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The Three Stages of Drying of a Field Soil[1]

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ABSTRACT

Six major drying experiments were conducted on a smooth, bare field of Avondale clay loam at Phoenix, Arizona, during all seasons of the year. Intensive measurements of evaporation, soil-water contents, soil temperatures, soil heat flux, albedo, and net radiation allowed us to delineate the three classical stages of soil drying. The first stage was characterized by potential evaporation. The second stage was characterized by drying of the soil surface, resulting in a significantly reduced evaporation rate. This stage continued until the volumetric water content at the soil surface reached a value of about 0.06, the predicted starting point for stage three for this soil—based on the assumption that physical adsorption takes place in the first two molecular layers of water surrounding the soil particles. Simple albedo measurements often predicted the transition points between the different stages.

Additional Index Words: evaporation, water content, albedo, soil moisture.

Evaporation of water from bare soil has been a primary concern of scientists for many years. The reasons for their interest in this subject are varied, but the common theme of much of the published information is that an inadequate water supply limits crop production, especially in dryland agriculture, and that soil-water evaporation is a primary factor contributing to the limited water conditions. Several reviews of soil-water evaporation describe the problem quite adequately and how it has been investigated both in the laboratory and in the field (5, 10, 18).

The classical concept derived from laboratory studies envisions evaporation or soil drying as occurring in three stages (1, 2, 3, 5, 11, 13, 14, 19). The first stage has been characterized generally by a relatively high evaporation rate controlled by atmospheric conditions. At a point where the soil water cannot be transmitted to the soil surface fast enough to meet the evaporative demand, the second stage has been considered to begin. Here evaporation rate declines, the soil surface experiences rapid drying with the mode of transfer shifting primarily from liquid to vapor movement. Finally, the third stage has usually been typified by a low, relatively constant evaporation rate controlled by adsorptive forces acting over molecular distances at the solid-liquid interfaces in the soil (10).

It is of interest to note that, to date, the three stages of soil drying have been demonstrated experimentally only in the laboratory under controlled conditions. Field studies have not shown that they can be detected under natural conditions (4, 7, 9, 12, 16, 17). In our continuing experimental study of diurnal soil-water evaporation, however, it gradually became clear that the approach needed to settle definitively the question of the existence or nonexistence of characteristic evaporation stages in the field required a much more refined time scale than had been used in the past. That is, most prior studies had looked only at daily totals of evaporation, while it seemed clear from the results of our soil-water flux calculations (8) that hourly or even more frequent measurements of evaporation may be required to show the characteristic evaporation patterns of the three stages successfully. Thus, several additional intensive experiments were conducted during 1973 to see if a comparison of diurnal evaporation traces would reveal stage transitions missed by utilizing only daily totals. Much auxiliary data was also obtained, as described in the following overview of the complete experimental program. Of primary interest were albedo measurements, which were shown by Idso, et al. (6) to depict three different types of variation with time as the soil dried. We wanted to see if these three types of response corresponded to the three stages of soil drying and if they could serve as a simple means of differentiating among them.

EXPERIMENTS

Six major drying experiments were conducted on an Avondale clay loam soil [fine-loamy, mixed (calcareous), hyperthermic Anthropic Torrifluvent] at Phoenix, Arizona in July 1970, March 1971, August 1972, and May, September, and December, 1973. In each of these experiments, the smooth bare field (72 m by 90 m) was irrigated with approximately 10 cm of water and then allowed to dry. Subsequently, measurements of the following parameters were made at intervals of 20 min (the last three experiments) or 30 min (the first three experiments) for time periods ranging from 1 to 3 weeks: (i) evaporation by two weighing lysimeters irrigated just prior to the field irrigations (all experiments); (ii) incoming solar radiation by an Epply pyranometer (all experiments); (iii) reflected solar radiation by an inverted Eppley pyranometer and an inverted Kipp solarimeter (all experiments); (iv) net radiation by three Fritschn net radiometers (all experiments); (v) air and soil temperatures at a variety of levels and depths by several fine wire thermocouples (all experiments); and (vi) soil heat flux at 1-cm depth by five National Laboratory heat flow discs (the last three experiments). (Trade names and company names are included for the benefit of the reader and imply no endorsement or preferential treatment of the product listed by the USDA.)

