Data

Daily data for the year 1973 have been used as follows:

a) Average, maximum and minimum temperature.
b) Relative humidity at 7.00 and 14.00 hs.
c) Sunshine.
d) Winds.
e) Evaporation from eight stations distributed in the region (Fig. 1).

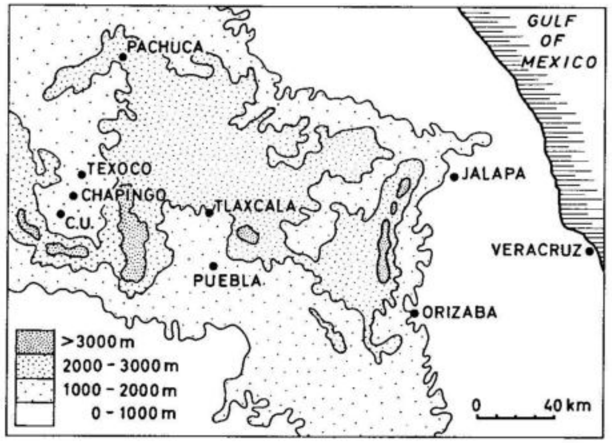

Fig. 1: The climatological stations

The meteorological data were obtained from the National Meteorological Service and the Secretariat for Hydraulic Resources. Daily global radiation data (1973) observed with a piranometer Kipp in Chapingo were also obtained. Also, global radiation for some completely clear or cloudy days (1973) as measured in the Solar Radiation Observatory of the Geographical Institute of the University of Mexico located in the Ciudad Universitaria in the southern section of Mexico City, was used. These data, which have been compared to the Ăngstrom Pyrheliometer model No. 166 installed in the observatory, served as a control to corresponding data from Chapingo Station.

3. The Climate

The climate of eastern central Mexico is characterized as is the climate of the greater part of the country, by having two contrasting seasons:

a) the wet and warm tropical season with abundant rain of convective type
b) the cool and relatively dry season.

Only during the rainy months does precipitation normally exceed evaporation (see table 1 of climatólogical data). But even during this period there are one or several dry days (from 5 to 7 approximately per month) and part of the rainfall after these dry periods evaporates. Almost all of the water from the first rains in April and May falling on the dry and warm soil of the plains is also lost by evaporation. The same occurs during the 'canicula' or little dry season in the middle of the rainy season. The light convective precipitation evaporates before the plants or ground can use it. In the midst of the dry season, clear skies prevail and consequently a high level of heat energy is available for evaporation (JAUREGUI, 1968).

Frequently, during the rainy season, the downpours develop in an isolated form over the plains during the day. It is possible, under these conditions, that the dry superficial air under the clouds helps to evaporate additional volumes of water. The lowest amounts of evaporation occur when the region is under the influence of a tropical disturbance (Easterly wave or hurricane) and precipitation or 'temporal' rains continue for several days or even weeks. In the midst of the rainy season a considerable amount of the precipitation occurs in late afternoon and during the first hours of the evening (LAUER/KLAUS, 1975) when the available energy for evaporation is much less than that of the midday hours.

These rainstorms are the most beneficial for the soil and plants since the reduced evaporation occurs with energy that has been stored in the ground during the day. This daily rain cycle changes from the eastern border of the plateau towards the coast (KLAUS, 1972). There, the effect of the orographic lifting over the slopes of the Sierra Madre Oriental accelerates the convective process and the rainstorms usually begin at an earlier time of the day. On the Gulf Coast the convective clouds that are formed during the night over the ocean, produce, on entering land and driven by the Trades, rainstorms at an earlier time of the day. Here, as in the flanks of the Sierra Madre, precipitation is more abundant, even in the winter semester, due to the more direct influence of the humid 'Nortes'. Although evaporation ought to be higher because of the higher temperature, it is somewhat inferior (in Veracruz only slightly higher) to the annual rainfall amounts.

Table 1: Climatological data (1973)

	J	F	M	A	M	J	J	A	S	O	N	D	anual
Tlaxcala													
T. med.	14	16	19	19	19	18	17	17	18	17	15	13	
H.R. (14 hs.)	54	36	33	41	42	57	56	60	57	54	43	42	
Insol. (hs.)	6.2	5.1	5.4	4.1	4.6	3.4	4.3	4.0	4.7	5.6	6.4	5.9	
Evap. (mm)	166	175	256	232	196	157	148	135	137	145	134	121	2003
Prec. (mm)	0	5	0	52	111	221	178	185	121	96	3	12	984
Chapingo													
T.med.	12	14	17	18	18	17	16	16	16	15	13	10	
H.R. (14 hs.)	22	30	26	36	37	50	62	65	57	55	48	36	
Insol. (hs)	9.0	8.7	9.4	9.0	8.3	6.5	4.8	5.0	6.3	6.0	7.6	7.0	
Evap. (mm)	166	163	259	216	228	181	135	116	131	127	124	115	1967
Prec. (mm)	0	5	8	30	57	82	130	197	73	56	23	1	662
Jalapa													
T.med.	15	15	21	20	22	20	20	19	20	19	19	16	
H.R. (14 hs)	62	72	42	56	48	64	64	68	63	64	53	54	
Insol. (hs)	4.0	3.1	7.4	2.7	5.2	3.4	4.6	2.4	4.2	4.2	6.5	3.4	
Evap. (mm)	65	54	150	118	145	101	122	111	121	92	107	84	1270
Prec. (mm)	44	77	8	119	144	444	123	223	157	91	118	67	1615
Veracruz													
T.med.	22	21	25	29	27	28	28	28	28	27	26	22	
H.R. (14 hs)	82	82	76	71	76	78	76	76	79	78	78	86	
Insol. (hs)	4.8	3.8	6.9	4.5	6.5	6.6	5.9	5.8	6.2	5.1	6.8	4.6	
Evap. (mm)	127	108	165	141	181	156	135	147	149	175	143	117	1744
Prec. (mm)	15	15	1	1	40	296	464	397	183	241	19	18	1690

4. Relationship between the Evaporation from Class A Pans and some Meteorological Factors

In order to find the degree of association that exists between the evaporimetric observations and some meteorological variables, the corresponding correlations were calculated. The percentual contribution of the meteorological factors to the total variance of the evaporation of the Class A tanks were also computed. These calculations were done by computer for all the stations. For the sake of brevity, only some results are presented here. Correlation coefficients for representative stations in the region under study are shown in table 2.

a) Temperature

The correlation between the pan evaporation and the average temperature shows a seasonal variation in the plateau. As expected, the most important variation occurs in the warm months (when radiation level is high) and decreases as the rains begin (Fig. 2). This tendency is also observed in the more humid areas of the slopes of the Sierra Madre (Jalapa). However, on the coast itself the correlation between both variables is insignificant. A general conclusion is that if in some months the correlation values between evaporation and temperature are high, considerable time and space variations are also observed.

