A Rational Parameterization of the Soil-Surface Evaporation for Estimating the Rate in Arid Regions by Remote Sensing

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Abstract

The evaporation from bare soil changes in mechanism as well as in magnitude and proceeds in three stages as the surface dries. Therefore, only the parameterization schemes for soil-surface evaporation which take account of this stage switching should be considered as rational. A rational parameterization of soil-surface evaporation is proposed, in which the switching from one stage to another is determined by the difference in temperature between soil surface and surface air in the midafternoon. The evaporation rate under dry condition, or during the third stage is parameterized by the DSL bulk formulation which demands only remotely sensed data on temperature and soil moisture.

1. Introduction

The mechanism of evaporation from bare soil changes as the soil surface dries. Most conventional parameterization schemes for soil-surface evaporation are based on the assumptions that the whole evaporation process can be described by a single model without regard to the surface dryness and the change in rate can be predicted by using a few parameters, such as “water availability” or “resistance of water transport”. However, these assumptions are divorced from reality, especially, under dry conditions.

In the last century, a lot of soil physicists and engineering chemists have studied on the mechanism of evaporation from, or for drying of, soil and concluded that the soil-surface evaporation proceeds in three stages as the surface dries (Lemon, 1956; Hillel, 1980). Thus, for the parameterization to be rational, this stage switching must be taken account of.

This paper describes a clear, objective definition of the three stages and a rational parameterization of the evaporation from bare soil. The evaporation rate from soil with a dry surface, or during the third stage is formulated by the parameters which can be evaluated by remote sensing techniques. The means of determining the stage switching is also discussed.

2. Three stages of soil-surface evaporation

The site of vaporization, or of phase transformation of water constitutes a zone (Phase Transformation Zone, PTZ), the location and thickness of which can be used to define the three stages of evaporation from bare soil.

1st stage : PTZ is located at the surface and its thickness is practically zero;
that is, complete vaporization occurs at the soil surface.

2nd stage: PTZ is located at the surface, but its thickness is not zero;
that is, vaporization occurs also within the soil.
3rd stage : PTZ is located within the soil and its thickness is not zero;
that is, complete vaporization occurs within the soil.

3. Structure of PTZ

In PTZ, water vapor density in soil pores decreases upward in linear fashion. During the third stage, a dry surface layer of soil (DSL), in which water moves exclusively in the vapor phase, is formed between the surface and PTZ. The gradient of water vapor density in the lower part of DSL is the same as that in PTZ, although the gradient in the upper part of DSL is not necessarily equal to it because the mechanism for water vapor transfer near the surface may differ from molecular diffusion. Thus, the thickness of PTZ increases with a increase in the thickness of DSL.

Soil moisture moves upward in both liquid and vapor phases in PTZ. If the ratio of the upward water flux in the liquid phase Q_L to the total one Q is denoted by γ, i.e.

$$\gamma \equiv Q_L/Q \qquad (1)$$

$0<\gamma<1$ in PTZ, $\gamma=0$ in DSL, and $\gamma=1$ below PTZ.

4. Models

4.1 First stage

The process of soil-surface evaporation during the first stage may be treated similarly to that of water-surface evaporation. Thus, the evaporation rate E_1 is nearly equal to the potential evaporation E_P, i.e.

$$E_1 = E_P \qquad (2)$$

4.2 Second stage

The second stage is a transition stage being on the way from atmosphere-controlled to soil-controlled evaporation, when the fraction of wet soil surface to the whole surface by geometric area may be approximately equal to γ (see (1)). Thus, the evaporation rate E_2 can be written in the form

$$E_2 = \gamma E_P + (1-\gamma) E_3 \qquad (3)$$

where E_3 is the rate during the third stage, which will be given later (see 4.3). Since $E_3 \ll E_P$, (3) becomes

$$E_2 \fallingdotseq \gamma E_P \qquad (3')$$

4.3 Third stage

During the third stage, water vapor produced within PTZ moves upward through DSL and comes out of the surface. Since the constant-flux layer of water vapor is not expected to develop in the surface air layer under these conditions (Tamagawa, 1996; Kobayashi et al., 1996), we shall focus attention on the water vapor flux in DSL.

