# Influence of soil moisture on the modelling of evapotranspiration in sparse vegetation

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## ABSTRACT

This work analyses the relevance of soil water content ($\theta$) on the estimation of actual evapotranspiration ($\lambda E$) in sparse vegetated areas. This importance is evaluated through the effect of the $\theta$ heterogeneity, both vertical and horizontal (differentiating between bare soil (bs) and soil under vegetation (s)), on $\lambda E$ estimates. A clumped evapotranspiration model (CM) that considers vegetation (p), bs and s as sources of evaporation, was used. This model estimates $\lambda E$ of the whole vegetated area, as well as the contribution of each source.

The field site is a sparse-vegetated patch of *Anthyllis cytisoides* (L.) located in the instrumental area of Rambla Honda in Tabernas (Almería), run by the Arid Zones Experimental Station (CSIC).

Values of $\theta$ measured at three depths (0.02 m, 0.05 m and 0.15 m) and the averaged for the whole 0.15 m soil profile were used to calculate parametric equations of surface soil resistances $r_s^{bs}$ and $r_s^{s}$ and the surface leaf conductance $g_s^{l}$. The parametric equations were introduced in the CM and the $\lambda E$ estimates obtained were compared with measured values from an Eddy covariance system. Results showed that $\theta$ has an important effect on the estimates of bs and s contributions. The modelled $\lambda E$ that provided the best results were obtained when $r_s^{bs}$ and $r_s^{s}$ were parameterised with $\theta$ measured at the surface at 0.02 m (RMSE = 0.2 mm day$^{-1}$), while the worst estimates were obtained when using $\theta$ measured deeper (RMSE = 0.75 mm day$^{-1}$).

**Keywords**: Clumped model, surface resistances parameterization, soil water content

## INTRODUCTION

The aim of this work was to explore the sensibility of an evapotranspiration (λE) clumped model (CM), that parameterises the surface resistances ($r_s$) with $\theta$ measured at different depths and positions. The CM used for this purpose, that considers plant, bare soil and soil under plant as evaporating sources, was developed for sparse vegetation and has been already successfully applied to a *Retama sphaerocarpa* (L.) Boiss stand in Rambla Honda experimental field site (Domingo et al., 1999) and recently in a vineyard in an arid desert region of northwest China (Zhang et al., 2008). The $\lambda E$ estimates obtained with the CM were compared to $\lambda E$ measured with an Eddy covariance system in a sparse-vegetated *Anthyllis cytisoides* L. stand in Rambla Honda field site. Comparisons were performed at daily time-scale to prevent poor hourly performance of soil evaporation models when using soil surface resistances estimated from $\theta$ (Daamen and Simmonds, 1996).

## METHODS

### Model description

The CM used in this work considers three evaporating sources; vegetation (p), soil under vegetation (s) and bare soil between vegetation (bs). The CM also considers that the energy available for evapotranspiration is distributed among the three sources. Thus, the total evapotranspiration ($\lambda E^{\mathrm{t}}$) of a vegetated area is calculated as follows:

$$\lambda E^{\mathrm{t}} = f(C^{\mathrm{p}} PM^{\mathrm{p}} + C^{\mathrm{s}} PM^{s}) + (1-f)(C^{\mathrm{bs}} PM^{\mathrm{bs}}) \qquad (1)$$

Eq.1 combines three Penman-Monteith-type equations ($PM^{\mathrm{p}}$, $PM^{\mathrm{s}}$ and $PM^{\mathrm{bs}}$), one for each source, with a set of coefficients ($C^{\mathrm{p}}$, $C^{\mathrm{s}}$ and $C^{\mathrm{bs}}$) that modify these equations according to their aerodynamic and surface resistances. The equations for each source are weighted by the fractional vegetation cover (*f*). These Penman-Monteith-type equations are as follows:

$$PM^{\mathrm{x}} = \frac{\Delta A + \left[(\rho C_{\mathrm{p}} D_r - \Delta r_{\mathrm{a}}^{\mathrm{x}} A^{\mathrm{x}} / (r_{\mathrm{a}}^{\mathrm{a}} + r_{\mathrm{a}}^{\mathrm{x}})\right]}{\Delta + \gamma\left[1 + r_{\mathrm{s}}^{\mathrm{x}} / (r_{\mathrm{a}}^{\mathrm{a}} + r_{\mathrm{a}}^{\mathrm{x}})\right]} \qquad (2)$$

where x represents the different sources (p, s and bs) and $r_{\mathrm{s}}^{\mathrm{x}}$ are the surface and $r_{\mathrm{a}}^{x}$ the aerodynamic resistances. For a more detailed description of the CM see Domingo et al.(1999).

