INFLUENCE OF EVAPOTRANSPIRATION RATES ON THE DEVELOPMENT OF THERMALS

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Summary

Hourly amounts of heat required for evapotranspiration (E) for seven days of the Great Plains Turbulence Field Program are determined by subtracting sensible heat conducted into the soil (G) and transferred to the air (Q) from net radiation (R). Q was calculated from wind and temperature profile data with a relationship derived by Webb. The daily sums of E ranged from 228 cal/sq cm on the day with the greatest soil moisture (S.M. = 9%), to 79 cal/sq cm on the day with the least, (2.5%). Corresponding values of Q ranged from 122 for the former to 218 for the latter, although (R-G) decreased from 350 to 258 cal/sq.cm for the same two days.

Bowen ratios determined from daytime sums were greater than unity (1.5, 2.8 and 1.7) for 3 days with S.M. < 6% and less than unity (0.54, 0.52 and 0.45) for 3 days with S.M. > 7%. Average Q was at a maximum an hour later for the former than for the latter. Average cumulative curves of Q/(R-G) for both were nearly linear, but divergent until midday. After noon the "dry-day" curve was concave upward and the "wet-day" curve concave downward. It is concluded that relatively small changes in available soil moisture, by changing the amount of evapotranspiration and hence the amount of Q, can make relatively large differences in convective layer growth and therefore in thermal strengths. Moreover, the different cumulative patterns for "wet" and "dry" days may account for correspondingly different times of maximum thermal development, independent of cloudiness.

1. Introduction

The strengths and sizes of thermals are known to increase with increase in depth of the convective layer. Often called the mixed layer, it grows in depth during the day by gaining sensible heat from the ground. Generally, the more the sun heats the ground, the deeper the convective layer becomes. Greatest depths are reached during summer afternoons in dry climates. If the ground is covered with transpiring plants or if the soil is moist, however, evaporation and transpiration, i.e., evapotranspiration, may require enough solar heat to limit the available sensible heat and restrict the growth of the convective layer. Heat available for convective layer growth may be regarded as the amount of solar heat incident outside the atmosphere, i.e., extra-terrestrial insolation, depleted by:

a) Absorption, scattering and reflection by the atmosphere and clouds;
b) Reflection from the ground;
c) Absorption by the soil; and
d) Evapotranspiration.

In dry climates the presence or absence of clouds and the amount of evapotranspiration are often the major controls of convective layer growth. Unlike control by clouds, that due to evapotranspiration is not easily recognized and evaluated. A major cause of the difficulty seems to be the lack of quantitative information for various weather, vegetation and ground conditions. Such information is scarce primarily because of the difficulty of measuring evapotranspiration in natural situations.

In a recent detailed work, Lindemann (1) showed the importance of evapotranspiration from various kinds of vegetative growth in controlling the amount of heat available for convective layer development. He emphasized the need for more quantitative information. The analysis described in this paper was designed to provide some of the needed information. A specific goal was to develop information useful for forecasting convective layer depths and their rates of growth for planning operations and setting tasks for soaring competition. The data used were those obtained by the Johns Hopkins University group during the Great Plains Turbulence Field Program at O'Neill, Nebraska, U.S.A., in August and

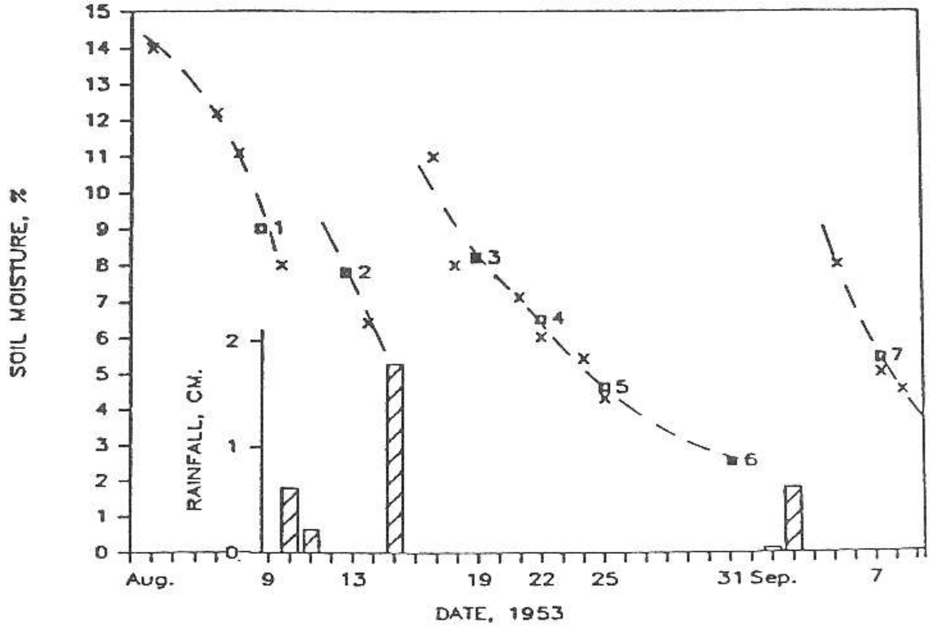

Figure 1. Soil moisture (X and ☐) and rainfall (vertical bars), O'Neill, Nebraska (USA). (Adapted from Ref. 3.)