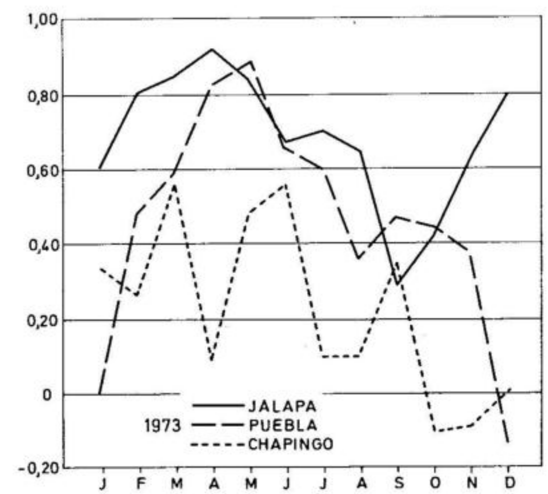

Fig. 2: Correlation between Class A Pan evaporation and air temperature

Table 2: Correlation coefficients between pan evaporation and several climatic variables (1973)

	J	F	M	A	M	J	J	A	S	O	N	D
Chapingo												
T.med.	.33	.26	.55	-.05	.49	.56	-.01	.10	.35	-.11	-.10	.33
H.R. (7 hs)	-.53	-.13	-.55	-.47	-.22	-.15	.36	.31	.27	.25	-.06	-.02
H.R. (14 hs)	.33	-.36	-.71	-.51	-.43	-.67	-.39	-.31	-.53	-.44	-.13	-.24
H.R. (med)	-.58	-.32	-.68	-.60	-.40	-.58	-.28	-.22	-.42	-.38	-.18	-.21
Insol.	-.09	.50	.15	.66	.50	.70	.53	.63	.59	.51	-.09	.17
Wind	.65	.61	.63	.29	.13	.10	-.08	.34	.51	.25	.58	-.08
Puebla												
T. med.	-.03	.48	.58	.82	.88	.66	.60	-.36	.47	.44	.38	-.14
H.R. (7 hs)	-.56	-.40	-.36	-.50	-.37	-.71	-.55	-.39	-.54	-.52	-.34	-.16
H.R. (14 hs)	-.12	-.63	-.73	-.57	-.50	-.93	-.79	-.80	-.64	-.65	-.57	-.22
H.R. (med)	-.38	-.56	-.63	-.67	-.52	-.90	-.77	-.74	-.68	-.73	-.54	-.24
Insol.	.23	.59	.38	.77	.57	.74	.93	-.59	-.51	.72	-.59	.23
Wind	.19	.06	.43	-.33	.30	.17	-.08	.80	.61	.34	.70	.34
Jalapa												
T.med.	.60	.81	.85	.92	.84	.67	.70	.65	.29	.42	.63	.80
H.R. (7 hs)	-.77	.12	-.55	-.69	-.66	-.63	-.46	-.48	-.13	-.26	-.44	-.73
H.R. (14 hs)	-.87	-.95	-.88	-.89	-.83	-.64	-.45	-.66	-.16	-.46	-.68	-.88
H.R. (med)	-.92	-.37	-.81	-.90	-.86	-.85	-.52	-.63	-.20	-.48	-.64	-.86
Insol.	.92	.93	.87	.86	.83	.78	.89	.82	.56	.73	.48	.68
Wind	.11	.32	.32	-.07	.36	.13	.49	.36	.18	-.17	.13	.07
Veracruz												
H.R. (14 hs)	-.22	-.14	-.60	-.47	-.68	-.36	-.36	-.15	-.19	-.48	-.65	-.14
Insol.	-.31	-.23	-.06	-.34	-.16	-.48	-.73	-.18	-.58	-.01	-.37	-.31
Wind	58	.31	.58	.57	.01	-.36	-.18	.04	.14	.50	.65	.72
T.med.	1	-.25	.03	.07	.07	.35	.75	-.15	-.38	-.14	-.56	-.27
H.R.	-.52	-.01	-.69	-.46	-.78	-.41	-.41	-.14	-.22	-.41	-.76	.12

These results indicate that in this region temperature cannot be used to estimate evaporation. Furthermore, the possibility of using THORNTHWAITE's method (1974) based exclusively on temperature (and the days length) to determine evaporation had to be eliminated. This author used air temperature as sole indicator for the amount of energy available for evaporation. However, as pointed out by several authors the temperature in a given area is not a single function of solar radiation, but it also incorporates to a great degree the thermal regime of air masses; also, on a daily and monthly basis the air temperature shows a lag with respect to radiation on account of the heat stored in the soil (DAVIES/McCAUGHEY, 1968; CHANG/ROOT, 1975). In fig. 3 it can be seen that in 1973 the maximum temperature occurred in the Plateau one or 2 months after the global radiation maximum in March-April. The relation between temperature radiation also depends on the albedo variations, the heat flow towards the air, and the advection energy; the latter being of great importance on the high lands of the plateau as well as on the coast.

