Modeling and Measurement of mass and heat transfer within the Soil-Plant-Atmosphere Continuum

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Abstract:
In this work, the issue of using the SVAT models in conjunction with aggregation schema to estimate turbulent fluxes over heterogeneous grids has been investigated. The scintillometry has been used for validating the simulated fluxes. The heterogeneity of the grid is associated with the cover of the vegetation canopy (tall and sparse olive trees) as well as the strong heterogeneity in terms of soil moisture caused by the flood irrigation method employed. Data collected within the SUDMED project over the oliveyard of Agdal which is located near the Marrakech city (Morocco), have been used to test the proposed approach. Except for some scattering which can be related to the footprint effect of the Scintillometer, the comparison between estimated and measured sensible heat fluxes yielded an acceptable agreement although the complexity of the study surface with a correlation coefficient (R^2) of 0.76 and root mean square error (RMSE) of 30 W.m-2. For the latent heat fluxes, the statistical result for the comparison between simulated and measured values showed a large scatter compared to that revealed for the sensible heat fluxes (R^2=0.7; RMSE=43 W.m-2).
Despite the complexity of the grid and the effect of the footprint especially in the current study where the irrigation method can create a strong heterogeneity in the soil moisture, the obtained statistical results showed that the proposed approach is successfully compared to the scintillometry and confirms its consistency with accurate estimates of the turbulent fluxes over heterogeneous grids.

Mots clés :

Keywords: Turbulent fluxes; SVAT models; aggregation scheme; heterogeneous grid; semi-arid regions.

1. Introduction

Due to the importance of the latent heat flux (ET) in water cycle, especially in arid and semi-arid regions, efforts have been particularly oriented toward improving its estimates at different space-time scales. However, quantifying diurnal ET variation over large and heterogeneous areas is not straightforward. In this regard, remotely sensed data can be a valuable tool to address this issue. Geostationary sensors can provide regional scale of ET with temporal sampling from 15 min to 1h, but their spatial resolution is very coarse. In contrast, sun-synchronous satellites provide data with better spatial resolution, but the temporal resolution is poor. Therefore the issue of discrepancy between the space-time scale of satellite observation and that at which the process need to be described is still an open research question.

For the irrigation water management purposed, the combination of the sun-synchronous sensors data and an aggregation schemes can provide a workable solution ([1]). The aggregation scheme is conceived as method which seeks to link the model parameters which control surface exchange at patch scale with the area-average value of equivalent model parameters applicable at larger scale or grid scale, assuming that the same equations are used to describe surface fluxes at both scales. Substantial progress has been made in the last decade to develop aggregation schemes which ranging from physically based through semi-empirical, to entirely empirical using numerical simulations studied ([2]) or experimental studies ([3]). However, one of the main difficulties regarding the development of these aggregation procedures concerned the evaluation of their outputs against ground observations. The straightforward solution is to deploy a network of patch scale measurement devices such as Eddy correlation (EC) systems. However, due to high cost of the devices and the requirement for continuous availability of well-trained staff to operate and maintain them, this solution cannot be implemented at operational basis.

In this context, the scintillometry can be considered as an attractive method for routinely measuring area-averaged surface fluxes. Using a Large Aperture scintillometer (LAS), one can obtain area-averaged surface fluxes over distances from a few hundreds of metres up to several kilometres. In the present study, the issue of using of the LAS to validate spatial and temporal aggregation schemes was investigated. Here, the grid consists of two distinct fields (or patches) with different characteristics, creating a heterogeneous (grid) surface. Compared to earlier studies, our investigations were done in difficult environment conditions due to the type of vegetation (tall and sparse vegetation), irrigation method which has an irregular pattern in space and time, and variable soil characteristics. Data used in these investigations were collected within the framework of the SUDMED project which has taken place in southern Mediterranean regions (Marrakech, Morocco), to assess the spatio-temporal variability of water needs and consumption for irrigated crops under water shortages.

2. Theory: Aggregation Procedure

In this section, two aggregation algorithms are presented to determine the grid scale latent heat flux: Spatial aggregation which consists of upscaling the patch measurements/or estimates to grid scale estimates and the temporal aggregation which consists of extrapolating the grid scale instantaneous values which can be derived from remote sensing to daily ones.