In addition to these data which were recorded automatically on punched paper tape, the soil water contents of several depth increments were gravimetrically sampled during selected periods of five of the experiments (August 1972 omitted) plus one shorter experiment (July 1973). The most intensive data were gathered during the four 1973 experiments, when soil samples were extracted for water content analysis from the 0- to 0.2-, 0- to 0.5-, 0- to 1.0-, 1- to 2-, 2- to 4-, 4- to 6-, 6- to 8-, and 8- to 10-cm depth intervals every 20 min at six different locations. Details of the sampling and data smoothing procedures for the soil water content determinations are given by Jackson (7) and Jackson et al. (8).

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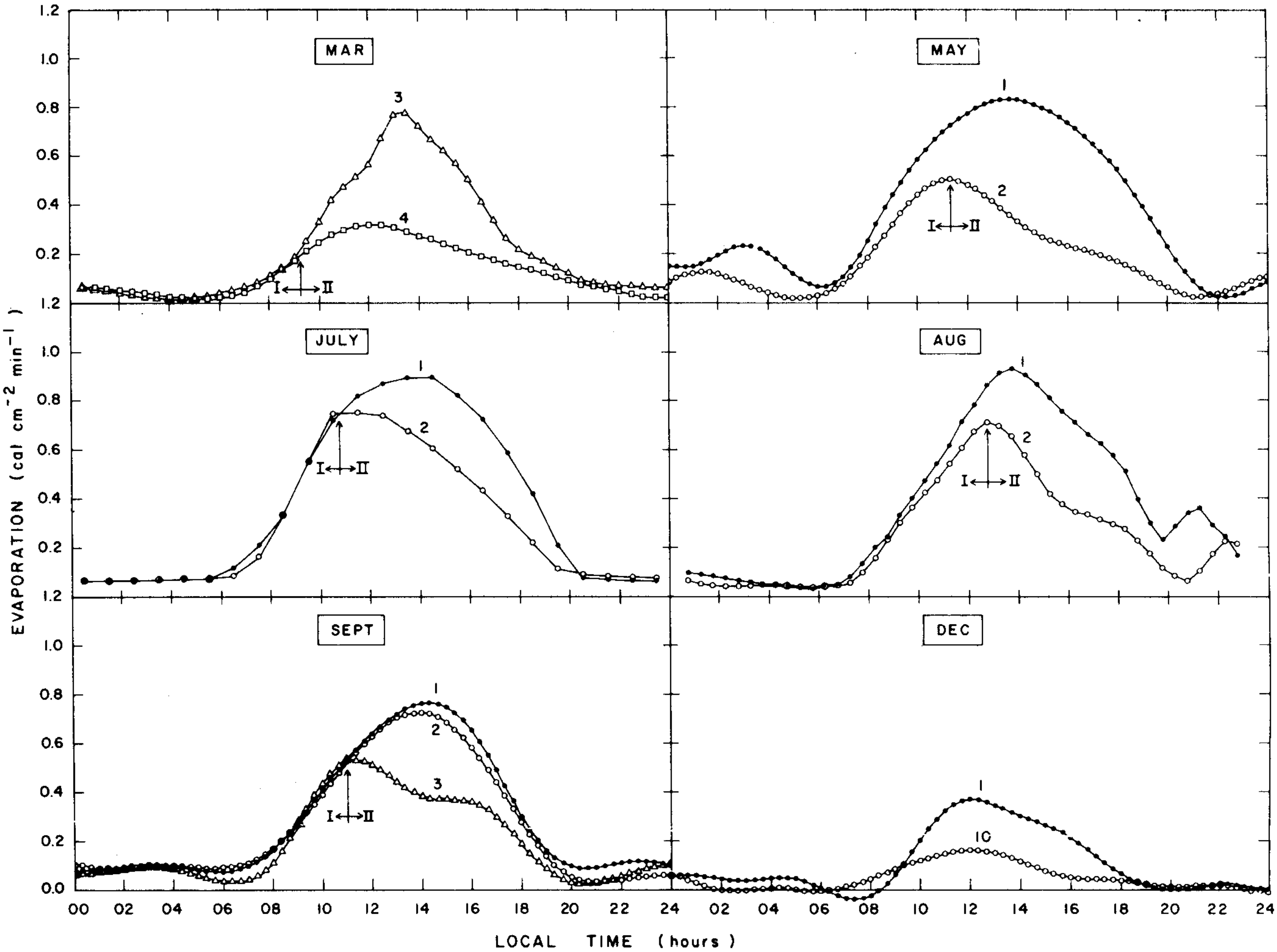