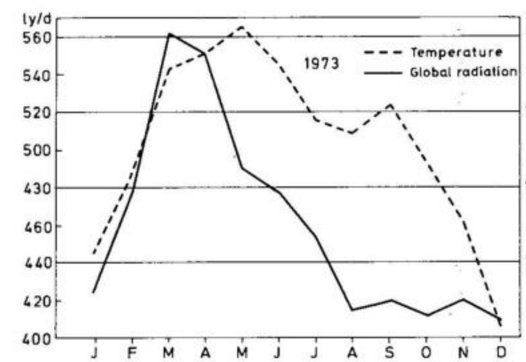

Fig. 3: Monthly values of global radiation (ly/d) at Chapingo

For the stated reasons, it could have been anticipated that air temperature offered few possibilities of success in the region under study for the assessment of evaporation.

b) Relative Humidity

Correlation coefficients between pan evaporation and relative humidity were calculated: the relative humidity at 7:00 and at 14:00 and the resulting average of these two values. The evaporation of the Class A Pan shows a high degree of correlation with relative humidity measured at 14 hs. and with the daily average during the warm and rainy months (when due to cloud inter-ception reduction of radiation coincides with an increase of humidity) corre-lation decreases in some places (Puebla) in the cold and dry months (Fig. 4). In the humid areas (Jalapa) of the Sierra, the high correlation of pan evapora-tion with humidity continues almost the whole year long. However, on the coast (Veracruz) it turns very poor and variable from month to month (Ta-ble 2). In general, the correlation with humidity at 7 a.m. was less than with the one at midday or with the average relative humidity.

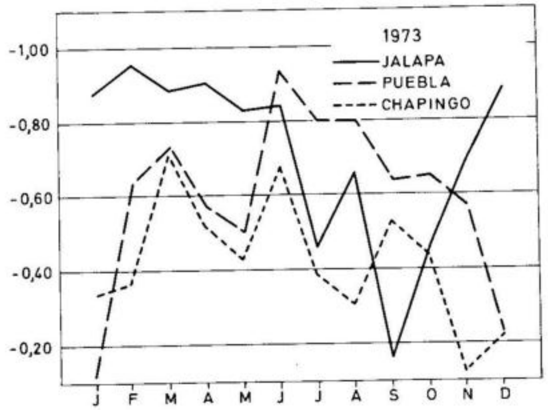

Fig. 4: Correlation between Class A Pan evaporation and relative humidity at 14 hs

The possibility that the evaporation of Class A Pans could be correlated with another measure of the dryness of the air (saturation deficit) was also ex-plored:

a) the difference of saturation vapour pressure at maximum (e_{tmax}) and minimum (e_{tmin}) temperatures
b) the difference of vapor pressure at a so called "synthetic" temperature (FITZPATRICK, 1963) and at mean temperature. This author expresses synthetic temperature θ as a function of maximum temperature and the days length as follows:

$$\theta = k_{tmax} (1+ \log N/12) \ldots\ldots 1)$$

where N is the mean length of day in hours, K is a constant factor; for stations in the continent it has a value of 0.9.

Table 3 shows the correlation between evaporation Class A Pans and the humidity expressions:

$$(e_{tmax} - e_{tmin}) \ldots\ldots 2)$$
$$(e_{\theta} - e_{s}) \ldots\ldots 3)$$

Table 3: Correlation between pan evaporation and saturation deficit as expressed by 2) and 3) for Chapingo station.

	J	F	M	A	M	J	J	A	S	O	N	D
2)	.17	.41	.21	.24	.50*	.60*	.47*	.47*	.39*	.22	.11	.12
3)	.36	.22	.58*	.62*	.11	.36	.27	.03	.26	.50*	.19	.09

* 1 % level of significance.

Although, in general the values are low, only in the rainy season is the correla-tion significant between Class A Pan evaporation and the humidity deficit eccording to expression 2), while with FITZPATRICK's formula the cor-relation was significant only for three months.

In summary, it can be concluded that if during some wet months the cor-relation between evaporation and humidity is relatively high, it is not pos-sible however to use in the central region of Mexico, and all along the year an empiric equation such as:
Eest = a+b (e_a - e_d) where evaporation is expressed only as a function of humidity.

On the other hand, this result could also have been anticipated since, as it is known, evaporation is proportional to the deficit of water vapor pressure only when the air temperature is equal to the surface water temperature, a condition which, as CHANG (1971) indicates, is rarely observed. In absence to the equality of air and surface water temperature, evaporation is propor-tional to the gradient of vapor pressure between the evaporating surface and the air. Unfortunately, in Mexico there do not exist systematic observations of this vertical hygrometric gradient; consequently, their degree of correla-tion with the pan evaporation can not be evaluated. For comparison, fig. 5 shows for a station on the plateau (Chapingo) the estimated potential evapora-tion a) with THORNTHWAITE's formula and b) with a formula based on the saturation deficit as suggested by PAPADAKIS (1966):

$$Eo = 7.5 (e_{tmax} - e_{tmin} - 2) \ldots\ldots 4)$$

Although both formulas underestimate the Class A Pan evaporation, the estimates with equation 4) were more approximate to the values observed. The variation of evaporation according to THORNTHWAITE's formula were very similar to those of temperature, as would be expected.

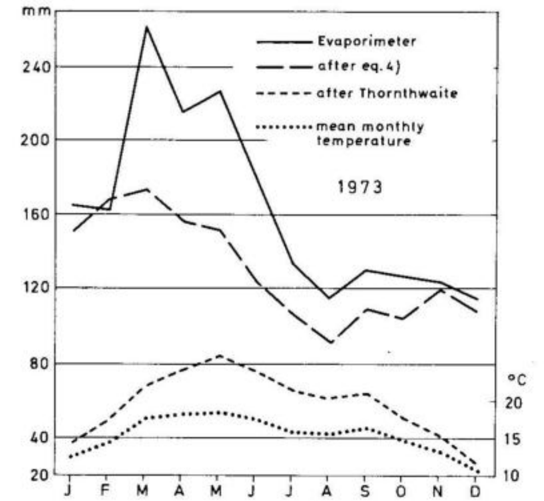

Fig. 5: Evaporation by saturation deficit (eq. 4) and according to THORNTHWAITE's method at Chapingo

c) Sunshine

There was a high degree of correlation between sunshine hours and pan evaporation during the warm months and the rainy season in the plateau. This agreement continued almost all year in the more humid climate of the Sierra Madre (Jalapa) (Fig. 6). This can be explained by the normally high level of correlation that exists between sunshine and radiation. However on the coast (Veracruz) the advected cool air coming from the sea in summer, and that associated to the 'Northers' in winter, result in a poor correlation.