September, 1953. They were published by Thornthwaite, et al. (2) and by Lettau and Davidson (3,4). Complete descriptions of instruments, measurement methods, and overall conditions are given in (3) and (4).

Central to the analysis is a relatively recent work of Webb (5) that made it possible to calculate sensible heat flux for daytime hours of the seven observation days of the O'Neill program. The results of those calculations were reported by Portman (6). In the present analysis, the calculated sensible heat flux values are combined with simultaneously measured net radiation and soil heat flux to obtain hourly amounts of latent heat flux required for evapotranspiration. Daytime sums of the hourly amounts are examined in relation to insolation components of the surface heat balance and to soil moisture. Amounts and patterns of available sensible heat are then shown to depend importantly on the amount of evapotranspiration.

2. Atmospheric and Surface Conditions During the O'Neill Program

The O'Neill observation site was chosen for its flatness and freedom from obstructions. All observations were made with southerly winds and the area south of the site had height differences of not more than three meters for a distance of more than a kilometer. A line of trees about 8 km to the south was the most prominent obstruction within about 16 km. The ground cover was a mixture of prairie grasses, about 75% Bouteloua gracillis (blue grama). There were scattered small spots of bare soil along with thin patches and thick clumps of grass.

Soil moisture, at 2.5 to 5 cm depth, and rainfall measurements are shown in **Figure 1**, adapted from (2). Observation dates are indicated on the abscissa and corresponding soil moisture percentages for each of the seven observation periods are shown in the body of the figure. As expected, soil moisture increased abruptly after each rainfall and then systematically decreased until the following rainfall. It was about 8%, or more, for the first three observation days and about 5%, or less, for the last three days. This diagram and data published in (3) were used to establish morning values of soil moisture. They are listed in Table I and used in the following to relate to evaporative heat flux amounts.

Cloud types and tenths of total sky cover as reported in (4) are listed in Table I for each of the observation days. Given also is the measured total insolation for each entire day and its ratio to the amount of extraterrestrial insolation. The latter was calculated with a solar constant of 1.965 cal/cm^2 min.

As can be seen, three periods, No's. 1,3 and 4, were mostly cloudy with middle and high clouds. The remaining four periods were either nearly or entirely clear. According to notes given in (4) the clouds in periods 6 and 7, all one tenth or less in total cover, were observed "in the distance." Apparently they did not interfere significantly with the amount of insolation at the ground because the radiation ratios for these two days, 0.75 and 0.76, were about the same as those for the two days reported to be completely clear, vis., 0.75 and 0.77. The ratios for the three cloudy days were 0.70, 0.71 and 0.73, indicative of thin cloud layers.

Daytime ranges of hourly average wind directions and speeds are also listed in Table I. Both the uniformity of direction and the high speeds are outstanding characteristics of these periods. The overall direction range was only 67 degrees (145 to 212 deg.) and the speed hourly averages ranged from about 5.5 to 12.6 mps., with relatively little variation during each period.

3. Data Characteristics and Analysis Methods

Hourly amounts of evaporative heat flux, E, were determined with the surface heat balance equation:

$$E = R - G - Q \qquad (1)$$

in which R is the net radiation exchange, G, the soil heat flux, and Q the turbulent transfer of sensible heat to the air.

The net radiation exchange is the difference between the downcoming and the outgoing thermal radiation. It includes both short-wave (solar) and long-wave (earth and atmosphere) components. The data used here were measured directly with a Gier and Dunkle aspirated, all-wave radiometer. They were published for each hour of observation in (2) and for every other hour in (4).

Table 1. Daytime heat flux totals and associated data for O'Neill observation days.