2.1. Spatial aggregation

The strategy explored in this current study to infer grid-scale surface fluxes at grid scale is based on two postulations ([1]): the first one consists in determining grid-scale surface fluxes in such way that the flux equations at the grid scale must have the same form as those used at patch–scale but whose arguments are the aggregate expressions of those at the patch scale. The second one stipulates that “the effective or area-average value of land surface parameters is estimated as a weighted average over the component cover types in each grid through that function involving the parameter which most succinctly expresses its relationship with the associated surface flux” ([4]). Grid-scale net radiation (<Rn>), soil heat flux (<G>) and sensible heat flux (<H_{Sim}>) (denoted by angle brackets) resulting from the application of this simple aggregation rule are given below:

$$\langle R_n \rangle = (1-\langle\alpha\rangle)R_g + \langle\varepsilon_S\rangle\sigma\left(\varepsilon_a T_a^4 - \langle T_S^4 \rangle\right) \qquad (1)$$

$$\frac{<G>}{<R_n>} = A\cos[2\pi(t+10800)/B] \qquad (2)$$

$$\langle H_{Sim}\rangle = \rho c_p \left[\frac{(\langle T_S\rangle - T_a) - \left[\left(\frac{\langle r_{as}\rangle}{\langle r_{as}\rangle + \langle r_{af}\rangle}\right) - f\right]\left(a(\langle T_S\rangle - T_a)^m\right)}{\langle r_a\rangle - \langle r_e\rangle}\right] \qquad \text{(Lhomme et al. 1994)}$$

(3)

where R_g is the solar global radiation, α is the surface albedo, ε_S is the surface emissivity, ε_a is the emissivity of the atmosphere, T_a is the air temperature, T_S is the radiative temperature, r_{as} is the aerodynamic resistance between the soil and the canopy source height and r_{af} is the bulk boundary layer resistance of the canopy, r_a is the aerodynamic resistance to heat transfer between the level of apparent sink of momentum and the reference height, and r_e ($r_e = \frac{r_{af}\, r_{as}}{r_{af} + r_{as}}$) is the equivalent resistance, t is the time of day in seconds, A and B are adjusting factors, *f* is the fractional vegetation cover, *a* and *m* are empirical coefficients.

Finally, the grid scale evapotranspiration (denoted <ET_{SA}>) can be obtained as the residual term of the energy balance equation:

$$<ET_{SA}>=<R_n>-<H_{Sim}>-<G> \qquad (9)$$

2.2 Temporal aggregation

Grid scale latent heat flux (<ET>) can be also determined using remote sensing data in conjunction with an energy balance model. Practically, the sun-synchronous sensors are the most suitable for deriving <ET> ([1]). However, these sensors provide only instantaneous values at the satellite overpass. These are of limited interest for water managers who are primarily focusing on daily values of <ET>. To extrapolate the instantaneous ET to daily values, the approach developed by [5] was adopted. The grid scale evaporation fraction <EF> when accounting for both atmospheric demand and soil moisture status is given by:

$$\left\langle EF_{Sim}^{ACT}\right\rangle = \begin{cases} \left\langle EF_{Sim}\right\rangle r_{EF}^{1130} & \text{for} \quad \left\langle \beta^{1130}\right\rangle \le 1.5 \\ \left\langle EF_{Rem}^{1130}\right\rangle & \qquad\; \left\langle \beta^{1130}\right\rangle > 1.5 \end{cases} \tag{10}$$

Where $\left\langle EF_{Sim}\right\rangle$ is the EF diurnal course parameterized when accounting for atmospheric demand (i.e. incoming solar radiation ($S^{\downarrow}$) and relative humidity (RH)) only, which is formulated as:

$$\left\langle EF_{Sim}\right\rangle = 1.2 - \left(0.4\frac{S^{\downarrow}}{1000} + 0.5\frac{RH}{100}\right) \tag{11}$$

r_{EF}^{1130} is a correction factor given by:

$$r_{EF}^{1130} = \frac{\left\langle EF_{Rem}^{1130}\right\rangle}{\left\langle EF_{Sim}^{1130}\right\rangle} \tag{12}$$

with $\left\langle EF_{Sim}^{1130}\right\rangle$ is $\left\langle EF_{Sim}\right\rangle$ at 1130 UTC, and $\left\langle EF_{Rem}^{1130}\right\rangle$ is the EF estimated from remote sensing observations at 1130 UTC. Here the Bowen ratio at 1130 UTC, labeled β^{1130}, is used to switch from a constant to a daily variable <EF>.

