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Evapotranspiration from heterogeneous terrain: averaging input parameters and modification of a point model

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Abstract At larger scales the determination of evapotranspiration for heterogeneous terrain by the summation of the sub-scale contributions is too time-consuming. In this study an estimation method is presented, that does not sum up subgrid evapotranspiration. The method is developed considering the summations of the Penman-Monteith equation. The amount of calculation for one heterogeneous area is nearly the same as for one homogeneous area. The deviation of the cumulated average evapotranspiration from the results of separate calculations for the sub-areas is usually far below 10%. The pre-processing of parameters and additional modifications of a one-dimensional Soil Vegetation Atmosphere Transfer (SVAT) model achieve this.

INTRODUCTION

The calculation of proper surface fluxes for heterogeneous terrain is increasingly recognized as a major problem in weather forecast modelling. The flux estimates for homogeneous areas are more or less satisfactory, whereas until now there has not been a suitable method for heterogeneous areas. The influence of heterogeneity has been analysed in several studies. In most studies one or more variables are allowed to vary over the terrain, while the others are supposed to be constant. The influence of the distribution of parameters on the resulting fluxes is compared with the fluxes estimated from the average parameters. Avissar (1992) allowed for statistically distributed bulk stomatal conductances. Wetzel & Chang (1988) analysed the impact of a variation of soil humidities on the resulting average evaporation. Li & Avissar (1994) studied the influence of variations of bulk stomatal conductance, soil water content, leaf area index, zero plane displacement and albedo. Claussen (1991) gives formulations for the mesoscale transport above heterogeneous terrain.

In other studies, flux estimates are determined separately for the subgrid elements (Seth *et al.*, 1994) or for clusters of similar subgrid elements (Avissar & Pielke, 1989). However, these methods need multiple numerical operations and detailed information of the subgrid composition that will not be available in most cases.

In this study a method for the estimation of average fluxes is presented, that is theoretically derived and integrated within a SVAT model. The input data requirement is restricted to subgrid information that is available in many regions. Among the subgrid elements of the heterogeneous terrain, different soil types, surface slopes and orientations and types of land use are allowed for.

The main aim of this work is to understand the impact of different land use on evapotranspiration. The proper methods of averaging the input quantities are determined by the averaging of the Penman-Monteith equation and applied to a SVAT model, which is briefly surveyed. The resulting SVAT model is named RegET (Regionalization of Evaporation and Transpiration).

ASSUMPTIONS AND BASIC EQUATIONS

The atmosphere above heterogeneous terrain with disorganized variability (heterogeneity in the micro-scale) can be assumed to be horizontally homogeneous and with constant meteorological conditions above a certain level (blending height) (Shuttleworth, 1988; Raupach, 1991; Wieringa, 1993). The meteorological boundary conditions for the SVAT model, taken as constant above the area considered, are the incoming global radiation R_g, the long-wave radiation R_l, the precipitation P, the air temperature T_a, the water vapour density deficit D'_a (= saturated – actual water vapour density) and the wind speed u_r, where the last three quantities are taken at the blending height.

In each sub-area i, ($i = 1,...,n$) individual values of the following quantities are allowed for: the surface albedo α_i , the long-wave emissivity ε_i , the canopy height h_{ci}, the aerodynamic resistance r_{ai} and the surface (or bulk stomatal) resistance r_{si}.

The averaging procedure described in this paper will be applied to scales of 1 to 10 km^2 or even more, including about 10 to 1000 sub-areas. Heterogeneous terrain of this type is common in western Europe and other densely populated regions.

Neglecting advective and other border effects, the average evaporation $\langle E \rangle$ of a heterogeneous surface can be expressed as the sum of individual evaporation values E_i of the subgrid elements i with the areal portion a_i:

$$\langle E \rangle \equiv \sum a_i E_i \tag{1}$$

For technical reasons the brackets stand for this weighted summation throughout this paper. Using the Penman-Monteith equation, the basis of most SVAT models, under the prerequisites mentioned above the summation can be expressed as:

$$\lambda \langle E \rangle = \langle \beta(1-\alpha) \rangle R_g + \langle \beta\varepsilon \rangle (R_l - \sigma T_a^4) + \langle \beta B / r_a \rangle \rho c_p D'_a / s' + \langle \beta G \rangle \tag{2}$$

Where λ is latent heat of evaporation, s' is slope of the vapour density function, c_p is specific heat of the air at constant pressure, σ is Stefan-Boltzmann constant and ρ is air density.