Fig. 1—Diurnal evaporation for specified days after irrigation of a smooth, bare field of Avondale clay loam at 6 different times of the year at Phoenix, Arizona.

RESULTS AND DISCUSSION

Determining Stage I to II Transitions from Evaporation Data

Diurnal evaporation traces for selected days of each experiment are plotted in Fig. 1. It can be seen there that evaporation proceeds at an initial high rate (potential) for at least 1 whole day after irrigation in each instance and for a varying length of time thereafter. This period of time represents Stage I of the three stages of drying. Arrows mark the points where we believe it to end and Stage II to begin. In almost all of the experiments these points are not difficult to discern: evaporation proceeds at a rate generally equivalent to that of the previous day's potential rate and then significantly deviates from it, even to the point of decreasing with time where it had been increasing the day before (May, July, August, September).

The data for March and December are presented in a slightly different manner from the other 4 months and deserve a few additional comments. In the March experiment, day 3 was rather windy; and evaporation that day exceeded the evaporation of days 1 and 2, implying that these days must have experienced potential evaporation, as well as day 3 itself. Thus, days 1 and 2 are omitted.

In December, all days had rather low evaporation rates, with instantaneous values approaching the resolving powers of the lysimeters. Maximum evaporation occurred on day 5. Over the entire period of data collection no clear-cut point could be discerned where a demarkation could be made between Stages I and II by this method of analysis. However, another method for differentiating between these two stages to be discussed next indicated that the transition occurred between days 9 and 10. Thus, only evaporation rates for days 1 and 10 are plotted for this month.

Determining Stage I to II Transitions from Albedo Data

We now introduce an additional means of detecting the transition from Stage I to II that will be important in determining the transition from Stage II to III. This procedure involves only the measurement of the soil albedo, defined as the ratio of reflected to incoming solar radiation. In Fig. 2 this parameter is plotted for several days of each experiment as normalized to remove solar zenith angle effects by the procedure of Idso et al. (6). It is to be noted there that each experiment exhibits three major regions of normalized albedo variation with time. In the first region albedo is essentially constant. Then comes a region of rapidly increas-