In this study, the time of 1130 UTC was chosen since it corresponds to the local time of overpass of the ASTER satellite ([5]). When choosing the AVHRR overpass time over north-western Mexico, i.e 14h00, [1] have shown that this parameterization was also pertinent.

In addition of the parameterization of the <EF>, the retrieval of the diurnal course <ET> requires also <AE> over the diurnal cycle, which is not routinely available. Here again, the same heuristic approach developed by [1] at the grid scale, was used in this specific study. This approach combines the instantaneous remote sensing observations of AE $\left(\left(\left\langle AE\right\rangle\right)_{Rem}^{1130}\right)$ at 1130 UTC with a simple parameterization schema to derive AE diurnal course. The latter is expressed as:

$$\left(\frac{\left(\left\langle AE\right\rangle\right)^{t}}{\left(\left\langle AE\right\rangle\right)_{Rem}^{1130}}\right) = f\left(\frac{\left\langle R^{*t}\right\rangle}{\left\langle R^{*1130}\right\rangle}\right) \tag{13}$$

where R^{*t} is a function given by :

$$\left\langle R^{*t}\right\rangle = \left(1-\left\langle \alpha\right\rangle\right)R_{g}^{t} + \left\langle \varepsilon\right\rangle \varepsilon_{a}^{t}\left(T_{a}^{t}\right)^{4} \tag{14}$$

with t is the time of the day, *f* is the following 2nd order function:

$$f\left(\frac{\left\langle R^{*t}\right\rangle}{\left\langle R^{*1130}\right\rangle}\right) = a_2\left(\frac{\left\langle R^{*t}\right\rangle}{\left\langle R^{*1130}\right\rangle}\right)^{2} + a_1\left(\frac{\left\langle R^{*t}\right\rangle}{\left\langle R^{*1130}\right\rangle}\right) + a_0 \tag{15}$$

where a_0, a_1 and a_2 are empirical coefficients established by [5] as 0.48495, 1.15120 and 0.34285, respectively, when calibrating this function over a homogenous olive orchard in Morocco.

3. Site description and experimental setup

The present study was carried out in the fall of 2002, between Day of Year (DOY) 294 and 308 at the 275 ha Agdal olive orchard, located southeastern of the Marrakech city, Morocco (31°36' N, 07°58' W) (Figure 1). In this section, only a brief summary of site description and experimental setup are provided, the reader is referred to [6], for a complete description. The experimental area is divided in two fields, which are referred to as the southern site and the northern site (see Figure 1).

Fig. 1: Overview of the location site and the experimental setup, locations of LAS and micrometeorological towers (MT) are marked

Both sites were equipped with a set of standard meteorological instruments to measure wind speed and direction (Young Wp200 anemometer); air temperature and humidity (Vaisala HMP45AC temperature and humidity probe). Net radiation was measured using a CNR1 (Kipp & Zonen) in the southern site and Q7 in the northern site. The soil heat flux density was measured at a depth of 0.01 m using soil heat flux plates (HFT3-L, Campbell Scientific Ltd.). Radiative soil and vegetation temperatures were measured using 2 IRTS-P's (Apogee). Two identical Large Aperture Scintillometers (LAS) were mounted at heights of 14 m in the southern site and 14.5 m in the northern site (see figure 1). In the southern site, the LAS was installed perpendicular to the dominant wind direction, over a pathlength of 1050m. In the northern site, the orientation of the LAS was almost parallel to the dominant wind direction, and it measured over a pathlength of 1070 m.