Using the temperature T_o (K) and the water-constant (on a volume basis) θ_o (cm^{3}cm^{-3}, %) in the uppermost about 2mm of bare soil, the average water content over a 5-cm slab of soil just below the surface θ_s , and the water content at the boundary between DSL and PTZ (hygroscopic coefficient, pF=4.5) θ_δ , the evaporation rate from soil with a dry surface can be formulated as

$$E_3 = D'\{\theta_o - \theta_\delta\} / \delta \qquad (4)$$

where D' is a kind of diffusion coefficient (cm^3s^{-1}) and is expressed as $D' = C_T D(T_o)$, C_T being a factor for nonisothermal effects (<1) and $D(T_o)$ a function of T_o determined on the basis of molecular diffusion. δ is the thickness of DSL(cm) and is assumed to be expressed by a function of θ_s, i.e. $\delta = \delta(\theta_s)$. θ_o is also assumed to be a function of T_o and θ_s.

Consequently, the rate of soil-surface evaporation in the third stage can be estimated from T_o and θ_s which may be evaluated by remote sensing techniques. This formulation will be called the "DSL bulk method".

5. An example application

An experiment was conducted in a sand field at Kyushu University to get the relations which is needed to apply the DSL bulk method to a soil. The Tottori Dune sand was used, and all measurements were made at about 1500 (JST) when the soil-surface evaporation can be considered as a near steady state process. The actual evaporation rate was measured by the DSL method (Kobayashi and Nagai, 1995).

The results obtained from the experiment are

$$D(T_o) = 7.53 \exp(0.0649\, T_o - 34.88) \qquad (5)$$

$$\delta(\theta_s) = 6.30 \exp(-0.41\, \theta_s) \qquad \text{(Fig. 1)} \qquad (6)$$

$$\theta_o(T_o, \theta_s) = 2.75 + 0.0267\, \theta_s - 0.00795\, T_o \qquad \text{(Fig. 2)} \qquad (7)$$

$$\theta_\delta = 1.53$$

$$C_T = 0.89$$

6. Estimation of daily evaporation by the DSL bulk method

The evaporation rate E_3 estimated using, for example, the relations obtained above is the rate at 1500 (JST). Since the rate of evaporation from soil exhibits a diurnal variation, it is necessary to clarify the pattern of diurnal change in evaporation rate and to integrate it in order to get the daily amount of evaporation.

Fig.3 shows the time changes of the daily mean evaporation rate E_{dm} (open circles), which is estimated based on four measurements made at 0600, 1000, 1500 and 1900 by the DSL method, and of the rate at 1500 E_{1500} (closed circles). On 25 July, the sand field was irrigated with approximately 5cm of water and then allowed to dry, the weather being fine during the period of study 25 to 31 July, 1995.

Dotted lines show 0.3 (open squares), 0.4 (closed squares) and 0.5 (open diamonds) the rate at 1500, respectively. In a few days after the irrigation, the ratio of E_{dm} to E_{1500}, denoted by R_{dm}, decreased and approached the value of 0.39. This value of R_{dm} is consistent with the result obtained at the HEIFE desert station in the northwest of China (Kobayashi and Nagai, 1995).

Although R_{dm} changes with time elapsed since the irrigation or rainfall, the daily evaporation from dry soil may be estimated from a measurement of evaporation rate made in the midafternoon by the DSL method or by the DSL bulk method along with R_{dm}.

