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Mixture of Time Scales in Evaporation: Desorption and Self-Similarity of Energy Fluxes

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ABSTRACT

The time evolution of evaporation from a bare soil, over a 9-d period following irrigation, is described by a combination of daily and hourly drying patterns. From the second day, the daily evaporation shows a second stage of drying that can be described as a desorptive process (evaporation proportional to $(t - t_o)^{-1/2}$, where t is time in days and t_o is the day when the second stage starts). The short time (hourly) evaporation rate can be modeled on the basis of a type of self-similarity in the energy balance components. Combining the evaporative flux behavior at the two time scales, desorption at the daily timescale and self-similarity for the diurnal variations, a robust description of evaporation for drying land surfaces is obtained. This approach is tested using accurate measurements of the different components of the energy balance at the soil surface, obtained at 20-min intervals. The model accurately describes the time evolution of the evaporative flux and could be used for the disaggregation of daily or weekly evaporation into hourly values.

The time evolution of evaporation has patterns of variability over various time scales. The day-to-day change in daily evaporation due to the loss of available water is modulated hour to hour by diurnal changes in available energy at the land surface. Several efforts have been made to obtain simple, semiempirical models to estimate evaporation fluxes at different time scales. A review of these efforts is given in the Theory section. After a certain time, t_o, daily evaporation during drying periods (with no rain or irrigation supplied) can be modeled as a desorptive process, that is, evaporation proportional to $(t - t_o)^{-1/2}$, where t is time in days (e.g., Gardner, 1959; Parlange *et al.*, 1992, 1993, 1999). However, in many applications, a daily time resolution is too coarse, and time steps of 30 min to 1 h are required. At the hourly time scale, there is evidence of similarity between the time variation of the latent heat flux and the time variation of the other components in the energy balance at the soil surface (namely net radiation, sensible heat flux, and soil heat flux) (e.g., Brutsaert and Sugita, 1994; Crago, 1996). Recently, Brutsaert and Chen (1996) proposed a simple model to account for both daily and hourly variations of evaporation over a grass prairie under intense drying (after the grass had wilted). This model combines desorption at the daily timescale with self-similarity at the hourly timescale to estimate the hourly variations of evaporation during the drying period. The objective of the present paper is to test the model proposed by Brutsaert and Chen (1996) for a bare soil during a 9-d drying period following irrigation. Note that this case differs from the case studied by Brutsaert and Chen (1996), mainly in the fact that the components of the energy balance are known better since the measurements are taken over a more homogeneous and flat land surface with well-defined wind direction and essentially cloud-free conditions. Effectively, this is a more "controlled" experimental investigation than that of Brutsaert and Chen (1996). Due to the different characteristics of the land surfaces, changes in the results obtained from the model can also be expected. In particular, the time shift t_o, from which evaporation can be described as a desorption phenomenon at a daily timescale, is significantly closer to the last irrigation (or rainfall) event for bare soil.

THEORY

Daily Timescale: Desorption

The time evolution of evaporation appears to be dominated by two different stages of drying. The first stage is characterized by an adequate water supply to the surface, and drying is controlled by available energy at the surface (e.g., Katul and Parlange, 1992; Parlange and Katul, 1992). In the second stage, after the upper level of the soil has dried to some extent, evaporation is controlled by the rate of water vapor supply from below, and it falls below the potential values of the first stage. The evaporation rate in the second stage can be described as a desorption phenomenon,

$$LE_d = \frac{1}{2} D_e(t - t_o)^{-1/2} \qquad [1]$$

where LE_d is the daily latent heat flux (in W m^{-2}) (d refers to daily totals), D_e is the desorptivity (in W m^{-2} d$^{1/2}$), t is the

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time (daily timestep) and t_o is the time at which the second stage starts (Gardner, 1959; Gardner and Hillel 1962). Several field studies (e.g., Jackson *et al.*, 1976; Parlange *et al.*, 1992, 1993) carried out over drying bare soil surfaces have demonstrated that, following irrigation, the first stage of drying normally lasts on the order of a day or less. After this, a desorptive second stage of drying followed, described by Eq. [1].

Brutsaert and Chen (1995) studied drying of a prairie grassland. As with bare soil evaporation, they also identified two stages of drying, separated in this case by a transitional period. Initially, after rainfall or irrigation, evaporation from the soil-plant continuum occurred at the so-called potential rate (first stage). As the soil surface dried out, there was a transitional period in which the vegetation continued to extract water from soil layers below the surface. Note that this transitional period was mainly a consequence of the active vegetation and thus it was longer than in the case of bare soil. Finally, a second stage (comparable to the second stage in bare soils) starts when the vegetation wilts and the roots cease extracting water from the soil. Then evaporation takes place only from the soil surface and it can be described as a desorption phenomenon at the daily timescale (Cahill and Parlange, 1998; Parlange et al., 1998).