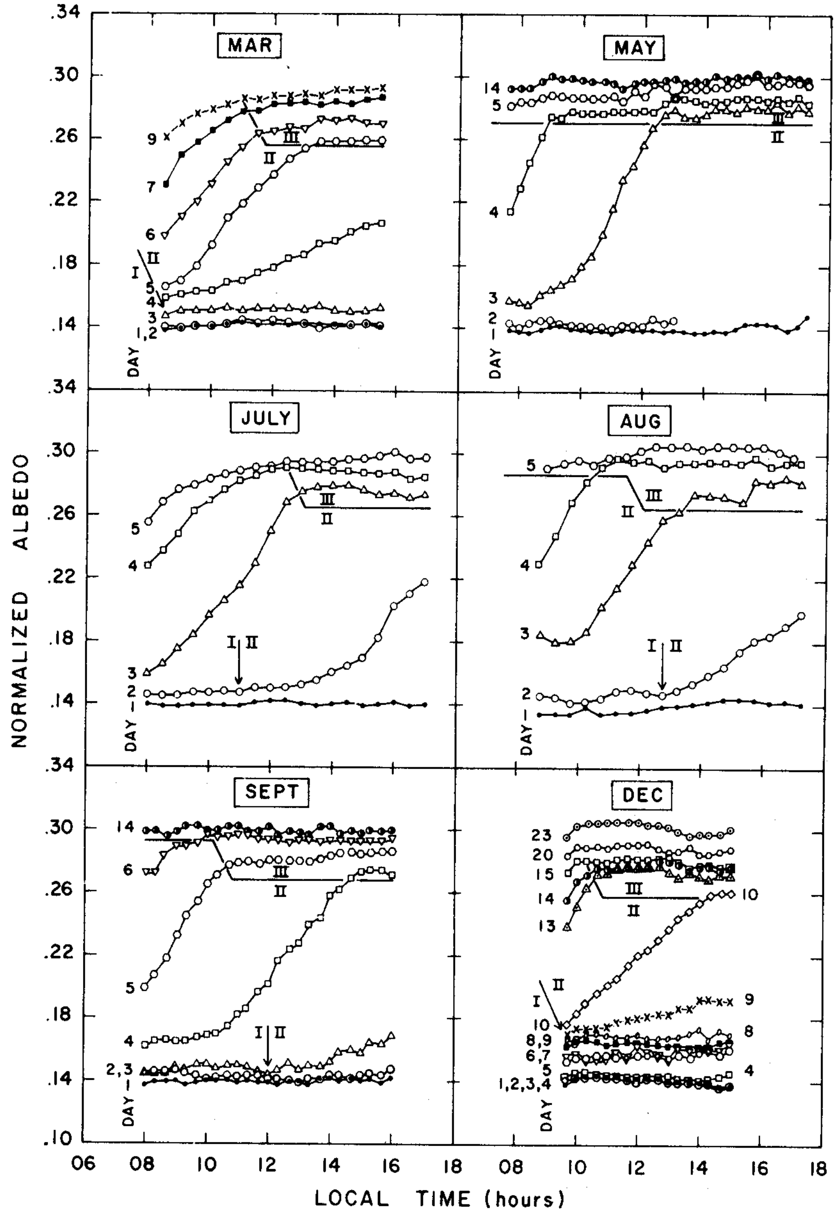

Fig. 2—Daily trends of albedo, normalized to remove solar zenith angle effects, of a smooth, bare field of Avondale clay loam at 6 different times of the year.

ing values with time. Lastly, a final region of again nearly constant or only slowly rising albedo is reached. It is postulated that these three regions of characteristic albedo variation with time correspond closely to the three stages of soil drying.

The only verification that can be made of our postulate at this point concerns the differentiation between Stages I and II; and a comparison of the locations of the subjectively placed arrows on Fig. 1 and 2 indicates fair agreement. Corresponding differentiation points determined by the two techniques for each of the four experiments for which both techniques could be applied differed from each other by no more than a few hours. This is a good comparison, considering the fact that the lysimeters were irrigated separately from the rest of the field where the solarimeters were located, and that they thus could easily have been somewhat out of phase with each other. Conversely, these results also indicate that the lysimeters and the field did behave quite similarly.

Determining Stage II to III Transitions from Albedo Data

To test the hypothesis that albedo measurements can depict transitions from Stage II to III, the family of curves of Fig. 3, derived by Idso et al. (6), must be introduced. These curves depict relations between the normalized albedo of our particular smooth, bare soil, and the volumetric water contents of several depth intervals. They were determined by intensive field sampling, and are considered to be reasonably accurate, except perhaps in the small hatched area where data were lacking and some interpolations required.