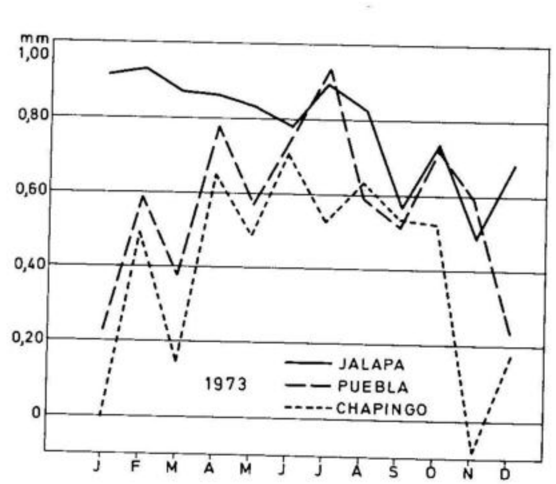

Fig. 6: Correlation between Class A Pan evaporation and hours of sunshine

d) Wind

This was one of the meteorological factors that indicated low values of correlation with Class A Pan evaporation in the rainy season (when the winds are weak); however it went up appreciably, on the plateau as well as on the coast, in the dry season, with the more vigorous influence of the 'northers' (Fig. 7).

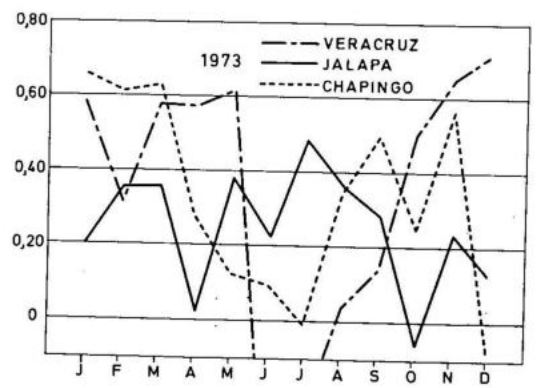

Fig. 7: Correlation between Class A Pan evaporation and wind velocity

The analysis of percentual contribution of the meteorological factors mentioned above, to the total variance of evaporation, in general gave similar results to the correlation analysis, though less conclusive. For that reason, they are not discussed here.

e) Solar radiation

The rate of evaporation depends on radiation, wind, and air humidity. Of the three, radiation is the most important. MUKAMAL and BRUCE (1960) found that the relative importance of radiation, wind, and humidity, to evaporate the water of an evaporimeter is 80 : 14 : 6 respectively. On the plateau the daily global radiation for 1973 shows a significant correlation of 0.562 (1 % level of significance) with the Class A Pan evaporation for Chapingo station (Fig.8), the regression equation being:

$$Eo = 0.0129R - 0.714 \quad \text{.....................5)}$$

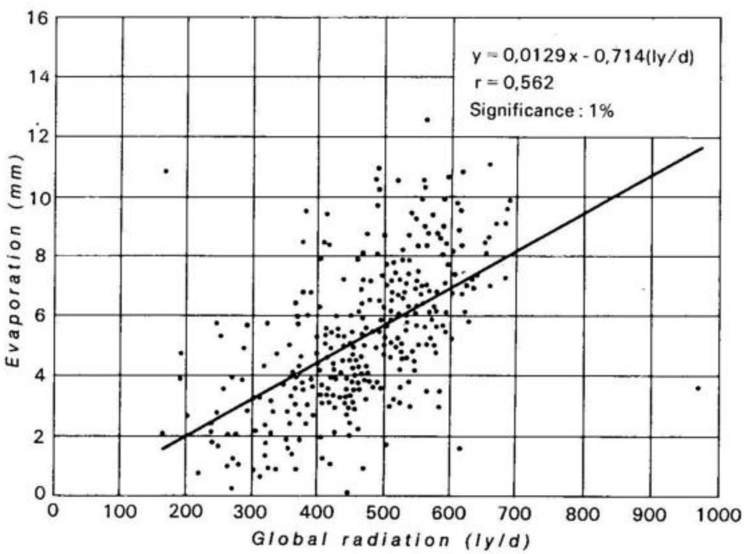

Fig. 8: Correlation between Class A Pan evaporation and global radiation (ly/d) at Chapingo

If the correlations are computed on a monthly basis, they are significant only during the months of the rainy season as is seen in table 4.

Table 4: Correlation between pan evaporation and global radiation in Chapingo (1973).

J	F	M	A	M	J	J	A	S	O	N	D
0.21	0.53*	0.32	0.39	0.20	0.77*	0.46*	0.63*	0.46*	0.50	0.27	0.26

* 1 % level of significance.

5. PENMAN's method to estimate evaporation

PENMAN's method to estimate evaporation is based on sound physical principles and is a simplified expression of the energy balance equation:

$$Ep = \frac{Rn\,\Delta + e_a}{\Delta + \gamma} = \frac{Rn\,\Delta/\gamma + \Delta}{\Delta/\gamma + 1} \quad \text{.....................6)}$$

Ep – evaporation of an open surface of water.

Δ – slope of saturation vapour pressure relative to temperature (de_a/dT); at temperature T (mb/C^o).

e_a – saturation vapour pressure in mmHg at temperature T. (see Smithsonian Meteorological Tables, p. 352).

Rn = $(1-r)Qa(0.18+0.55\,n/N)-T^4\sigma(0.56-0.92\sqrt{e_d})(0.10+0.9\,n/N)$ ....6)

r – Reflection coefficient. For an open surface of water PENMAN uses an annual mean value of 0.05.

Qa – Angot's radiation; that is, the intensity of solar radiation in the upper limit of the atmosphere, which is a function of latitude, and the time of year. (Smithsonian Meteorological Tables).

n/N – Observed hours of sunshine divided by possible sunshine hours. The values of N are found in Smithsonian Meteorological Tables.

σ – Stefan-Boltzman constant; 2.01×10^{-9}, mm/d

ad – Saturation vapour pressure, mm Hg at dewpoint temperature.