Diurnal Cycle: Self-Preservation

In addition to changes in evaporation observed at daily timescales, evaporation from a drying surface shows a clear diurnal cycle due to solar forcing, even after the soil has dried considerably. Daytime variation of the major energy fluxes at the land surface have similar cycles. As suggested by Brutsaert and Sugita (1992), this may be indicative of some kind of "self-similarity". Taking advantage of this fact, we can write:

$$LE_i = R_d F_i \qquad [2]$$

where F_i is some other (beside LE) flux term in the surface energy budget, taken as a reference flux, and R_d is the so-called evaporative flux ratio. The subscript i refers to instantaneous values (typically hourly or half-hourly values). The evaporative flux ratio R_d appears to be quite constant during the daytime hours, which justifies the use of a single value for the same day. Note that the total daytime evaporation rate can be estimated from

$$LE_d = R_d F_d \qquad [3]$$

in which d refers to daily totals, such that $LE_d = \Sigma_1^n LE_i$, $F_d = \Sigma_1^n F_i$, and $R_d = LE_d/F_d$; n is the number of instantaneous (e.g., hourly or half-hourly) values used to obtain the daytime values.

The idea of self-preservation was first used to estimate the total daily LE_d on the basis of one-time-of-day value. Jackson *et al.* (1983) used $F = S\downarrow$, the downward shortwave radiation. For the same purpose, Shuttleworth *et al.* (1989), Gurney and Hsu (1990), Sugita and Brutsaert (1991), and Nichols and Cuenca (1993) used $F = (R_n - G)$ or $F = (LE + H)$, where R_n is the net radiation, H is the sensible heat flux, and G is the ground heat flux. Crago (1996) explored the use of $F = LE_e$, as proposed by Priestley and Taylor (1972), in which LE_e is the "equilibrium evaporation" defined as

$$LE_e = \frac{\Delta}{\Delta + \gamma}(R_n - G) \qquad [4]$$

where $\Delta = de^*/dT$ is the slope of the saturation vapor pressure curve, $e^* = e^*(T)$, T is the temperature of air and γ is the psychrometric constant. Note that for the case of $F = LE_e$ we can write the evaporative flux ration as $R = LE/F = LE/LE_e$, and therefore R equals $\alpha = LE/LE_e$, as defined by Priestley and Taylor (1972). See Eichinger *et al.* (1996) for a discussion on the experimentally observed value of the Priestley-Taylor coefficient.

The assumption of self-preservation works well when F is taken as net radiation, R_n, available energy flux, $(R_n - G)$ or $(LE + H)$, incoming shortwave radiation $S\downarrow$ (Brutsaert and Sugita, 1992), and LE_e (so that $R = \alpha$) (Crago, 1996). However, self-preservation appears to be less robust in the case of $F = H$, for which R^{-1} is the Bowen ratio β. Crago and Brutsaert (1996) showed that this is caused by the difference in error propagation between R and β.

Combining Desorption and Self-Preservation

Brutsaert and Chen (1996) proposed a parameterization for the second stage of drying of a grass covered soil surface (after grass has wilted), based on the combination of the desorptive behavior for the daily variation as described by Eq. [1] and the self-preservation assumption to describe the diurnal variation as given by Eq. [2].

Combination of Eq. [1] with Eq. [2] and [3] yields a parameterization for the 'instantaneous' latent heat flux (over the ith period of the day),

$$LE_i = \frac{1}{2} D_e (t - t_o)^{-1/2} F_d^{-1} F_i \qquad [5]$$

This formulation was used to obtain hourly values of evaporation from daily or even weekly totals. Three values of F, namely $F = R_n$, $F = (R_n - G)$ and $F = LE_e$, were used and the model appeared to give good results for the three cases (Brutsaert and Chen, 1996).