We initially need to use the first curve of Fig. 3 to determine the water content of the uppermost soil layer (the site

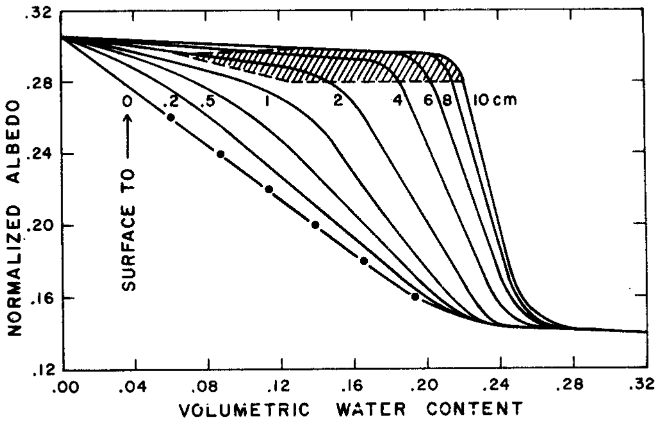

Fig. 3—Normalized albedo vs. average volumetric water content of 9 different soil layers having the surface as their upper boundary. The hatched area is one of some uncertainty.

of evaporation) at the postulated time of transition from Stage II to III, when forces acting over molecular distances at the solid-liquid interfaces in the soil come into play, and the level of critical conditions for evaporation must be near the surface. A difficulty arises here, however, for it is seen from Fig. 2 that there are oscillations between the postulated Stages II and III. That is, after Stage III is once reached, the soil surface rewets the following night to such an extent that evaporation the next day is back in Stage II. Drying then proceeds more rapidly, however, and Stage III is reached at a correspondingly earlier time of day and at a slightly higher albedo value (or slightly lower soil water content) than on the day it was first reached. In some instances this pattern is repeated for several days. Thus, we have chosen to look at the albedo value when Stage III is *first* reached. Its mean value for the six experiments depicted in Fig. 2 is 0.263, which corresponds to a volumetric water content of 0.056. Assuming that physical adsorption (the controlling factor of Stage III evaporation) takes place over the first two molecular layers of water surrounding the soil particles, Jackson (7) has calculated that the transition point between Stage II and III evaporation for our soil (if it exists at all) should occur at a volumetric water content of about 0.06. Thus, this agreement tends to confirm our postulate that the normalized albedo traces of Fig. 2 can be used to differentiate between Stages II and III of soil drying.

Determining Stage II to III Transitions from Evaporation Data

1) *A Success and a Failure.*—We are now dealing with much lower evaporation rates than we were working with in determining Stage I to II transitions; and raw evaporation data are insufficient for our purposes. Thus, we need to normalize them in some manner; and we have chosen to do it by dividing the instantaneous evaporation rate by the "potential advectionless" evaporation calculated from the equation of Priestley and Taylor (15):