γ – Psychrometric constant (0.49 for ^oC and mm Hg)

Ea = $0.35\,(e_d - e_a)(1 + U_2/100)$ ....7)

Ea = aerodynamic component

U_2 – run of the wind in miles/day.

PENMAN's equation establishes that evaporation is a function of available radiant energy, and secondly depends on an aerodynamic factor (Ea) expressed by saturation deficit and wind speed.

The non-dimensional ratio $\frac{\Delta}{\gamma}$ is a function of temperature and determines the relative importance of above mentioned factors (PENMAN 1956). For the range of mean temperatures that prevail in the central plateau the energy term (Rn) usually has a higher weight than the aerodynamic term (Ea) as will be seen.

Therefore the accuracy of the estimate of evaporation depends on the precision with which the Rn term has been measured or estimated. Since up to the present time in this region there are not as yet any measurements of net radiation, it was decided to use PENMAN's original formula for Rn (eq. 6). YOUNG's (1963) program to obtain Ep by computer on a daily basis was used with modifications to do the calculations.

The daily computations for Ep, as well as the correlations and monthly evapotranspiration were done at the Mathematical Institute of the University of Bonn. The estimates for Ep on a monthly basis were done with a pocket calculator. Although PENMAN does not recommend the use of his method to obtain daily values, this was done in order to compare the results with daily pan evaporation, and with the estimated monthly climatic averages.

6. Results

a) Daily evaporation

Figs. 9, 10, 11 show the daily values of evaporation of Class A Pan, and the corresponding estimates with PENMAN's formula in months for the wet season as well as for the dry season for a characteristic Plateau station (Chapingo). Stations typical of the more humid climates of the Sierra slopes (Jalapa) and the coast (Veracruz) were also included for comparison.

P l a t e a u: It is readily seen as was expected, that the quotient Ep/Eo (estimated value/observed pan evaporation) approaches unity in the subhumid plateau during the rainy months and the estimated daily evaporation values Ep are very close (although with short amplitude) to those of the evaporimeter. For example, in Chapingo the correlation coefficient between Ep and Eo is an average of 0.63 to the 1 % level from June-September, decreasing the rest of the year as seen in table 5.

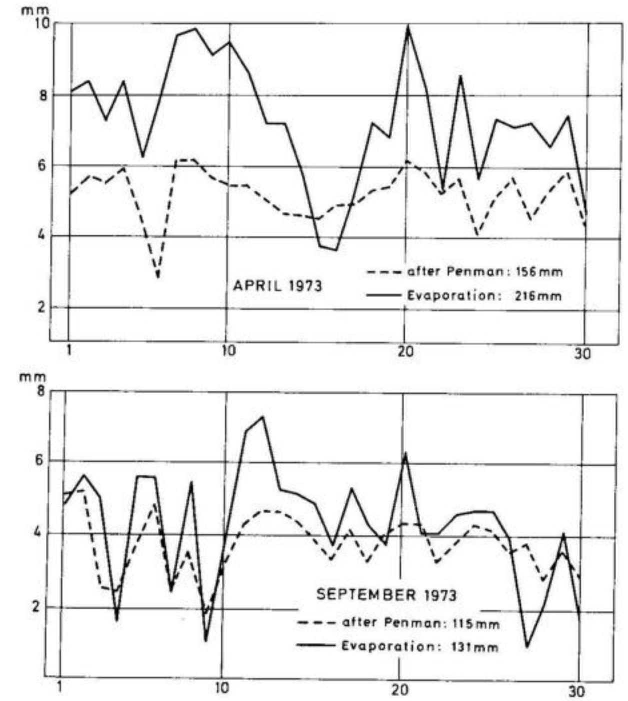

Fig. 9: Daily values of Class A Pan evaporation and PENMAN's corresponding estimates at Chapingo

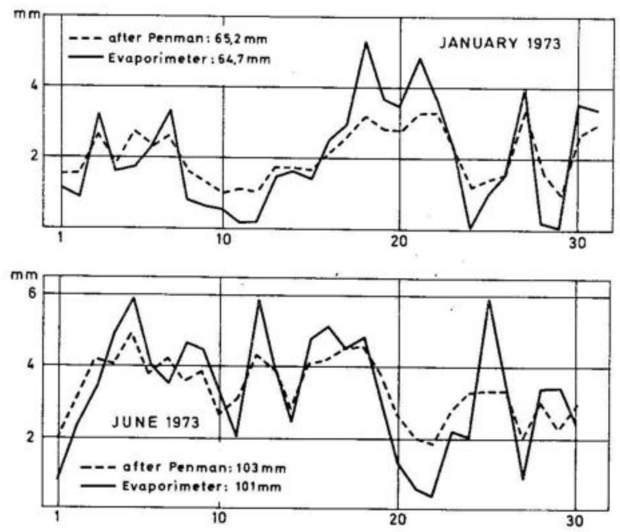

Fig. 10: Daily values of Class A Pan evaporation and PENMAN's corresponding estimates at Jalapa

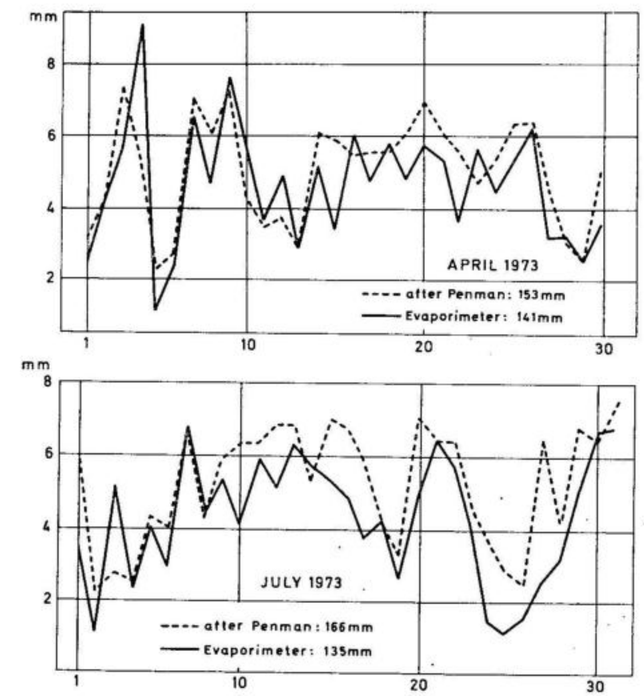

Fig. 11: Daily values of Class A Pan evaporation and PENMAN's corresponding estimates at Veracruz