Period No.	1	2	3	4	5	6	7
Date, 1953	8/9	8/13	8/19	8/22	8/25	8/31	9/7
I	634	678	624	600	619	592	570
I/Ex	0.70	0.77	0.73	0.71	0.75	0.75	0.76
R	394	404	361	330	347	335	297
G	44	62	46	47	48	38	39
Q	122	117	98	135	180	218	163
S.M.	9.0	7.8	8.2	6.5	4.6	2.5	5.4
W.S.	8-11	7-9	5-6	6-8	10-12	8-10	7-10
W.D.	178- 181	204- 213	145- 188	157- 181	181- 192	177- 183	176- 184
Cloud Observations							
0630 CST	4AcCs	Clear	9AcCs	3AcCs	Clear	1ScAc	1Ci
0830 "	5AcCs	Clear	9AcCs	1Cs	Clear	Clear	1Ac
1030 "	9AcCs	Clear	7AcCs	9AcCs	Clear	1Ac	FewAcCi
1230 "	9AcCs	Clear	7AcCs	8Cs	Clear	Clear	FewCu
1430 "	7AcCs	Clear	7CuCs	9CuCs	Clear	1Cu	FewCuAc
1630 "	1Cs	Clear	4CuCs	--	Clear	Clear	FewCu

I = Insolation, Ex = Extraterrestrial Insolation, R = Net radiation, G = Soil heat flux, and Q = Sensible heat flux to air, cal/sq cm; S.M. = soil moisture, %; W.S. = Wind speed, mps; W.D. = Wind direction, degrees.

Soil heat flux for each hour was determined by Portman (6) from continuous recording made with a heat-flow transducer implanted about 2.5 cm below the surface. The measurements were supplemented with depth integrations of hourly temperature differences multiplied by appropriate heat capacities. The latter were indirectly determined from soil moisture and bulk density measurements. Details are given in (2) and (7).

As noted above, values of sensible flux, Q, were calculated with a relationship derived by Webb for vertical turbulent transfer in unstable conditions in the atmospheric surface layer. It is:

$$Q = \rho c_p k_u k_\Theta (U_b - U_a)(\Theta_b - \Theta_a) S_u^{-1} S_\Theta^{-1} \qquad (2)$$

in which ρ is density, c_p specific heat at constant pressure, k_u and k_Θ von Karman constants for wind and temperature, respectively, U_a and U_b average wind speeds at heights a & b, Θ_a and Θ_b average potential temperatures at the same two heights and S_u and S_Θ are functions of stability determinable from the Richardson number. Webb derived S functions for each of four stability ranges, making use of O'Neill data as well as data from similar field experiments in Australia. His analysis was based on similarity of wind and temperature profiles and did not depend on direct heat flux measurements.

For each hour's calculation, hour-average wind speeds at 0.8 and 3.2 meters height were used with 10-minute average temperatures at the same two heights. The temperatures were recorded at about the center of the hour for the wind speed means. Neither hour-long temperature averages nor ten-minute wind speed averages exist in the basic data. It is difficult to assess the influence of the unequal averaging periods for these calculations; they should be considered when evaluating the results of this analysis.

Accuracy of the temperature data was estimated to be within 0.02 deg C for the difference between measurements at two heights (3, p. 166). Errors in wind speed vertical differences were thought to be seldom more than 1 percent (3, pp. 32 and 133).

To determine Webb's S functions, Richardson numbers were calculated with the same wind and temperature data by the finite-difference method used by Lettau (3), Webb (5) and by others. A value of 0.41 was used for both von Karman numbers.

Finally, it should be noted that the reported soil moisture percentages were computed on a wet-weight basis. Soil samples were taken at different depths at different, apparently representative, locations in the measurement area. They were then weighed both before and after drying in an electric oven. The percentages were obtained by dividing the weight loss by the original "wet" weight.

4. Results

Daytime sums of net radiation, soil heat flux and sensible heat flux are listed in Table I. Hourly sums for the three "wet" days (soil moisture about 8% or more) and the three "dry" days (soil moisture about 5% or less) are shown graphically in **Figure 2**. In this diagram the length of each "stacked bar," positioned at the mid-point label for each hour, represents the net radiation for the hour. Calculated soil and sensible heat flux values are shown as portions of this amount, with the remainder representing the amount of evaporative heat flux for the hour in accordance with Equation 1. In **Figure 3** the sums of the components for each day are similarly shown.

Net radiation for the clear and essentially clear days shows uniform patterns, characteristic of clear-day insolation. The cloudy-day patterns, Periods 1 and 3, show considerably more variation from hour to hour. The evaporative heat flux pattern is also uniform for the clear "wet" day, Period 2, but has noticeably more variation from hour to hour on the "dry" days, Periods 5, 6, and 7.

The daily totals in Figure 3 show a small, general decrease of net radiation through the four-week period, apparently in correspondence with the changing season. The daily soil heat flux totals remains about the same, but the evaporative flux totals show a large decrease through the period similar to the general decrease in soil moisture clearly shown in Figure 1. There is a corresponding general increase in sensible heat flux during this time.