$$PE = 1.26\,[s/(s+\gamma)]\,(R_N - G) \quad [1]$$

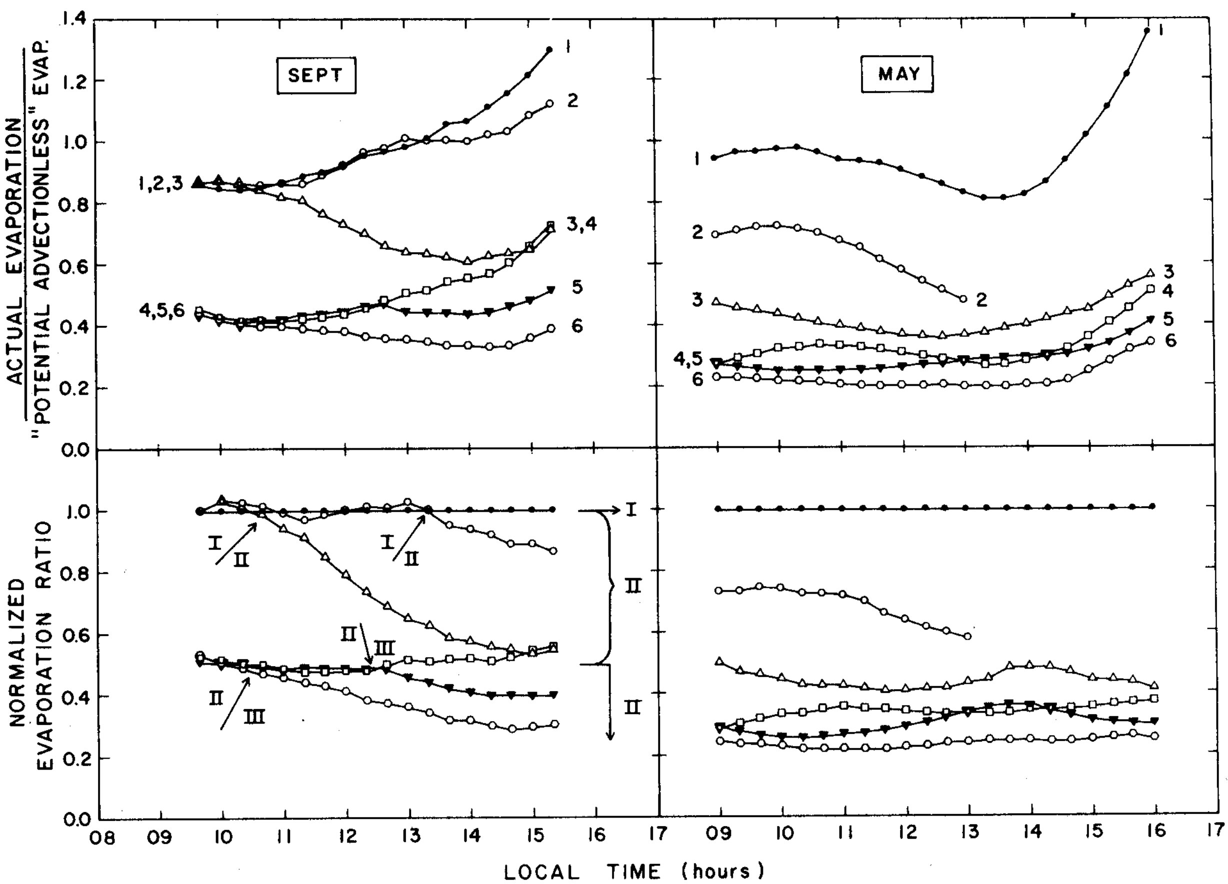

Fig. 4—Various evaporation ratios vs. time for September and May.

where R_N is net radiation, G is soil heat flux, and $s/(s+\gamma)$ is a term dependent solely on the mean of the soil surface and ambient air temperatures. Since soil heat flux measurements were available for only the 1973 experiments, our data base was immediately cut in half by this decision; and since the evaporation rates were so low in the December experiment as to lack the required accuracy, we were left with only May and September as suitable for testing.

The results of dividing the evaporation rates of these last two experiments by the predictions of Eq. [1] are plotted in the two upper portions of Fig. 4. These curves are further normalized in the two bottom portions of Fig. 4 by dividing all curves by the corresponding values of the curves for day 1, so as to do away with mean advective effects. Although no real pattern emerges from the May data, the results clearly indicate a pattern of evaporation rate changes in September consistent with the identification of all three of the stages of soil drying, although some minor differences are apparent. For instance, there is an indication that Stage II evaporation may have been initiated near the middle of the afternoon on day 2 in September, whereas both the evaporation and albedo data of Fig. 1 and 2 indicate that it did not occur until somewhat before noon on day 3. Also, the first occurrence of Stage III evaporation by this approach appears to be near solar noon on day 5, while the albedo data of Fig. 2 indicate it may have been reached near the end of day 4. Thus, while there are minor discrepancies between this approach and the others, the same basic pattern of three stages of drying emerges from them all—except for May by this last technique, where only the departure from Stage I is apparent.

2) *Explaining the Failure*—At this point recourse again must be made to Fig. 3. It is used to transform the normalized albedo traces of Fig. 2 into the water content traces of Fig. 5. All of the Stage II albedo traces were used in this procedure. With respect to Stage III, however, only those albedo traces showing a net rise with time were used. Since we intend to contrast the high drying rates of Stage II with the low drying rates of Stage III, this procedure is slanted towards masking what we hope to find, and therefore acceptable.