### Surface resistances ($r_{\mathrm{s}}^{\mathrm{p}}$, $r_{\mathrm{s}}^{\mathrm{bs}}$ and $r_{\mathrm{s}}^{\mathrm{s}}$)

Plant surface resistance ($r_{\mathrm{s}}^{\mathrm{p}}$) was estimated with the equation used by Brenner and Incoll (1997) to integrate stomatal leaf conductance ($g_{\mathrm{s}}^{\mathrm{l}}$) of all the plants into a sole surface plant conductance ($g_{\mathrm{s}}^{\mathrm{p}}$ = $1/r_{\mathrm{s}}^{\mathrm{p}}$), calculated as:

$$g_{\mathrm{s}}^{\mathrm{p}} = (g_{\mathrm{s}}^{\mathrm{m}} / \kappa) \ln\left[(b_{\mathrm{q}} + \kappa Q)/(b_{\mathrm{q}} + \kappa Q e^{-\kappa L})\right] \qquad (3)$$

where $g_{\mathrm{s}}^{\mathrm{m}}$ is the maximum $g_{\mathrm{s}}^{\mathrm{l}}$ at light saturation. This $g_{\mathrm{s}}^{\mathrm{m}}$ was related to the vapour pressure deficit ($D_0$) at $z_{\mathrm{m}}$ as follows:

$$g_{\mathrm{s}}^{\mathrm{m}} = g_{\mathrm{s}}^{\mathrm{max}} + b_{\mathrm{d}} D_0 \qquad (4)$$

where $g_{\mathrm{s}}^{\mathrm{max}}$, is the maximum stomatal conductance for water vapour saturation of air, and shows how $g_{\mathrm{s}}^{\mathrm{l}}$ changes with $D_0$. Finally, in order to estimate $g_{\mathrm{s}}^{\mathrm{max}}$ and $b_{\mathrm{d}}$ these variables were related to *θ*, following the method used by Brenner and Incoll (1997).

$r_{\mathrm{s}}^{\mathrm{s}}$ and $r_{\mathrm{s}}^{\mathrm{bs}}$ were calculated by relating the evaporative demand with soil evaporation (*E*) (Jones, 1992), and solving for $r_{\mathrm{s}}$. Using the example of bare soil, the equation is as follows:

$$E = \left[\frac{(0.622\rho/\mathrm{P})(e_{T\mathrm{bs}}^{*} - e_{\mathrm{r}})}{(r_{\mathrm{a}}^{\mathrm{bs}} + r_{\mathrm{s}}^{\mathrm{bs}})}\right] \qquad r_{\mathrm{s}}^{\mathrm{bs}} = \left[\frac{(0.622\rho/P)(e_{T\mathrm{bs}}^{*} - e_{\mathrm{r}})}{E} - r_{\mathrm{a}}^{\mathrm{bs}}\right] \qquad (5)$$

For simplicity, Mahfouf and Noihlan (1991), Kondo et al. (1990) and Daamen and Simmonds (1996) proposed the use of relationships between the resistances calculated with Eq. 5 and $\theta$ to estimate $r_{\mathrm{s}}^{\mathrm{bs}}$ and $r_{\mathrm{s}}^{\mathrm{s}}$,

### Other complementary measurements

- Field experiments for measuring *λE*, aerodynamic and surface resistances, and micro-meteorological variables necessary to parameterise the CM were carried out at a sparse-vegetated stand of *Anthyllis cytisoides* at the Rambla Honda field site (Puigdefabregas et al., 1996),a dry valley near Tabernas, (Almería, Spain; 37º8'N, 2º22'W, 630 m altitude).
- Relationships between $r_{\mathrm{s}}^{\mathrm{s}}$, $r_{\mathrm{s}}^{\mathrm{bs}}$, $g_{\mathrm{s}}^{\mathrm{max}}$ and $b_{\mathrm{d}}$ with measured *θ* were obtained and applied in the CM. To study the effect on *λE* estimates of the depth at which *θ* was measured, these variables were related to *θ* measured at 0.02 m, 0.05 m, 0.15 m, and *θ* averaged for the whole 0.15 m soil profile. In Table 1 are indicated the CM runs carried out using different combinations of *θ* measurements to estimate the surface resistances. *θ* was measured with Self Balanced Impedance Bridge (SBIB) probes (Vidal, 1994).