In equation (2) the summations are only drawn to the individual sub-area properties α_i, ε_i, r_{ai} and r_{si} or their related functions like the entity $B_i = 1 + 4\varepsilon_i \sigma T_a^3 r_{ai}/(\rho c_p)$ and the soil heat flux density G_i . The terms of the sum are all weighted with the expression

$$\beta_i = \left[1 + \gamma' B_i (1 + r_{si} / r_{ai}) / s'\right]^{-1} \tag{3}$$

where $\gamma' = \rho c_p/\lambda$.

The formulation of equation (2) does not reduce the required number of computational operations, but it gives helpful indications for the proper estimation of the areal evaporation average $\langle E\rangle$ (Braden, 1995a). "Effective" input parameters for the whole area and other quantities inside the model have to be modified in order to result in invariant expressions $\langle \beta x\rangle$ (with $x = 1 - \alpha$, ε, B/r_a, G). If this is possible without subscale computations at every time step (e.g. hourly) but only once a day, then computations can be remarkably reduced.

EXTENSION TO THE SVAT MODEL

For the calculation of evaporation in practice, several entities of the Penman-Monteith equation have to be estimated. Namely the bulk stomatal resistance, the surface resistance of bare soil, the aerodynamic resistance and the soil heat flux have to be calculated, which results in SVAT models. The model presented for heterogeneous terrain is a generalization of the one-dimensional SVAT model AMBETI (Agrometeorological Model for the Calculation (Berechnung) of Evaporation, Transpiration and Interception) (Braden, 1995b). The model has been developed for the calculation of evapotranspiration and micrometeorological entities in plant stands and the soil, namely: absorbed visible, near infrared and infrared radiation for the plants and the soil surface, thermal and hydraulic functions, derived from soil composition, soil heat fluxes and temperatures in several layers, interception of precipitation, surface runoff and infiltration, bulk stomatal resistance (depending on plant type, plant age, absorbed visible radiation, water supply), soil evaporation, plant transpiration, melting of snow cover, as well as freezing and melting of water in soil layers.

The model considers additional properties of the study area: slope and orientation of the surface, soil properties (main particle size fractions, organic matter content), type of vegetation and morphometric data: plant density, plant height, leaf area index, rooting depth.

The bulk stomatal parameters of the model AMBETI have been calibrated for several field crops by comparison with lysimetric evapotranspiration data. Model validations for deciduous and coniferous forests are in preparation. The model is used operationally for daily routine advisory purposes in the Agrometeorological Section of the Deutscher Wetterdienst.

AVERAGING APPLIED TO THE SVAT MODEL AMBETI

The corresponding areal-averaged Penman-Monteith equations for soil evaporation E_{so} and plant transpiration E_{pl} in the SVAT model AMBETI (Braden, 1995b) can be expressed as

$$\lambda\langle E_{so}\rangle = \langle \beta_{so} A_{so}\rangle R_g + \langle \beta_{so} R_{nlso}\rangle + \langle \beta_{so} B_{so} / r_{apl}\rangle \rho c_p D'_a / s' + \langle \beta_{so} G\rangle \tag{4a}$$

$$\lambda\langle E_{pl}\rangle = \langle \beta_{pl} A_{pl}\rangle R_g + \langle \beta_{pl} R_{nlpl}\rangle + \langle \beta_{pl} B_{pl} / r_{apl}\rangle \rho c_p D'_a / s' \tag{4b}$$

where A_{so} and A_{pl} denote the portions of the global radiation absorbed by the soil surface and the plants, respectively. The weighting factors β_{so} and β_{pl} are similar to equation (3) with the respective aerodynamic resistances, the bulk stomatal resistance and the resistance for soil evaporation, respectively. In contrast to equation (2) the net long-wave component ($R_1 - \varepsilon\sigma T_a^4$) cannot be separated in equations (4a,b), because the plants and the soil surface influence each other by the exchange of long-wave radiation.