A second formulation was proposed by Brutsaert and Chen (1996), based on the assumption that over relatively short time periods the average total reference flux F_d is not likely to change very much. Given that F_d can be considered time invariant, $R_d = LE_d/F_d$ is expected to have similar time variation as LE_d (given by Eq. [1]). Therefore, R_d can also be described as a desorption phenomenon,

$$R_d = a(t - t_o)^{-1/2} \qquad [6]$$

where a is a constant. With an assumed self-preservation, namely $R_i = R_d$, during the daytime, we have

$$LE_i = a(t - t_o)^{-1/2} F_i \qquad [7]$$

Again, this formulation was applied by Brutsaert and Chen (1996) using $F = R_n$, $F = (R_n - G)$ and $F = S\downarrow$ with good results (similar to the ones obtained with Eq. [5]. Also $F = LE_e$, (i.e., $R = \alpha = LE/LE_e$) was used, yielding results considerably better than all the other cases. This suggests that the effect of net radiation may be temperature dependent and this effect can be captured by the term $\Delta_i/(\Delta_i + \gamma_i)$.

In this study we test the simple evaporation model proposed by Brutsaert and Chen (1996) given in Eq. [5], where $F = LE_e$, for a drying bare soil field for a 9-d drying period following irrigation.

EXPERIMENT

The data used in this study were obtained in a field experiment carried out over a bare soil at the Campbell Tract research field of the University of California at Davis during the summer of 1994. The soil is a uniform Yolo silt loam with no layering within the top 1 m. The section of the field used in the experiment has approximately 500 × 500 m. Further details of the site are presented in Cahill *et al.* (1997, 1999).

The data presented and analyzed here were from a 9-d period, from 22 June (Day 173) to 30 June (Day 181). The

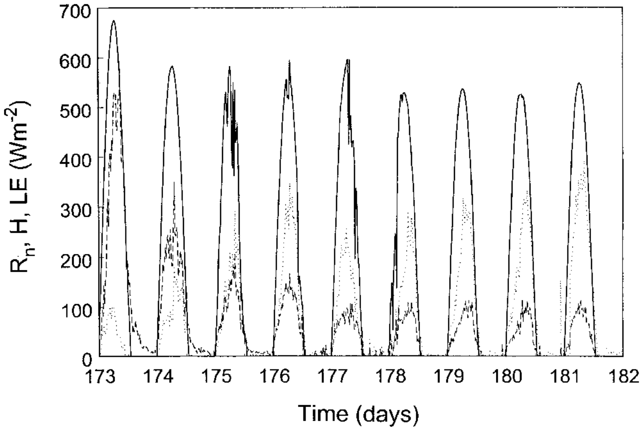

Fig. 1. Twenty-minute mean values of net radiation (R_n) (solid line), sensible heat flux (*H*) (dotted line) and latent heat flux (*LE*) (dashed line) measured over a flat bare-soil field during 9 d of drying (Day 173 through Day 181) following irrigation.

drying period was rain free and followed an 8-h sprinkle irrigation, starting at 2100 h on 21 June, at 5 mm h^{-1}. The micrometeorological instruments used in the experiment were situated in the center of the field to provide a long homogeneous fetch (more than 200 m). The data collected included the different components of the energy balance at the soil surface, namely net radiation, latent heat flux, sensible heat flux, and soil heat flux. A Campbell Scientific eddy correlation system (a 1D sonic anemometer with a fine-wire thermocouple and a krypton hygrometer), placed at a height of 0.95 m, was used to measure the latent heat flux LE ($= \rho L_e \overline{w'q'_a}$, where ρ is the air density, L_e is the latent heat of vaporization, w is the vertical wind velocity, q_a is the air humidity, the prime denotes fluctuations from the mean, and the overbar denotes time averages) and the sensible heat flux H ($= \rho c_p \overline{w'T'}$ where c_p is the specific heat of air and T is the air temperature). The net radiation (R_n) was measured with a REBS Q-7 net radiometer placed at a height of 1.30 m, and the soil heat flux (G) was measured with two soil heat flux plates buried at approximately 0.5-cm depth. Measurements of R_n and G were collected at 1 Hz and stored as 20-min averages. The eddy correlation measurements of H and LE were taken at 10 Hz and were saved at the same 20-min intervals as the other measurements.

RESULTS

The time evolution of the net radiation, sensible heat flux and latent heat flux, measured over 20-min intervals during the measurement period, is presented in Fig. 1. Daily values of the fluxes (denoted by the subscript d) are computed by adding all the 20-min measurements obtained during the daytime hours.