4- Résultats

4.1. Spatial aggregation

The grid scale latent heat flux ,$<ET_{SA}>$, (estimated using the Eq. (9)) was compared to the grid scale latent heat flux (denoted $<ET_{LAS}>$) derived from the LAS in Figure 2. The RMSE between $<ET_{SA}>$ and $<ET_{LAS}>$ was 46 Wm^{-2} and the correlation coefficient and the slope associated with the linear regression forced to the origin were 0.78 and 0.87, respectively. It should be noted that the problem of disclosure of the energy balance has no big effect on the results, because both approaches forced the energy balance closure. In spite of the observed scatter which can be related to the error associated to the impact of the footprint and to the aggregation procedure, the correspondence between $<ET_{SA}>$ and $<ET_{LAS}>$ is acceptable considering the difficulty in estimating grid scale latent heat flux over such complex grid. Finally, it can be concluded that the spatial aggregation procedure yielded a reasonable grid surfaces fluxes.

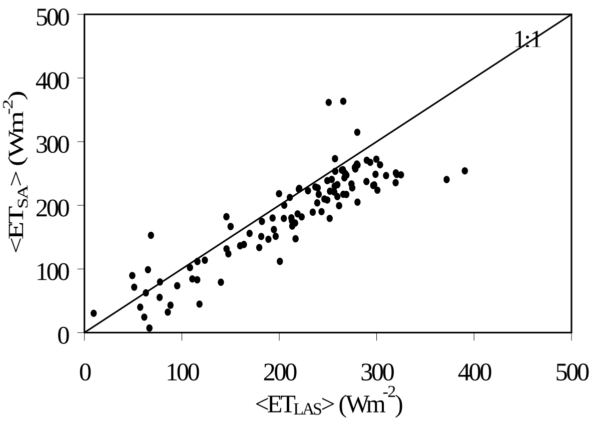

Fig. 2. Comparison between the latent heat fluxes, $<ET_{Sim}>$ (simulated using the spatial aggregation scheme) and $<ET_{LAS}>$ (obtained form the LAS)

4.2. Temporal aggregation

Figure 3 shows the comparison between the grid scale latent heat flux ,$<ET_{TA}>$, retrieved through the Eqs (10)–(15) and the ground truth derived from the LAS ($<ET_{LAS}>$). The statistical results of this comparison showed that the RMSE between $<ET_{TA}>$ and $<ET_{LAS}>$ was about 43 Wm^{-2} and the correlation coefficient and the slope associated with the linear regression forced to the origin were 0.7 and 0.88 respectively. The results indicate that by properly taking into account the effect of the grid heterogeneity due to both vegetation and soil moisture variations along the grid, the agreement between the $<ET_{TA}>$ and $<ET_{LAS}>$ simulated and observed area average of the latent heat fluxes is deemed acceptable. These results collaborated with those established for spatial aggregation scheme.

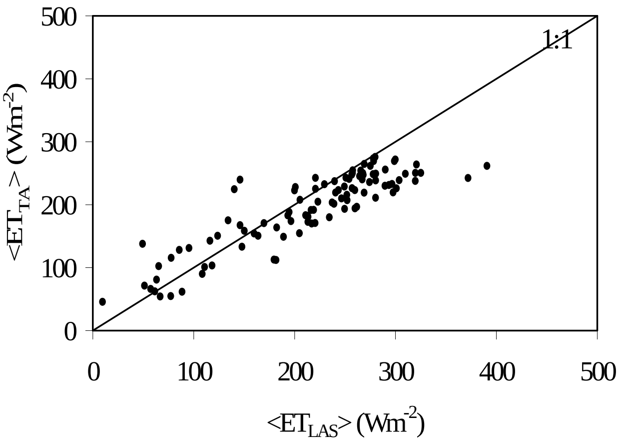

Fig. 3: Comparison between the latent heat fluxes, $<ET_{Sim}>$ (simulated using the temporal aggregation scheme through the Eqs (10)–(15)) and $<ET_{LAS}>$.

5. Conclusion

The obtained results are very encouraging when we compared the values of <ET> derived using spatial and temporal aggregation schemes to those obtained from the LAS ($<ET_{LAS}>$) using the measured area-averaged of the available energy. Therefore, this result confirms the consistency of the spatial and temporal aggregation schemes to accurate estimates diurnal course of the evaportanspiration over heterogeneous grids. This is of importance for sustainable water management especially in the arid and semi arid regions, since the main interest of water managers is the daily value of ET at large scale.

6. References

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