It is apparent from Fig. 5, then, that there is a great difference in the drying rates of Stages II and III in the uppermost soil layers. As the depth of integration of soil water content increases, however, the drying rates of the two stages converge. The apparent separation of Stage III drying rates into two groups noted in the 0- to 2-cm and 0- to 4-cm layers is ficticious. It arises from the fact that the

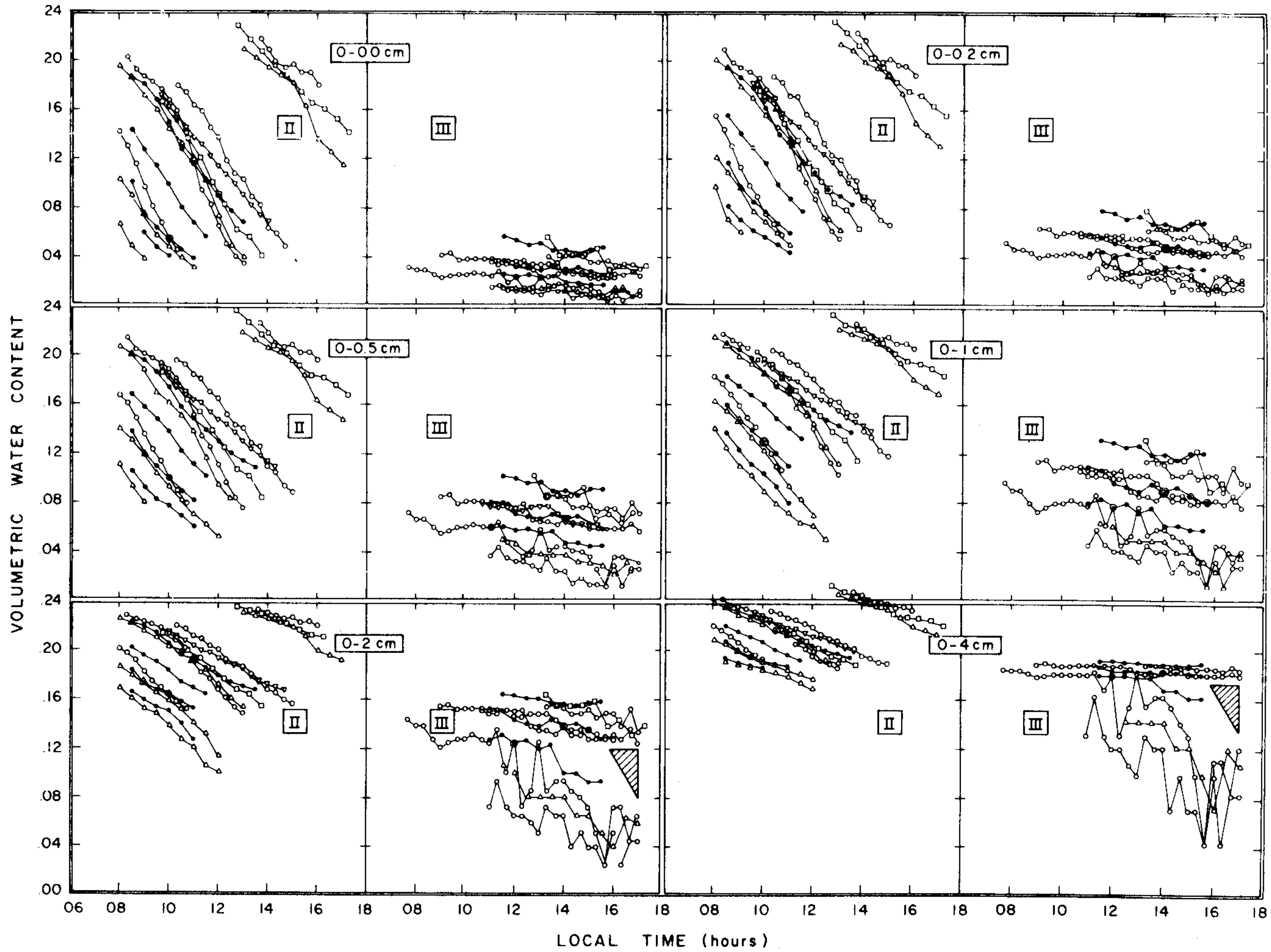

Fig. 5—Volumetric water content vs. time for 6 specified soil layers undergoing postulated Stage II and Stage III drying.