The same daily totals are shown also in **Figure 4**, along

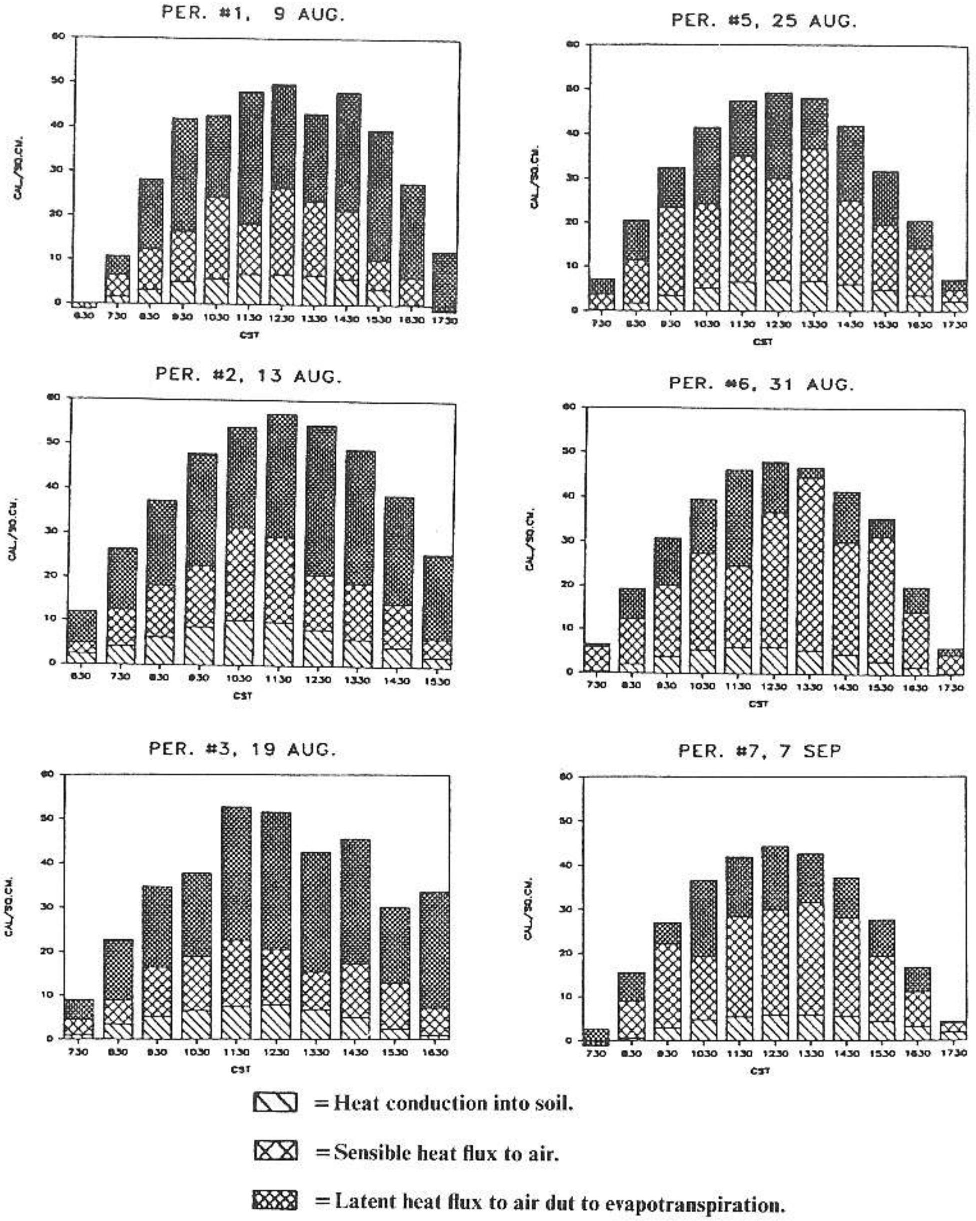

Figure 2. Heat Exchange components, hourly sums, for six observation periods.

with daily totals of 1) extraterrestrial insolation and 2) estimated insolation reflected from the ground. For each day the extraterrestrial insolation is proportioned into the amount of insolation measured at the ground, indicated by "A" and the amount depleted by the atmosphere, indicated by "C". The latter values were determined by subtracting the measured insolation daily sums from the calculated extraterrestrial sums. The amounts of insolation reflected from the ground shown here were obtained by assuming a constant albedo of 25%. Albedo measurements were made only during the first week in September, producing a daily average of about 25%.

This value was used to show the approximate magnitude of reflected insolation for each day for comparison with the calculated sensible and evaporative terms of the surface heat exchange.

Figure 4 clearly shows that the greatest variation among the heat exchange components for the seven observation days occurred in the sensible and evaporative components. The extraterrestrial insolation systematically decreased throughout the four-week period because of the decrease in solar declination angle. Atmospheric depletion, of course, is larger for cloudy days, but the differences are small compared to the variations in sensible and evaporative fluxes.