At first sight the calculation of acceptable estimates for the areal averages $\langle\beta_x\, Y_x\rangle$ in equations (4a,b) without hourly summations seems to be hopeless, since β_x varies strongly during the day. However in spite of this, it will be demonstrated, how the averaging has been successfully done with the SVAT model AMBETI.

In addition to the expressions in equations (4a,b) that are to be kept invariant, it seems to be advisable to keep the estimates for the portions of short-wave radiation, absorbed by the plants $\overline{A}_{pl}$, constant during the calculation of the areal averages:

$$\overline{A}_{pl} = \left\langle A_{pl} \right\rangle \tag{5}$$

This is achieved by the calculation of an effective leaf area index and an effective stem area index from simplified expressions for the absorbed short-wave radiation.

For the bulk stomatal resistance the parameterization used in the model AMBETI is analysed, resulting in parameters for effective bulk resistances of the composed area. This is done with equation (3) and the relation for averaged β_{pl}-coefficients:

$$\left\langle \beta_{pl} \right\rangle = \Sigma a_i \beta_{Pli} \tag{6}$$

The areal averages $\langle\beta_{pl}\, A_{pl}\rangle$ and $\langle\beta_{pl}\, B_{pl}/r_{apl}\rangle$ in equation (4b) have to be replaced by products of the resulting estimates $\langle\beta_{Pl}\rangle$, $\overline{A}_{pl}$ and $\overline{B}_{pl}$, because the subgrid information summed up at the beginning of the day is not available in the internal part of the model RegET. For the balance of differences, from the preliminary estimates the daily correction factors:

$$f_A = \left\langle \beta_{pl} A_{pl} \right\rangle / \left(\left\langle \beta_{pl} \right\rangle \overline{A}_{pl} \right) \tag{7a}$$

and

$$f_r = \left(\left\langle \beta_{Pl} \right\rangle / \overline{r}_{apl} \right) / \left\langle \beta_{Pl} / r_{apl} \right\rangle \tag{7b}$$

are determined. During the following actual calculations for the time steps of the day, the quantity $\overline{A}_{pl}$ (equation (5)) is multiplied by the factor f_A and the aerodynamic resistance r_{apl} is multiplied by the factor f_r.

For heterogeneous areas consisting of partially non-vegetated as well as partially sealed areas, no suitable averages can be determined for the leaf area index and other morphometric data. Moreover, the sealed portions have to be omitted during the calculation of water infiltration into the soil. Therefore, as the only subgrid properties, the two properties "non-vegetated areal portion" a_u and "sealed areal portion" a_s are used in modifications of the model AMBETI. The fraction of short-wave radiation absorbed by plants $\overline{A}_{pl}$ is determined for the vegetated portion $(1 - a_s - a_u)$ only. With the help of a_u the differences in water stress between vegetated areal portions with plant water extraction from the soil on the one hand, and non-vegetated areal portions with stronger water extraction by evaporation from the uppermost soil layers on the other hand, are distinguished. These are further considered during the reduction of transpiration and the reduction of soil evaporation for reasons of water shortage.

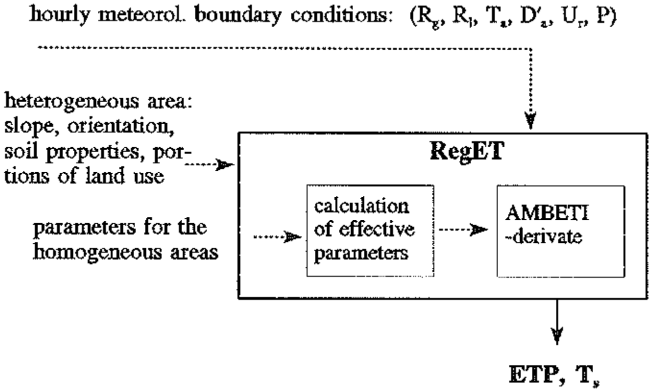

Fig. 1 The structure of the model RegET.