- Soil evaporation (*E*) was measured weighting six small PVC lysimeters following the methodology proposed by Daamen et al. (1993).
- Stomatal conductance was measured with an IRGA porometer (LCA-3, ADC, Hoddesdon, Hertfordshire, UK) with a PLC-3C chamber (ADC, Hoddesdon, UK), corrected by relating it to leaf area units and included in Eq. 3 as $g_s^m$ to get $g_s^{max}$ and $b_d$ which were related to an averaged $\theta_{bs}$ and $\theta_s$, weighted by the vegetation cover fraction ($\theta = f\theta_s + (1-f)\theta_{bs}$). This weighted average was calculated for $\theta$ at 0.02 m, 0.05 m, and 0.15 m depth, and for $\theta$ averaged over the 0.15 m profile.

Table 1: CM simulations by depth of measured $\theta$ used in the parameterisation of the soil surface resistances ($r_s^s$ and $r_s^{bs}$) and plant surface resistance ($r_s^p$).

| | | $r_s^p$ | | | |
|---|---|---|---|---|---|
| | **$\theta$ depth (m)** | **0.02** | **0.05** | **0.15** | **Aveg.** |
| $r_s^s$ and $r_s^{bs}$ | **0.02** | S1 | S5 | S9 | S13 |
| | **0.05** | S2 | S6 | S10 | S14 |
| | **0.15** | S3 | S7 | S11 | S15 |
| | **Aveg.** | S4 | S8 | S12 | S16 |

- $\lambda E$ of the *A. cytisoides* stand was measured with an Eddy covariance system. To correct for terrain slope assuming that the instruments in the tower are perpendicular to the surface the coordinate system was rotated (Kowalski et al., 1997).
- $\lambda$E and the rest of micrometeorological variables needed to run CM were logged in Campbell scientific dataloggers (CR10X, 2X1) and averaged every 20 minutes from the 24th of April to the 18th of June.
- Finally, as reported in the introduction, all comparisons were performed at daily time-scale to prevent poor hourly performance of soil evaporation models using soil surface resistances estimated from $\theta$ (Daamen and Simmonds, 1996).

## RESULTS AND DISCUSSION

Figure 1 (a and b) shows the regressions between $r_s^{bs}$ and $r_s^s$, from morning to midday, with measured values of $\theta$. These regressions are within the range of similar regressions found by other authors (i.e. Camillo and Gurney, 1986; Daamen and Simmonds, 1996).

Figure 1 (c and d) shows linear regressions between $g_s^{max}$ and $b_d$, and $\theta$.

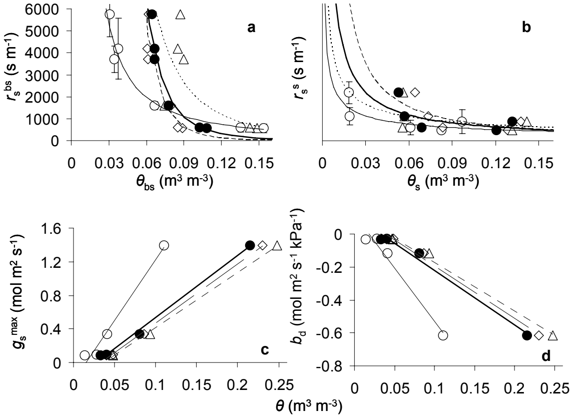

Figure 1: a) $r_s^{bs}$, b) $r_s^s$, c) $g_s^{max}$ and d) $b_d$ related to volumetric soil water content ($\theta$) measured at 0.02 m (○, thin continuous line), 0.05 m (◊, dashed line), 0.15 m (Δ, dotted line) and average for the 0.15-m profile (●, continuous thick line).

Figure 1 shows that, both, $r_s^{bs}$, $r_s^s$, $b_d$ and $g_s^{max}$ respond quickly to $\theta$ changes measured at 0.02 m, while no significant effects were observed when using $\theta$ measured more deeply.
Comparison of modelled results for $\lambda E$ estimated by each of the 16 CM runs (Table 1) and the measured eddy covariance system are shown in Table 2
The best CM $\lambda E$ estimates were obtained when using $\theta$ measured at 0.02 m (S1, S5, S9 and S13 with RMSE ranging from 0.3 to 0.2 mmday-1) although bias in S13 runs was two times lower than in S9. However, the CM overestimated $\lambda E$ when deeper $\theta$ values were used (RMSE ranging from 0.75 to 0.61 mmday-1).