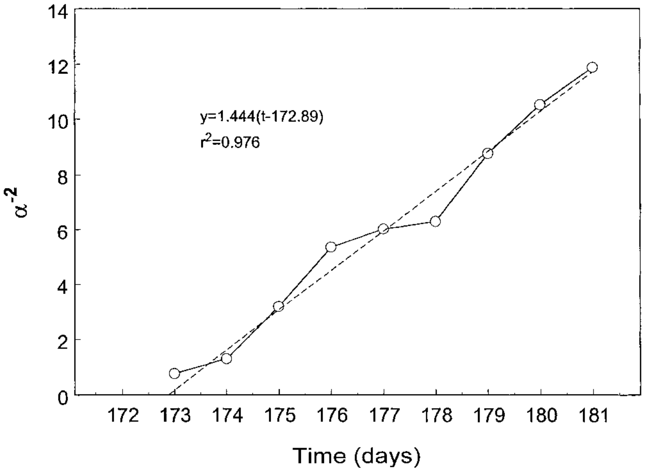

Fig. 2. Evolution of daily values of α^{-2} during the drying period.

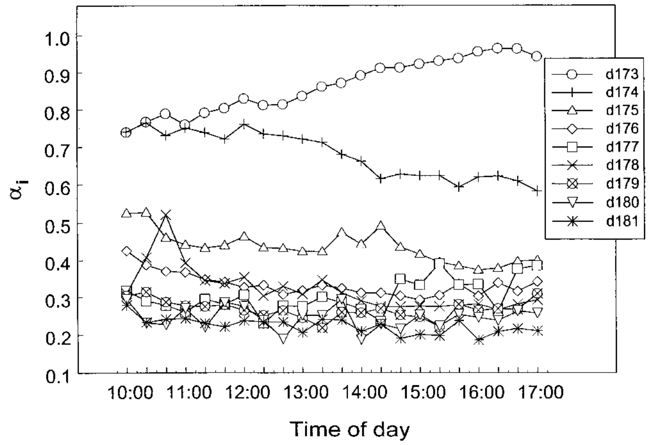

Fig. 3. Diurnal values (from 1000–1700 h) of $\alpha_i = LE_i/LE_{ei}$ for different days during the drying period.

We test here the validity of describing daily evaporation as a desorption phenomenon given by Eq. [6] with $ER_d = \alpha = LE_d/LE_e$; we can write

$$\alpha^{-2} = a^{-2}(t - t_o) \qquad [8]$$

The daily progression of α^{-2} during the drying period is presented in Fig. 2. After the first day of drying, α^{-2} is given by

$$\alpha^{-2} = 1.444(t - 172.87) \qquad [9]$$

such that $a = (1.444)^{-1/2} = 0.832$ d$^{1/2}$ and $t_o = 172.87 \simeq 173$. The fact that all the points fall close to a straight line suggests that the second stage of drying starts within a day after the cessation of the irrigation. The value of the time shift $t_o \simeq 173$ indicates that Eq. [6] is likely to provide a good estimate for $ER_d = \alpha$ for all but the first day of the drying period (Day 173, right after the night of irrigation). This agrees with the fact that during part of the first day evaporation is at its potential (stage one) and therefore the evaporative flux cannot be modeled as a desorptive diffusion process (Jackson et al., 1976; Parlange et al., 1992).

After estimating α (Eq. [9]), daily evaporation can be computed with Eq. [3] (with $F_d = LE_e$) and Eq. [4] such that

$$LE_d = \alpha \frac{\Delta_d}{\Delta_d + \gamma_d} (R_n - G)_d \qquad [10]$$

Next, we investigate the validity of self-similarity of the different energy fluxes to model the short time (e.g., 20-min) rate of evaporation. The assumption of self-preservation requires that the 'instantaneous' evaporative flux ratio $R_i = LE_i/F_i$ (subscript i refers to 20-min values) be relatively constant during the daytime hours. In Fig. 3, for the 9-d period, the 20-min values of R_i (equal to α for $F_i = LE_{ei}$) are plotted for each day of drying. There is a clear decrease in R_i from day to day, due to the fact that LE_i decreases as the soil dries out, whereas LE_{ei} has a similar value from day to day. R_i does not appear to change substantially in the course of a single day, which suggests it is appropriate to make

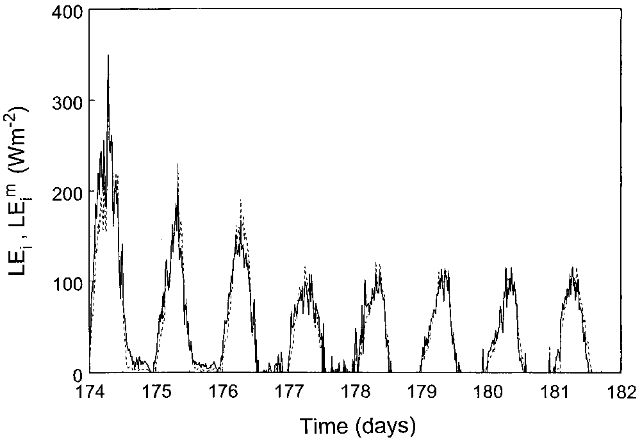

Fig. 4. Comparison of time evolution (20-min intervals) of the measured latent heat flux LE_i (solid line) and the modeled evaporative flux LE_i^m (dashed line).