Table 5: Correlation coefficients between pan evaporation (E) and estimates with PENMAN's formula (Ep)

E	F	M	A	M	J	J	A	S	O	N	D
0.71*	0.58*	0.58*	0.67*	0.54*	0.72*	0.60*	0.63*	0.68*	0.47*	0.10	0.11

* 1 % level of significance

In the dry season the daily estimated evaporation values are much less than those observed in the pan due to the strong energy advection. During this period the loss of water by evaporation in the evaporimeter exceeds that attributed to net radiation (Rn). This phenomenon has been observed in different regions with arid and semiarid climates (TANNER/PELTON, 1960; LEMON/LAZER/SATTERWHITE, 1957; LANG/EVANS/HO, 1974). It is very likely that the subsiding movements that predominate in the plateau during this period, contribute with additional amounts of energy to increase evaporation, as has been observed by McILROY/ANGUS (1964) and EVANS (1971) in the arid regions of Australia.

S i e r r a a n d C o a s t a l P l a i n s: In the eastern limits of the plateau, on the slopes of the Sierra Madre (Jalapa) and on the coast the relation Ep/Eo is close to unity not only in the rainy season, but also in the cold season due to the influence of the humid 'Northers'. In Veracruz, the cool sea air advection preduces a reduction of the pan evaporation (especially in the rainy season when the breezes are strengthened by the more vigorous Trades) and PENMAN's values slightly overestimate evaporation.

b) Monthly evaporation

Using the monthly averages for temperature, relative humidity, sunshine and wind, the monthly evaporation was calculated with PENMAN's formula, and compared with the corresponding values of Class A Pans for the different stations (Figs. 12/13). In these figures the sum total of PENMAN's daily values calculates by computer is also shown. These values do not differ significantly from the estimated monthly averages, which shows that on the average for the month the daily differences are compensated.

P l a t e a u: It can be seen that, as with daily evaporation, there is a strong effect of energy advection during the dry months in the Plateau (Chapingo); this effect decreases with decreasing altitude and distance to the sea (Fig. 13).

T h e A d v e c t i o n E f f e c t: If the wind that passes through the evaporimeter comes from neighbouring dry and warm areas, the sensible heat transferred results in an additional increment of evaporation in the pan. If, on the contrary, the air comes from a cool and humid area as the sea, the evaporation

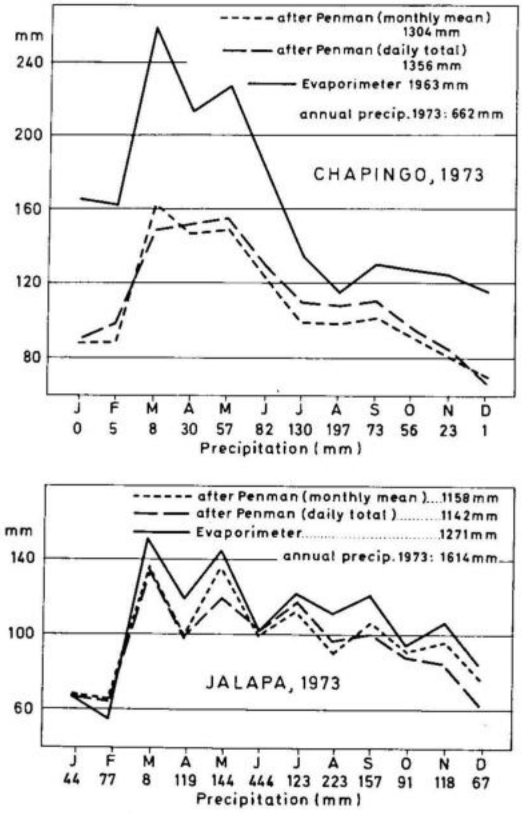

Fig. 12: PENMAN's estimated monthly values of evaporation at Chapingo and Jalapa

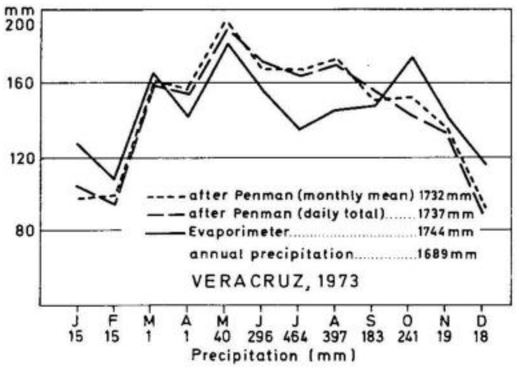

Fig. 13: PENMAN's estimated monthly values and pan evaporation at Veracruz

in the pan is reduced. Thus, in the coastal areas, the advection of the cool air in the afternoons of the wet season acts as an evaporation reducer as was noted in the daily evaporation at Veracruz. Since PENMAN's formula does not allow for the effect of energy advection, so prevalent in the subhumid climate of the Plateau during the dry season, the difference of the values that result utilizing PENMAN's formula which those of the evaporimeter, are a rough estimate of the energy advection. As a first approximation the advection fraction also can be evaluated as a fraction of net radiation Rn.

If stored soil heat is disregarded (which for a monthly period is small in a tropical region (DAVIES, 1966), then the evaporation E of the evaporimeter is:

$$E = Rn/1 + \quad \text{...................8)}$$

and if a wet surface is considered, then almost all the net radiation would be used in evaporation. Thus BOWEN's ratio (ß) would be small. Evaporation or 'potential water loss' can be calculated thus as DAVIES has proposed assuming that all the energy of net radiation is used for evaporation.