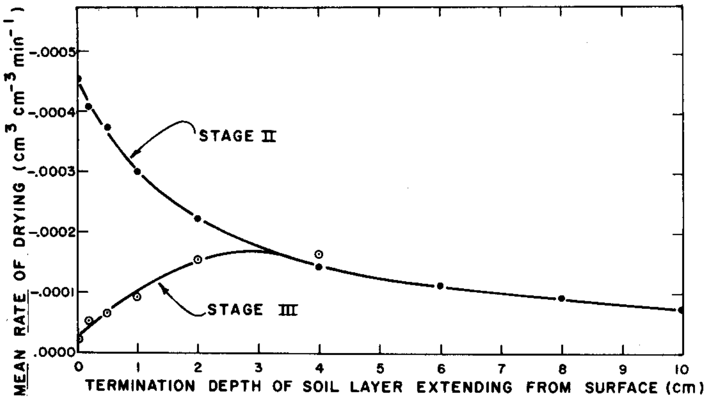

Fig. 6—Mean drying rates of Stage II and Stage III as a function of depth of integration used for computing water loss.

points of maximum curvature in the lines of Fig. 3 occur at greater albedo values for these depth intervals. There was a gap in the original water content data for the greater soil depth intervals at the albedo values at which these points occur (hatched area of Fig. 3); and presumably they were located at albedo values that were slightly too high, so that some Stage III albedo traces of smallest absolute value were evaluated on the wrong portions of the greater depth interval curves. Thus, only those Stage III drying rates that comprised the group that increased with depth were used in the next step, which was to determine the mean drying rates of Stages II and III for all depth intervals.

Results of this last procedure are plotted in Fig. 6. It is noted there that the Stage II drying rate of the soil surface is fully 20 times greater than that of Stage III. As the depth interval over which the soil water content is averaged increases, however, Stage II and III drying rates rapidly converge, so that by the time an interval of 3 cm is considered, the two stages are indistinguishable.

Consider these results in conjunction with the concept of the location of the plane of zero total water flux. Since the evaportaion rate is equal to the rate of soil drying above the plane dividing upward from downward total water flux, if this plane of zero water flux is located at a depth of more than 3 cm, the rate of water loss above the plane (the evaporative rate) will not exhibit a marked reduction in going from Stage II to Stage III of soil drying. Only when the plane of zero flux is located at depths shallower than 3 cm, for our soil, will there be a noticeable change in the evaporation rate when this transition occurs.

To see if these ideas could explain the success of evaporation data in detecting Stage II to III transitions in September but their inability to do so in May, total water flux calculations were carried out for several depths in the soil profile by the procedures described by Jackson et al. (8). From those results it was determined that the plane of zero total water flux for the daylight hours of day 3 in May was located at a mean depth of 4.2 cm, while for day 4 in September it was located at a mean depth of 2.2 cm. Thus, the location of the plane of zero total water flux is indeed crucial to the question of whether Stage II to III soil drying transitions will be evident in evaporation data; and it is apparent that the three stages of soil drying are perhaps best defined in terms of net water loss from specific soil layers, and that they may not always be seen in large depth integrations or in total evaporation measurements. That is, there are times when the evaporation rate may remain unaffected when going from Stage II and III, even though the rates of drying of very shallow soil layers may change significantly.

CONCLUSIONS

1) The three classical stages of soil drying may occur in naturally varying field conditions.

2) Simple albedo measurements can often successfully distinguish the transition points between the different stages.

3) Stage III drying appears to be initiated at a *surface* water content that corresponds to a retention of two molecular layers of water about the soil particles at that level.

4) Rewetting of the surface soil at night may reinstate Stage II drying on the morning of the day following Stage III initiation. During seasons of low evaporative demand, this oscillation between Stages II and III may continue for several days.

5) Transitions between Stages II and III of soil drying may not be apparent from evaporation data if the plane of zero total water flux is located below a certain critical level.

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