Heat flux into the soil is greatest on the clear day with relatively large soil moisture. It is about 40% greater than the average for the other six days. The otherwise small variability of this quantity was unexpected because of the observed changes in soil moisture. It is possible that the measurement methods were insensitive to such changes, but a re-examination of available data could not support this contention.

It is noted in (4) that the albedo may have varied significantly throughout the four-week period because of plant wilting in response to soil moisture depletions. If these were as much as 10 percentage points, they could be responsible for changes in sensible flux as large as those caused by variations in evaporative flux for these days.

The foregoing summary of daily variations in the different surface heat exchange components brings into focus the obvi-

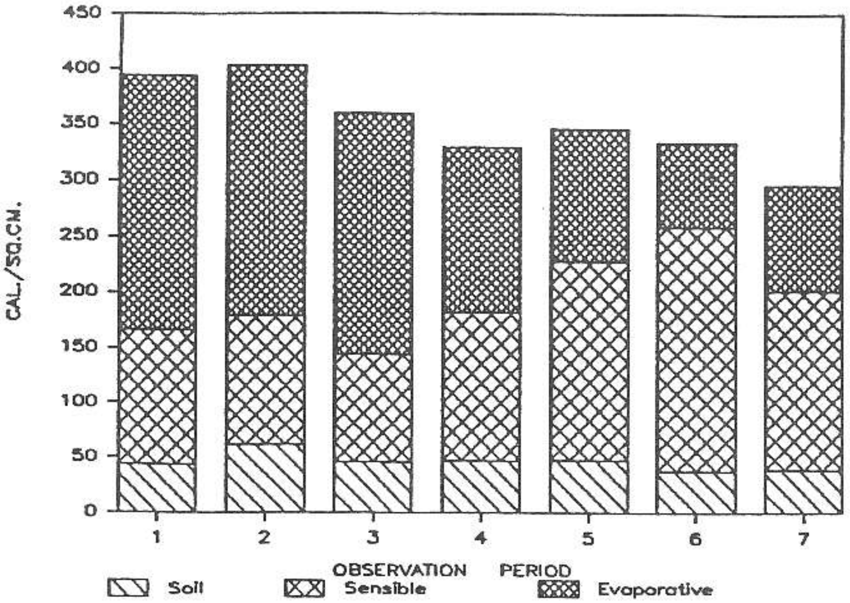

Figure 3. Heat exchange components, daytime sums for the seven observation periods.

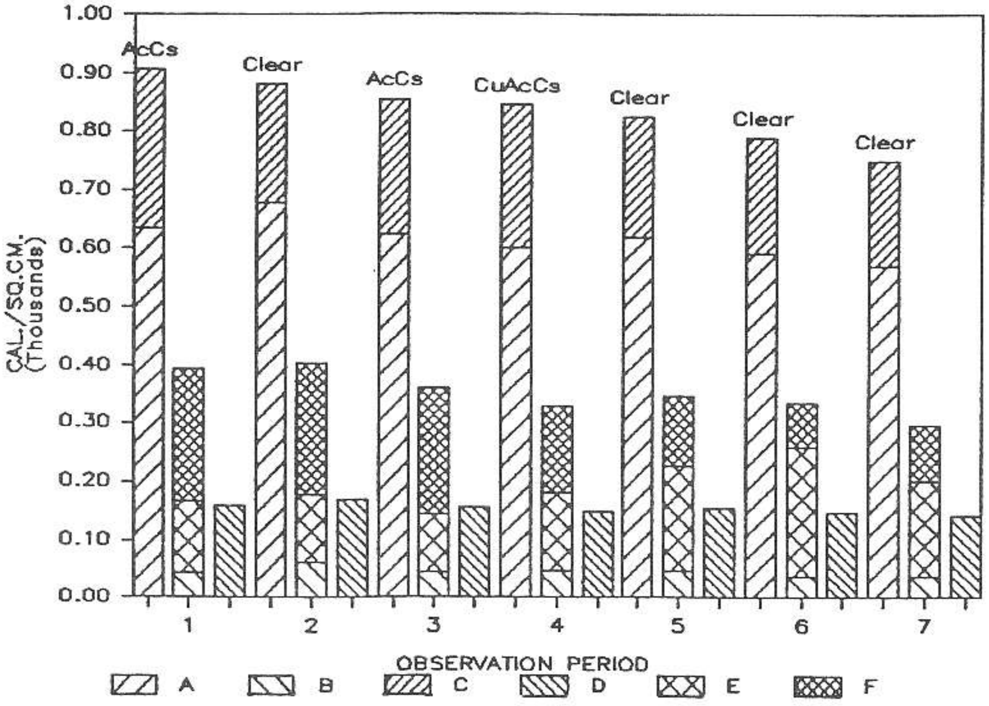

Figure 4. Insolation and heat exchange components for the seven observation periods.