Table 2: Parameters found by comparing daily $\lambda E$ estimated with the 16 different CM simulations (Table 1) and the Eddy covariance measurements ($n$ = 45): bias and root mean square error (RMSE).

| | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 | S11 | S12 | S13 | S14 | S15 | S16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Bias (mm day$^{-1}$)** | 0.06 | -0.57 | -0.57 | -0.60 | 0.12 | -0.51 | -0.51 | -0.54 | 0.06 | -0.58 | -0.58 | -0.61 | 0.03 | -0.60 | -0.60 | -0.63 |
| **RMSE (mm day$^{-1}$)** | 0.30 | 0.73 | 0.65 | 0.71 | 0.23 | 0.67 | 0.61 | 0.66 | 0.20 | 0.72 | 0.68 | 0.71 | 0.20 | 0.75 | 0.69 | 0.74 |

## CONCLUSIONS

The clumping model (CM) applied to an *A. cytisoides* stand is very sensitive to the measuring depth of the soil water content ($\theta$) using in parameterization of soil surface resistances within the model. The results of this work show that $\theta$ should be measured as close to the surface as possible, as differences of only 0.03 m in the measuring depth of $\theta$ can generate differences between measured and estimated $\lambda E$ greater than 100% (see Table 2, S1 and S2).

## ACKNOWLEDGEMENTS

This work received financial support from several research projects: PROBASE (Ref.: CGL2006-11619/HID) funded by the Ministry of Education and Science; AQUASEM ('Balance hídrico en zonas degradadas semiáridas', P06-RNM-01732) and BACAEMÁ ('Balance de carbono y de agua en ecosistemas de matorral mediterráneo en Andalucía: Efecto del cambio climático', RNM-332) financed by the regional government Junta de Andalucía. The authors would like to thank especially Alfredo Durán (and Carmen) whose help was essential on the installation of field instrumentation.

## REFERENCES

- Brenner AJ, Incoll LD (1997) The effect of clumpling and stomatal response on evaporation from sparsely vegetated shrublands. Agr Forest Meteorol 84: 187-205
- Camillo J, Gurney RJ (1986). A resistance parameter for bare-soil evaporation models. Soil Sci 141:95-105.
- Daamen CC, Simmonds LP, Wallace JS, Laryea KB, Sivakumar MVK (1993) Use of microlysimeters to measure evaporation from sandy soils. Agr Forest Meteorol 65, 159-173
- Daamen CC, Simmonds LP (1996) Measurement of evaporation from bare soil and its estimation using surface resistance. Water Resour Res 32: 1393-1402
- Domingo F, Villagarcía L, Brenner AJ, Puigdefábregas J (1999) Evapotranspiration model for semi-arid shrub-lands tested against data from SE Spain. Agr Forest Meteorol 95: 67-84
- Kondo J, Saigusa N, Sato T (1990) A parameterisation of evaporation from bare soil surfaces. J Appl Meteorol 29, 385-389
- Kowalski AS, Anthoni PM, Vong RJ, Delany AC, Maclean GD (1997) Deployment and evaluation of a system for groundbased measurement of cloud liquid water turbulent fluxes. J Atmos Ocean Tech 14, 468–479
- Mahfouf JF, Noilhan J (1991) Comparative study of various formulations of evaporation from bare soil using in situ data. J Appl Meteorol 30, 1354-1365
- Puigdefábregas J, Sánchez G (1996) Geomorphological implications of vegetation patchiness on semi- arid slopes. In: Anderson M, Brooks S (eds) Advances in Hillslope Processes, John Wiley and Sons Ltd, London, Chapter 2, pp.1028-1060
- Vidal S, (1994) A device for simultaneous measurement of soil moisture and electrical conductivity (Patent nº 9401681)
- Zhang, B., Kang, S., Li, F., Zhang, L (2008) Comparison of three evapotranspiration models to Bowen ratio-energy balance method for a vineyard in an arid desert region of northwest China. Agr Forest Meteorol 148 (10): 1629-1640.