The model described above is called RegET (Regionalization of Evaporation and Transpiration), and a survey of its structure is given in Fig. 1. It combines the model AMBETI with the modifications mentioned above and the pre-processing of subgrid information concerning the areal portions with different types of field crops, each with a typical canopy structure. As the bulk stomatal parameters of the model AMBETI have been calibrated, the model RegET needs no further calibration. The model RegET has been tested and adjusted by comparisons with the results for the sub-areas of the model AMBETI. These comparisons had also been used to learn about the recommended procedures for averaging and compensation.

EXTERNALLY-AVERAGED INPUT QUANTITIES

At the scale of 1 to some 10 km^2, where the model RegET will be applied, sub-scale information about soil properties as well as about surface slopes and slope orientation frequently exists. But the correlation of these parameters with land use will not be available in general. For this reason these quantities are externally averaged before the run of the model RegET.

For the soil properties, arithmetic averaging of the clay and silt portions was found to give acceptable effective input quantities for the use in RegET. This was tested for the 465 couples of combinations of the 31 main classes of particle sizes considered in the German soil classification. For each couple the resulting cumulated evapotranspiration $E\{\frac{1}{2}(soil_1 + soil_2)\}$ was compared with the average resulting from separate model runs for the two soils $\frac{1}{2}(E\{soil_1\} + E\{soil_2\})$ as a reference. The percentage deviation of the former from the reference has been plotted on the abscissa of the histogram in Fig. 2. Obviously the deviations are far below 10% in most cases, while the yearly sums of evapotranspiration varied from 324 up to 458 mm. The small deviations gave the justification for the use of arithmetic averaged portions of clay and silt as input quantities to the model RegET.

For the calculation of the incident short-wave radiation that is converted to heat fluxes on the considered heterogeneous area, its effective slope and orientation are used. For the conversion of the effective areal normal vector $\underline{n}_e$ from the corresponding

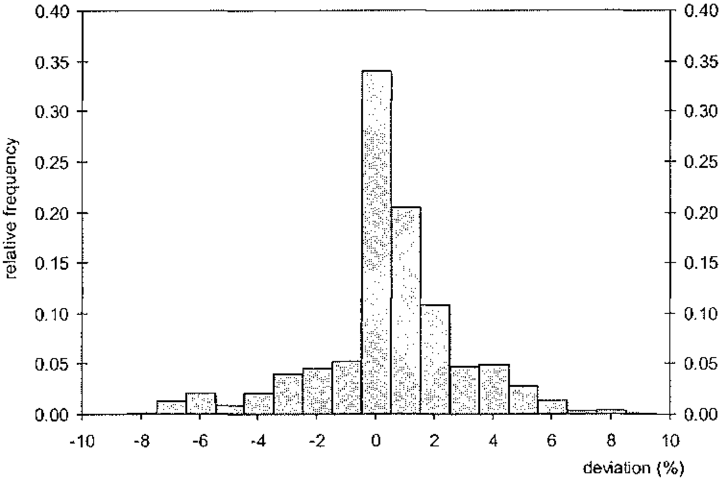

Fig. 2 Histogram of deviations of annual evaporation sums calculated for averaged soil particle size fractions (AMBETI: winter wheat).

subgrid information $\underline{n}_i$, the conservation of the scalar product of $\underline{n}_i$ and an effective sun vector $\underline{n}_s$ is used

$$\Sigma a_i(\underline{n}_i \cdot \underline{n}_s) = (\underline{n}_e \cdot \underline{n}_s) \tag{8}$$

RESULTS

Two examples of results from the model RegET will be given, both for horizontal areas with identical soil (loamy sand). Figure 3 shows the results of RegET for two different types of land use (50% winter wheat, 50% sugar beet), together with the results for the homogeneous sub-areas. Obviously the result of RegET is close to the average of the separate simulations.