7. Determination of the stage switching

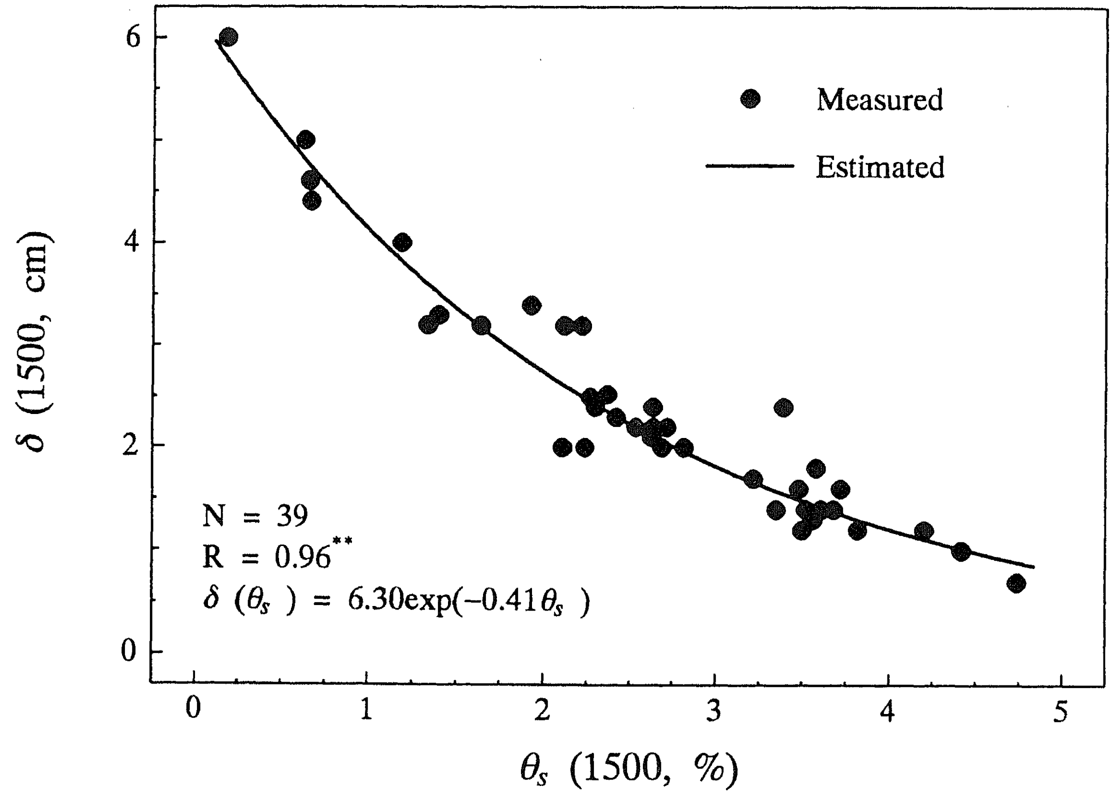

Fig.1 Relation between δ and θ_s at 1500 on clear days

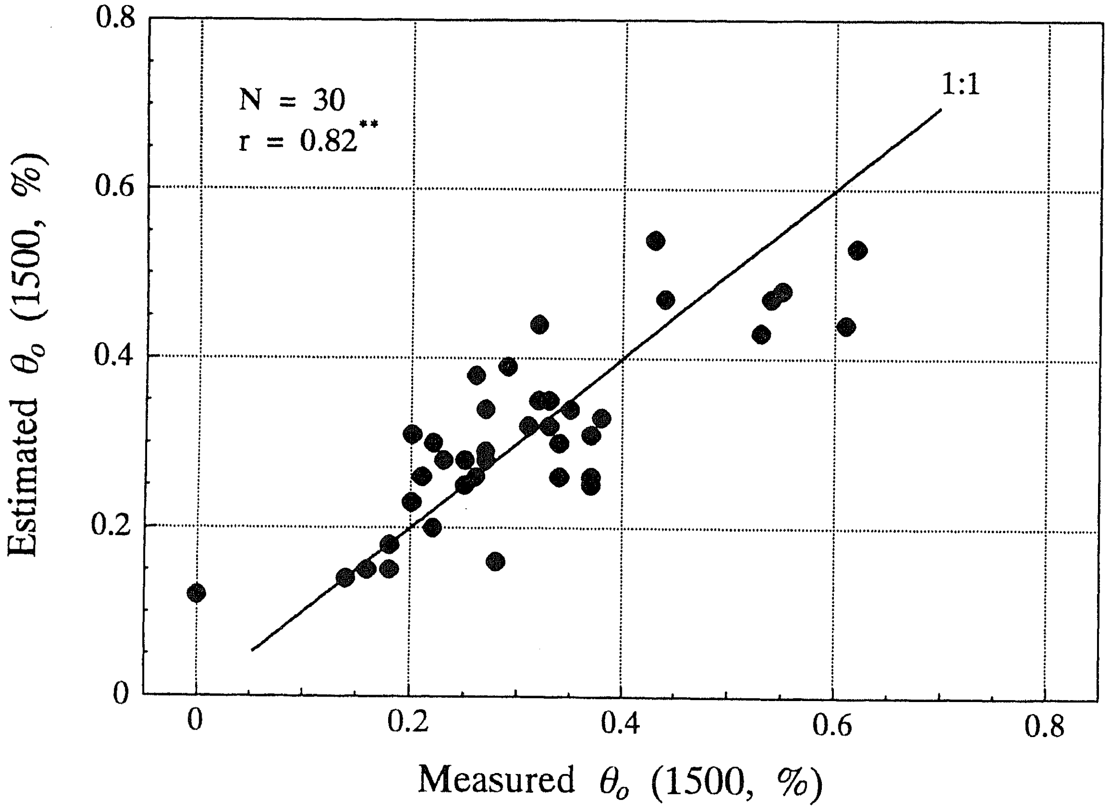

Fig.2 Relation between θ_o and its estimate made with a regression equation on θ_s and T_o (see (1))