A = measured insolation
B = soil heat flux
C = atmospheric depletion
D = estimated reflected insolation
E = sensible heat flux

ous dependence of evapotranspiration on soil moisture for these days. **Figure 5** shows this dependence. With allowance for sampling error in soil moisture measurements and sensible heat flux calculations, there appears to be a linear increase in evaporative flux with increase in soil moisture. The variation of evaporative flux is large. The day with the least soil moisture, Period 6 with 2.5%, had a total evaporative heat flux of 79 cal/sq cm, only one-third of that for the day with the most soil moisture, Period 1 with 9% and 228 cal sq cm. In contrast, net radiation for the "dry" day was only 15% less than that for the "wet" day and the total insolation, 7% less on the "dry" day.

The relationship between evapotranspiration and sensible heat flux is conveniently studied in terms of the Bowen Ratio,

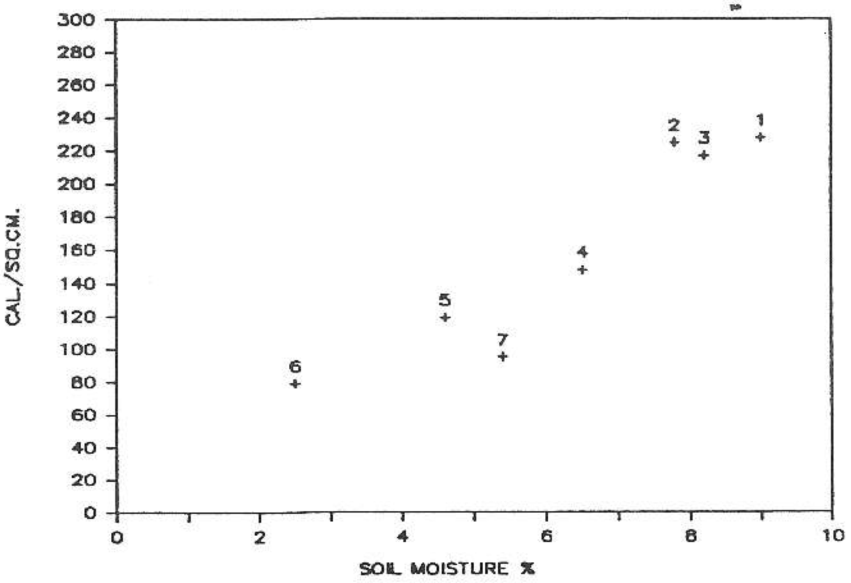

Figure 5. Evaporative heat flux, daytime totals, and morning soil moisture percentages for the seven observation periods.

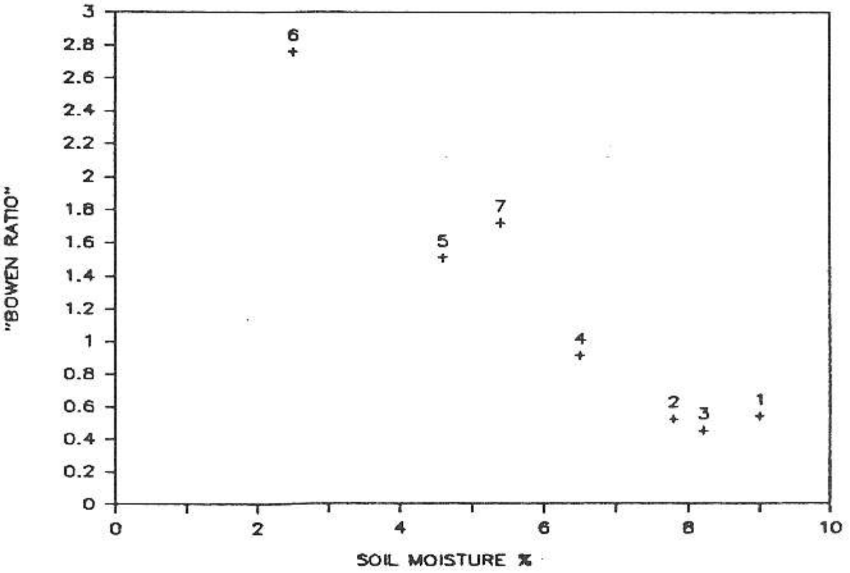

Figure 6. Bowen ratios, computed from daytime heat flux totals, and morning soil moisture percentages for the seven observation periods.

i.e. the ratio of sensible heat flux to evaporative heat flux. It is commonly used in examination of turbulent transfer processes near the ground for time periods of an hour or less. Here the ratio is computed from sums of 10 or 11 hours of data and designated BR. **Figure 6** shows the computed ratios for the seven days in relation to soil moisture. For all three "dry" days BR $>$ 1, for the three "wet" days BR $<$ 1 and for Period 4 the BR is near unity. This separation serves as a convenient way to examine the influence of evapotranspiration on sensible heat flux shown in the following three figures.