The results for three different types of land use among the sub-areas are presented in Fig. 4. The remaining deviations compared with the averaged AMBETI-results do not exceed 5% and are mainly caused by transpiration. Obviously the compensations for water shortage on the vegetated and the non-vegetated areas do not yet work totally satisfactorily and these will be revised in a future version of the model.

CONCLUSIONS

The method described above can be easily applied to SVAT models with alternative bulk stomatal parameterizations.

Errors may arise from disregarding the dependencies among the distributions of the three categories soil type, surface slope and orientation, and land use. However, this information will not be available in general.

Moreover errors may arise from the use of temperatures and humidities measured at a height of 2 m as meteorological boundary conditions at the blending height.

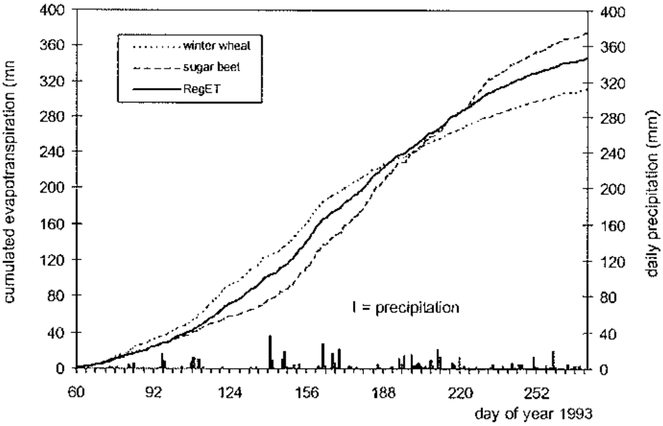

Fig. 3 Calculated courses of evaporation for two different types of sub-area properties (portions: 0.5, 0.5); total precipitation = 507 mm.

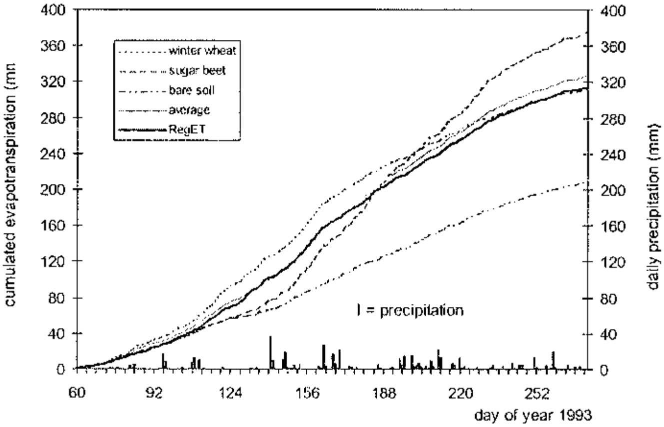

Fig. 4 Evapotranspiration for three different types of sub-area properties (portions: 0.5, 0.4, 0.1); total precipitation = 507 mm.

However this problem is overcome by coupling the model RegET to a numerical forecast model, which is being developed.

At present the method described is applied to a drainage basin of the Weser River, where about 1000 areas of 1 km^2 are considered. The basic sub-pixel information comes from digital soil maps at scales of 1:50 000 and 1:100 000, digital terrain maps and land classifications from Landsat TM. This information is prepared at the 1 km^2 scale with the help of a GIS. For the agricultural land use, additional statistical information is used as well as the phenological stages of plants, that have been observed and recorded by the Deutscher Wetterdienst. The meteorological boundary conditions for each of the 1 km^2 areas are derived from time series of several meteorological stations situated inside and around the region.

It is planned for the future, to compare results of the model RegET with occasional NOAA AVHRR-data. Severe deviations are thought to indicate discrepancies between precipitation used as model input and actual precipitation, or even to shortcomings inside the model or its parameterization. To allow for these comparisons, the model RegET also calculates the effective apparent surface temperatures (Braden, 1995a,b).

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