Net radiation can also be estimated from monthly global radiation. Using radiation data from characteristic stations in a wide range of climates and latitudes, DAVIES (1966) found the following linear relation between Rn and global radiation.

$$Rn = 0.617\,Q - 24\ \text{cal/cm}^2. \quad \text{....................9)}$$

In order to evaporate 10 mm of water, 590 calories are needed; therefore from eq.9):

$$Rn = 0.017\,(0.617\,Q - 24)\ \text{mm.d} \quad \text{...................10)}$$

Table 6 shows the monthly values of Eo/Rn ratio between pan evaporation and net radiation for Chapingo (calculated from eq. 10).

Table 6: Monthly values of ratio between pan evaporation (Eo) and net radiation Rn (mm) in Chapingo.

	J	F	M	A	M	J	J	A	S	O	N	D
Q	424	477	563	552	491	478	455	415	505	411	452	409
R_n	125	129	170	161	147	138	135	122	147	121	129	129
E_o/R_n	1.33	1.26	1.62	1.34	1.55	1.31	1.00	0.95	0.89	1.04	0.96	0.96

In this area of the plateau, the advective energy is up to 50 % higher than the energy of net radiation Rn used for evaporation in the warm months of the dry season. However this is an underestimation: the energy for advection should be even higher since Rn according to DAVIES' formula (9) has been calculated for albedos of approximatly 0.20 to 0.25.

In the rainy season the relation Eo/Rn is close to one, which corroborates that in a humid environment the energy term Rn in PENMAN's formula is more important then the aerodynamic term (Ea). This is readily seen in table 7 where monthly values of the energy (Rn), and aerodynamic (Ea) terms and PENMAN's evaporation (Eo), as well as the relative weight of Rn and Ea for several stations are given. The relative weights were calculated as follows:

$$WH = (Eo - Ea)/(Rn - Ea); \; WE = (Eo - Rn)/(Ea - Rn) \quad \text{...................11)}$$

Table 7: Relative weight of energy and aerodynamic terms in relation to PENMAN's evaporation (Eo) for typical stations

Chapingo

	J	F	M	A	M	J	J	A	S	O	N	D
R_n	2.75	3.25	5.17	629	5.36	4.73	4.08	4.12	4.21	3.51	3.16	2.33
E_a	3.05	3.15	5.46	4.24	3.76	2.99	1.68	1.57	1.99	2.03	2.02	2.06
E_o	2.86	3.19	5.27	4.94	4.83	4.11	3.20	3.19	3.42	2.95	2.69	2.21
W_H	.63	.50	.66	.65	.67	.64	.63	.64	.64	.62	.59	.56
W_E	.37	.50	.34	.34	.33	.36	.37	.36	.36	.38	.41	.44

Jalapa

	J	F	M	A	M	J	J	A	S	O	N	D
R_n	2.28	2.59	4.18	3.22	4.32	3.68	4.03	3.12	3.76	3.19	2.79	2.14
E_a	1.85	1.49	4.90	3.34	4.52	2.49	2.59	2.33	2.80	2.38	3.89	2.86
E_o	2.11	2.18	4.39	3.26	4.38	3.30	3.58	2.87	3.47	2.91	3.15	2.41
W_H	.60	.63	.71	.66	.70	.69	.69	.68	.70	.65	.67	.63
W_E	.40	.37	.29	.34	.30	.31	.31	.32	.30	.35	;33	.37

Veracruz

	J	F	M	A	M	J	J	A	S	O	N	D
R_n	2.39	2.94	4.91	4.32	5.67	5.66	5.57	5.25	5.29	4.10	3.99	2.76
E_a	4.84	4.81	5.87	7.93	8.11	5.49	4.99	6.57	4.31	5.85	5.98	3.41
E_o	3.12	3.51	5.16	5.25	6.26	5.62	5.43	5.56	5.05	4.53	4.49	2.95
W_H	.70	.70	.74	.74	.76	.76	.76	.77	.76	.75	.75	.71
W_E	.30	.30	.26	.26	.24	.24	.24	.23	.24	.25	.25	.29

The weight of the heat term is always larger than the aerodynamic term Ea and increases even more in the lower, warmer lands (up to 76 % in Veracruz); on the other hand the aerodynamic term exhibits a seasonal variation; it is large during the dry season due to the simultaneous influence of a decrease in humidity and a greater intensity of "Northers" which sweep over the region in the winter.

The preceeding results indicate that the weights given to the energy and aerodynamic components in estimating evaporation with PENMAN's formula are adequate for the region.

Proof that the relative importance given by PENMAN to the above mentioned components is correct is the fact that the energy term shows a greater correlation with pan evaporation during the rainy months (when it has a relatively greater weight) while the aerodynamic component Ea shows a higher correlation with the pan evaporation during the windy months of the second half of the dry season for the plateau region (Chapingo). The same occurs in the flanks of the Sierra Madre (Jalapa) although here the correlation of evaporation with the energy component registered the highest values for all the region and was significant all year (except October). In the slopes of the Sierra Madre, the aerodynamic component is highly correlated with evaporation during the winter months, when the Northers are more frequent. In the coastal lowlands where the cool air advection considerably modifies the relationship between radiation and temperature, the correlation between

evaporation and the energy component is very low; on the other hand the aerodynamic component shows the same high correlation that exists in the plateau and in the Sierra Madre with the Northers. This is shown in table 8.

Table 8: Correlation coefficients between pan evaporation and energy (Rn) and aerodynamic (Ea) terms.

	J	F	M	A	M	J	J	A	S	O	N	D
						Chapingo						
R_n	.01	.33	.06	.47	.51	.70	.53	.64	.64	.47	.06	.12
E_a	.72	.62	.69	.64	.44	.54	.20	.37	.63	.39	.45	.05
						Jalapa						
R_n	.89	.92	.86	.84	.78	.77	.88	.79	.60	.75	.37	.57
E_a	.88	.61	.87	.88	.87	.86	.66	.55	.27	.45	.69	.85
						Veracruz						
R_n	-.30	.20	.00	.31	.10	.47	.73	.18	.58	-.03	-.40	-.29
E_a	.70	.37	.73	.66	.83	.20	.25	.06	.34	.52	.75	.25

1 % level of significance

During November and December the oasis effect is at a minimum on the plateau due to the moisture that remains in the soil after the rainy season, as shown by the ratios (lower than unity) Eo/Rn for those months (Table 6).