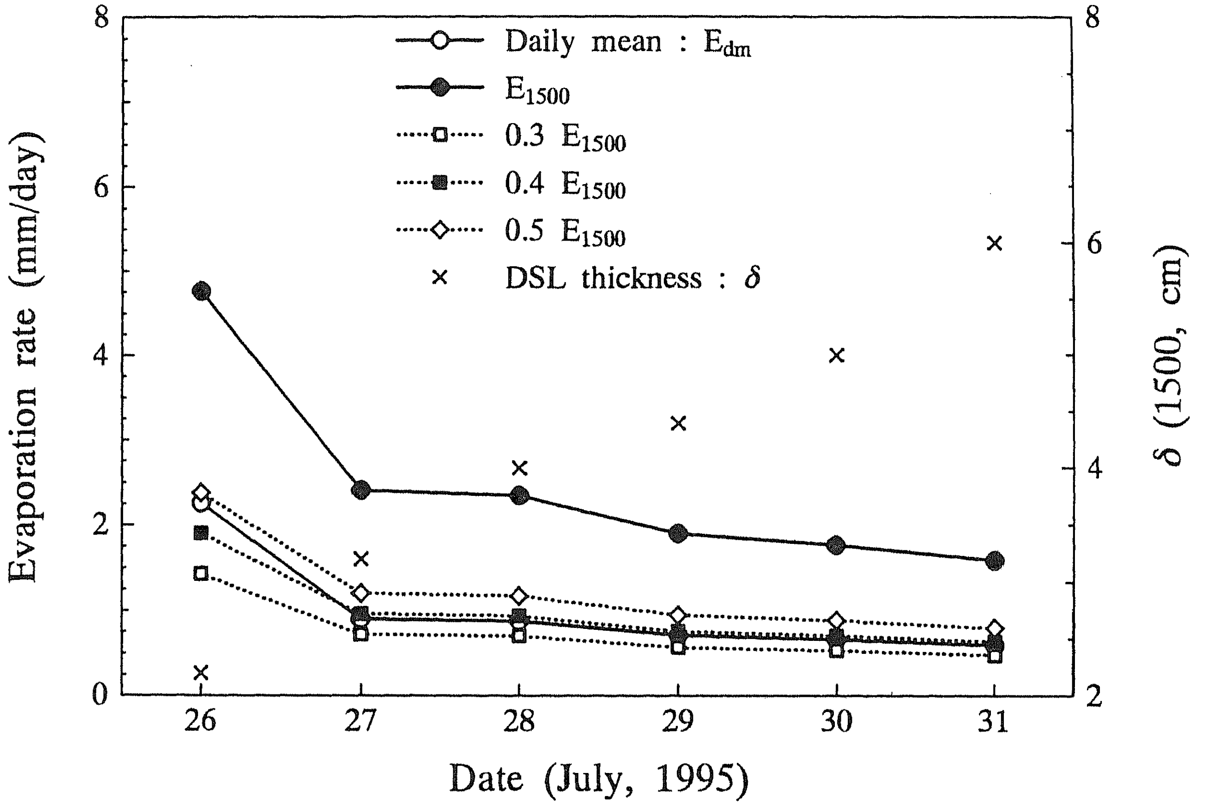

Fig.3 The variations of the daily mean evaporation rate obtained by the DSL method, E_{dm} and the rate at 1500, E_{1500} The cross showes the thickness of DSL at 1500.