In **Figure 7** hourly averages of sensible heat flux for both the "wet" and "dry" days are shown in relation to time of day. The "dry-day" averages are significantly larger throughout the day, reaching the greatest difference early in the afternoon when the value is more than twice the maximum of the "wet-day" curve. The maximum of the "dry-day" curve occurs at 1330 CST, an hour later than that of the "wet-day" curve.

A similar shift in maxima can be observed in sensible heat flux data associated with potential evapotranspiration data reported by van Bavel and Hillel (8) and by Brooks, Pruitt, et al. (9). Potential evapotranspiration is usually defined as water vapor flux from a saturated surface and, consequently, the appropriate Bowen Ratio is significantly less than unity in most circumstances. Data in both these references show sensible heat flux maxima an hour or two before solar noon, with evaporative flux maxima about an hour after noon. There is clear indication, furthermore, that the time difference between the two maxima increases with increase in evapotranspiration. It appears that the sensible heat flux maximum occurs earlier while the evaporative flux occurs later for increased evapotranspiration. It is suggested that

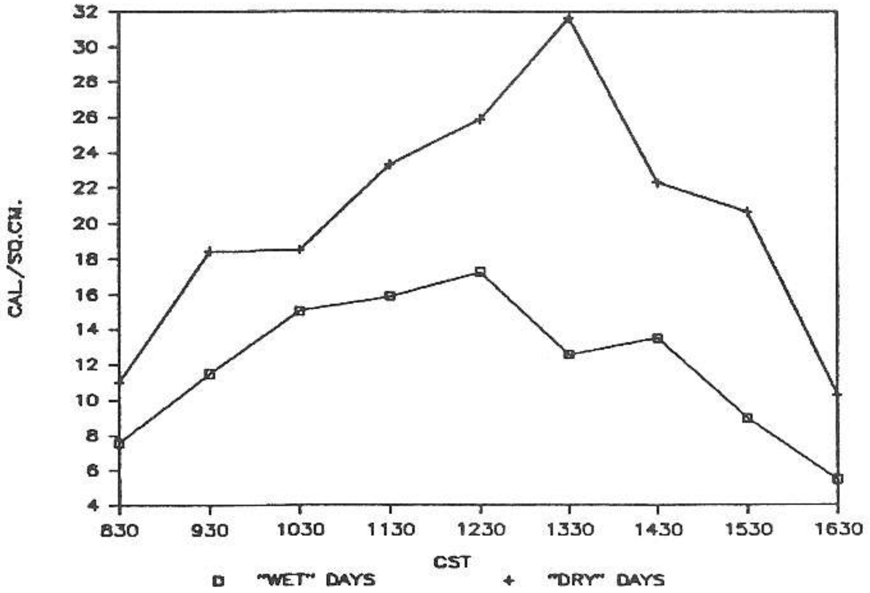

Figure 7. Sensible heat flux, hourly averages for three "wet" days and three "dry" days, and time of day.

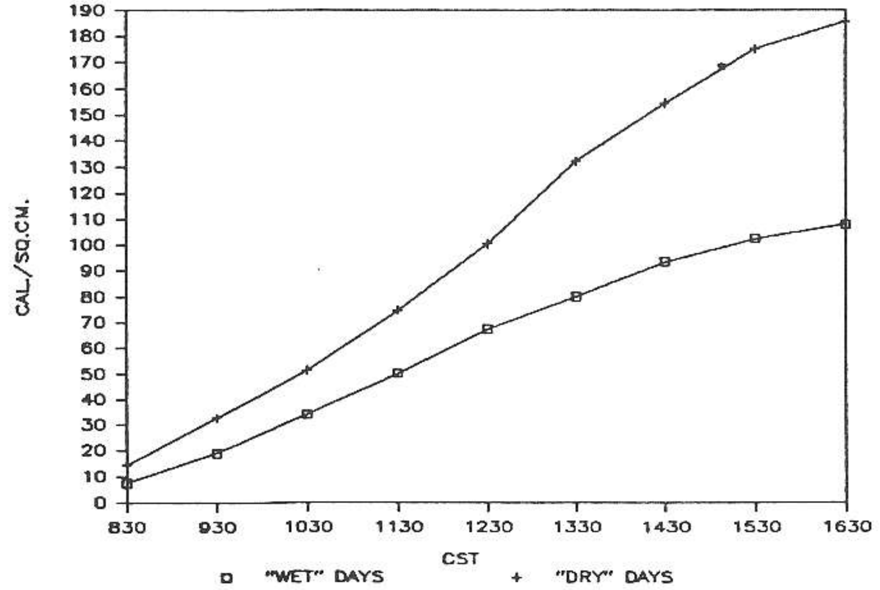

Figure 8. Average daytime accumulated sensible heat fluxex for the three "wet" days and the three "dry" days.

this phenomenon is related to the rate of upward flux of moisture within the soil, itself dependent on vertical gradients of soil moisture and temperature.