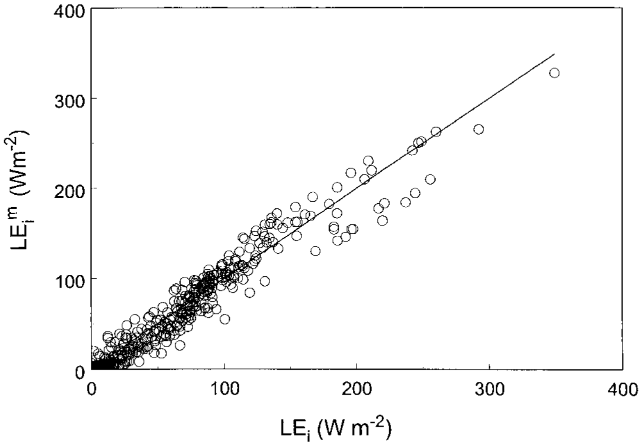

Fig. 5. Comparison between modeled and measured 20-min latent heat flux values.

use of self-similarity to model the diurnal variation of the evaporative flux.

The model for the 'instantaneous' latent heat flux (20-min values), given by Eq. [7] with $F_i = LE_{ei} = (R_n - G)_i\Delta_i/(\Delta_i + \gamma_i)$, is applied. Using the values of $\alpha = 0.832$ d$^{1/2}$ and $t_o = 172.87$ found above (see Fig. 2), the modeled latent heat (LE_i^m) are computed using

$$LE_i^m = 0.832(t - 172.87)^{-1/2}\frac{\Delta_i}{\Delta_i + \gamma_i}(R_n - G)_i \qquad [11]$$

Figure 4 shows the time series of the measured (by eddy correlation) and modeled (Eq. [11]) latent heat flux during the 9-d drying period. It is evident that the model is able to reproduce most of the features of the measured flux. In Fig. 5, the 20-min values of the modeled flux are plotted against the measured flux. The ratio $\langle LE_i^m\rangle/\langle LE_i\rangle$ is 0.981, and the correlation coefficient r between modeled and measured quantities is 0.974. Brutsaert and Chen (1996) found that the evaporation predictions obtained with Eq. [11] are better than when the reference flux F is $(R_n - G)$ or R_n. We found the same results but for brevity we do not include the additional analysis here. As suggested by Brutsaert and Chen (1996), this may indicate that the modulating effect of $(R_n - G)_i$ is temperature dependent and given by the term $\Delta_i/(\Delta_i + \gamma_i)$.

The results presented above show the satisfactory ability of the model proposed by Brutsaert and Chen (1996) to describe evaporation at both daily and hourly time scales over a bare soil during a 9-d drying period following irrigation. The model performance is similar to that obtained by Brutsaert and Chen (1996) in their study over a wilted grass prairie. An important difference between both studies is the starting time t_o for the second stage of drying (and thus for the desorptive behavior of evaporation at a daily timescale). In the case of the grass prairie, the second stage starts after the plants have wilted, and it is difficult to predict. In the case of bare soil, the second stage starts short (<1 d) after irrigation, and it is more predictable.

CONCLUSIONS

A carefully designed field experiment was undertaken to study the diurnal and long time behavior of the evaporation over a bare soil surface during a 9-d period of drying following irrigation. As observed in previous studies over bare soil surfaces, the first stage of drying, characterized by potential evaporation which is controlled by the available energy, appears to be on the order of 1 d. Indeed it is probably restricted to part of the first day of the drying period. The desorptive model for the second stage of drying is appropriate from the second day at the daily timescale. The daily evaporative flux is modulated from hour to hour by the available energy at the surface resulting from the radiative input. The assumption of self similarity is valid provided that the evaporation rate $ER_i = LE_i/F_i$ (where F is any component of the energy balance different from LE, taken as reference) does not change substantially during the daytime for every single day.

The desorptive behavior at the daily timescale and self-similarity at the hourly timescale, are combined as proposed by Brutsaert and Chen (1996), to form a simple model of water vapor flux into the atmosphere. Similar to the results obtained by Brutsaert and Chen (1996), the model gives excellent estimates for the 'instantaneous' (20-min) evaporation flux. This modeling approach can be used for the disaggregation of daily or weekly evaporation into 'instantaneous' (e.g., hourly) values.

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