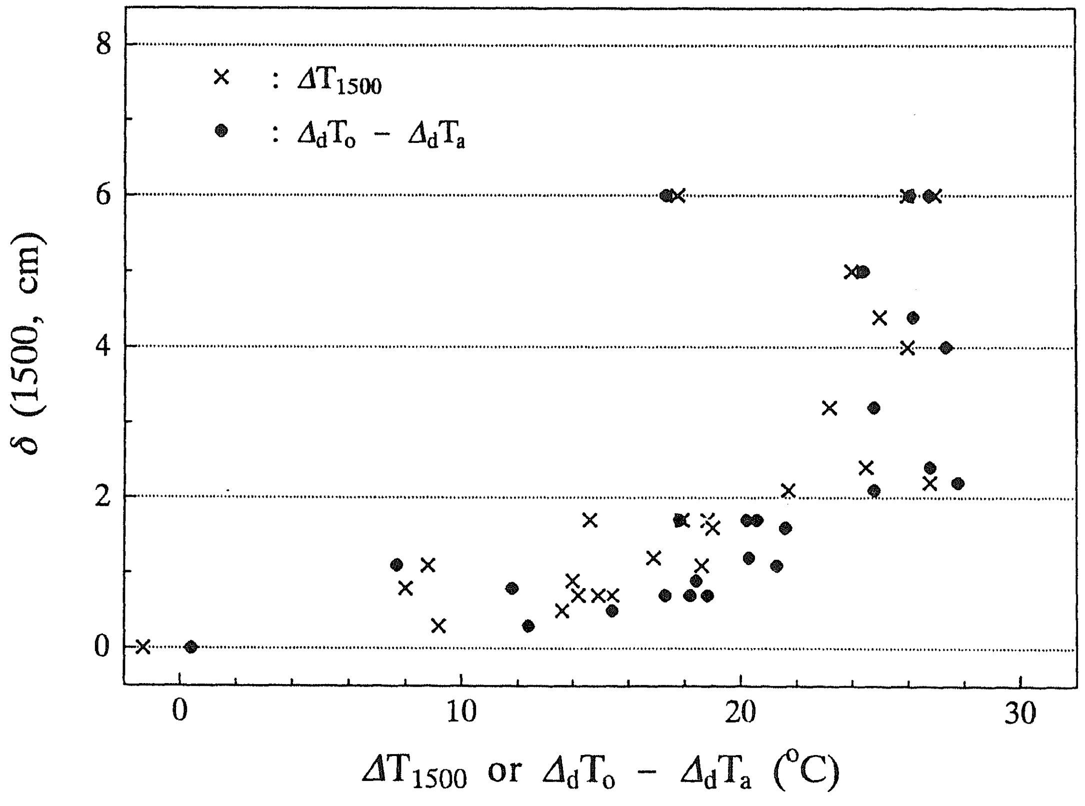

Fig.4 Relation between δ and ΔT_{1500} or $\Delta_d T_o - \Delta_d T_a$ at 1500 on clear days.

The transition points between the different stages have been investigated by a few scientists (Idso et al., 1974; van Bavel and Hillel, 1976). They pointed out that albedo measurements or diurnal surface temperature amplitudes might be effective to depict transitions from one stage to another. In the present study, the difference in diurnal range between surface temperature and air temperature at 1.2m height, $\Delta_d T_o - \Delta_d T_a$, and the difference between surface temperature and air temperature at 1.2m height in the midafternoon (1500 JST), ΔT_{1500} are utilized.

Fig.4 shows the relation between the thickness of DSL and ΔT_{1500}(crosses) or $\Delta_d T_o - \Delta_d T_a$ (closed circles), which were obtained in the sand field at Kyushu University on clear days. When DSL is visible, the third stage evaporation is occurring. From these results it might be concluded that if the temperature difference ΔT_{1500} is larger than about 10℃ on clear days, the third stage of soil-surface evaporation is already reached. During the first and second stages DSL is not formed yet, and so ΔT_{1500} should be smaller than several degree C, although few data were taken because DSL was formed in the clear, midafernoon except immediately after irrigation or rainfall in the sand field.

8. Concluding remarks

Most parameterization schemes for soil-surface evaporation heretofore in use are based on the concept that vaporization of liquid water occurs at the surface and the effects of the drying of soil surface can be represented by such parameters as "water availability" or "resistance of water transport". However, in the present scheme, the change in mechanism as the stage progresses was accepted as an essential idea.

A new parameterization of soil-surface evaporation during the third stage (DSL bulk method) was proposed, which demands the data on temperature and soil moisture that can be evaluated by remote sensing.

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