Finally, if the monthly values of evaporation calculated with PENMAN's method are divided by the pan observations for those 1973 months when precipitation was greater than evaporation, in 6 stations from the plateau to the coast, the ratio gets close to the unit, in the average of June to September for all the region.

Table 9: Relation between the PENMAN evaporation values (Ep) and pan evaporation (Eo) for several months in 1973 when rain exceeded evaporation in Class A type Pans:

	JUN.	JUL.	AUG.	SEPT.	
Chapingo	-	0.85	0.85	-	
Puebla	1.25	1.52	1.18	0.97	
Orizaba	0.69	1.01	0.94	1.00	
Jalapa	0.98	0.91	0.80	0.87	
Veracruz	1.08	1.24	1.17	1.01	
Pachuca	0.96	-	-	-	
average	0.99	1.10	0.94	0.95	1.00

Since the selected months were those when rain exceeded evaporation, it is valid to assume that this was the 'potential' (that is, with a minimum of advection and a continous availability of water for evaporation) of PENMAN's model. The results obtained thus, in these months on a regional scale would be, on the average similar to the pan observations, as can be seen in table 9. Consequently, PENMAN's formula can be used as a first approximation during the wet months to predict evaporation with a reasonable degree of accuracy in the central area of Mexico.

7. Relationship between evaporation and potential evapotranspiration

Numerous studies have been made of the relationship between potential evapotranspiration (Ep) and the evaporation of Class A type Pans (Eo). Results show that the pan evaporation is very similar to the evapotranspiration of some crops, for example:

Crop	Ep/Eo	Reference
Rice	0.98	EVANS (1971)
Sugar cane	1.10	CHANG (1961)
Corn (ripe)	0.90	FRISCHEN/SHAW (1961)
Grass (avg)	0.90	ECKERN (1959)

Consequently, PENMAN's formula as well as the evaporimetric observations may be used in the area as a first approximation to determine the water needs of a given crop in an agricultural cycle, bearing in mind that the ratio Ep/Eo varies in an increasing fashion as the crop grows, reaching its maximum value at maturation.

In spite of the descrepencies that may exist due to the improper exposure of the pan or that the crop does not completely cover the ground, the ratio Ep/Eo between evapotranspiration and pan evaporation increases approximately from 0.8 for short crops to about 1.0 or slightly more for taller crops such as corn or sugar cane (CHANG, 1971). A better approximation of evapotranspiration estimate with PENMAN's method could be obtained if instead of estimating the energy term, net radiation measurements in the region were available.

8. Conclusions

In Central Mexico the days in which evapotranspiration reaches its maximum or potential value, occur in the rainy months, May to October. In the dry season a high proportion of residual energy is used to heat the air at the same time that the lack of homogeneity of the plateau natural surfaces results in a marked oasis effect.

The natural vegetation, as well as perennial crops from lack of water, especially in the second half of this period, when the soil humidity has been considerable reduced by the combined effect of a high level of radiant energy and a marked deficit of air humidity. The present study has examined various methods to estimate evaporation from ordinary climatic data. These methods are of particular interest in view of the lack of evapotranspiration observations in the region. PENMAN's method of e nergy balance generally gives better results in the central region of Mexico than those based on temperature (THORNTHWHAITE) or the saturation deficit.

In the rainy season months, the evaporation estimates of an open pan of water with PENMAN's formula, show good agreement with the observations of Class A Pans. This confirms the findings made by other authors (LINSLEY, 1958; CHAPAS/REES, 1964) that in reality PENMAN's formula is a method of estimating pan evaporation.

There were not any high, significant, general and persistent correlations found for the whole year between the pan evaporation and meteorological factors (temperature, humidity sunshine and wind) that would allow a reliable regression that would permit the prediction of evaporation as a function of a single climatic variable. The correlation between global solar radiation and pan evaporation in the plateau (Chapingo) was 0,562, at 1 % level of significance.

Because the accuracy of evaporation estimate with PENMAN's formula depends mainly in the precision with which available radiation for evaporation (net radiation) is estimated, it would be advisable that measurements of this parameter be started in Central Mexico in order to determine if the constants given by PENMAN for the energy term are appropriate for this region. It has been noted in other countries (FITZPATRICK 1956) that most errors made in the estimation of the energy component are usually due to the use of inappropriate constants in the empiric formulas that the method requires.

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Zusammenfassung

In großen Gebieten Zentralmexikos übersteigt die jährliche Verdunstung die jährlichen Niederschlagshöhen. Da sich die Stärke der Verdunstungskraft der Luft aus Feuchte, Temperatur, Windgeschwindigkeit und Strahlung ergibt, wird der Versuch unternommen, funktionale Beziehungen zwischen diesen meteorologischen Parametern und der in Class A Wannen gemessenen Verdunstung herzuleiten. Unter gleichzeitiger Berücksichtigung von Regenzeit und Trockenzeit konnten keine persistenten Korrelationen für Zentralmexiko zwischen diesen Größen bestimmt werden.

Nach der PENMAN Formel, wobei auf Tages- und Monatsbasis gerechnet wurde, ergeben sich nur für die Regenzeit (Mai-Oktober) in den subhumiden Bereichen des Hochplateaus Werte, die etwa den empirischen Class A Pan Messungen entsprechen. In den Monaten der Trockenzeit sind die nach PENMAN berechneten Werte erheblich geringer, als die Class A Pan Meßwerte. Das ist eine Folge der beständigen Energieadvektion während der Trockenzeit. Dieser sogenannte Oaseneffekt ist weniger stark an den Osthängen der Sierra Madre Oriental und in den Küstenniederungen ausgebildet als auf dem Hochland.

Eine vergleichende Betrachtung des Energieterms und des aerodynamischen Terms zeigt die besondere Bedeutung des Energieterms. Die Werte dieses Terms sind beständig größer als die des aerodynamischen Terms, obwohl letzterer starke jahreszeitliche Variationen erfährt. Maximalwerte des aerodynamischen Terms werden in der Trockenzeit als Folge der geringen Feuchte und der mit den "Nortes" verbundenen starken Luftmassenadvektion beobachtet.

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