Effects of differences in times of maxima of sensible heat flux for "dry" and "wet" days appear in daytime cumulative curves in **Figure 8**. The "wet-day" cumulative curve is nearly linear until 1430 CST but the "dry-day" curve is concave upward, a significant feature for late-morning and mid-day convective layer growth rates. This feature, combined with the larger flux values for "dry" days and appropriate characteristics of the convective layer's capping inversion, may be responsible for the often-experienced, and sometimes unexpected, late afternoon thermal development. The opposite effect, i.e., disappointing afternoon thermal growth may be related to the fact that the concave downward curvature of the "wet-day": curve appears earlier in the day than that of the "dry" days.

Differences between the "wet-" and "dry-day" cumulative patterns are seen in a different way in **Figure 9**. For this figure hourly fluxes of sensible heat were divided by the difference between net radiation and soil heat flux. This ratio may be viewed as the fraction of heat available for convective growth, limited to less than unity by that taken for evapotranspiration. The curves are nearly linear, uniformly diver-

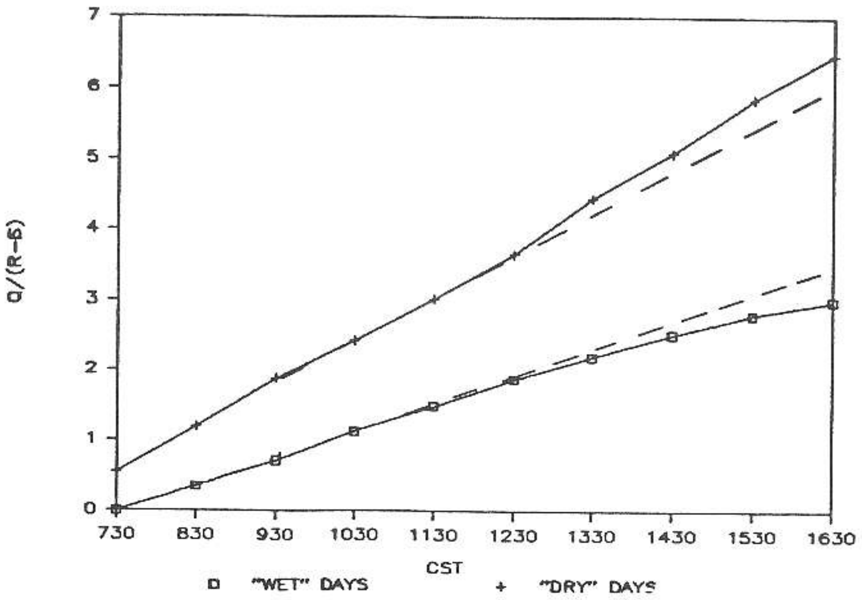

Figure 9. Average daytime accumulated values of the quantity Q/(R-G) for the three "wet" days and the three "dry" days.

gent, until midday when the "dry-day" curve begins a steeper slope and the "wet-day" a less-steep one. The dashed lines are extensions of approximate straight lines representing the morning data. If these differences are primarily the result of morning and midday evapotranspiration rates, and hence morning soil moisture amounts, afternoon convective layer development should show corresponding differences independent of changes in net radiation and soil heat flux that may be caused, for example, by variations in cloudiness.

5. Summary and Conclusions

Detailed determinations of net radiation, soil heat flux, and sensible heat flux into the air for seven summer daytime periods showed that evapotranspiration amounts were highly dependent upon soil moisture. Four days were essentially cloudless and three had thin layers of middle or high clouds. The observations were made in northeastern Nebraska, U.S.A., over flat prairie land covered with short grass. Sensible heat available for convective layer growth, in turn, depended upon the amount of evapotranspiration. Bowen Ratios computed from daytime sums of hourly fluxes decrease with increasing soil moisture, being greater than unity for soil moisture less than about 6%.

The daytime patterns of sensible heat flux peak after solar noon on days with high Bowen Ratios. The peak shifts to earlier times as evapotranspiration increases, and the amount of sensible heat flux shows a corresponding decrease. The effect is seen in cumulative curves of fraction of total heat available for convective layer development and may account for varying times of maximum thermal development, independent of cloudiness.

Acknowledgement I am indebted to Ed Ryznar for many helpful suggestions during the preparation of this paper.

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