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Evaluation of land surface model simulations of evapotranspiration over a 12 year crop succession: impact of the soil hydraulic properties

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Abstract

Evapotranspiration has been recognized as one of the most uncertain term in the surface water balance simulated by land surface models. In this study, the SURFEX/ISBA-A-gs simulations of evapotranspiration are assessed at local scale over a 12 year Mediterranean crop succession. The model is evaluated in its standard implementation which relies on the use of the ISBA pedotransfer estimates of the soil properties. The originality of this work consists in explicitly representing the succession of crop cycles and inter-crop bare soil periods in the simulations and assessing its impact on the dynamic of simulated and measured evapotranspiration over a long period of time. The analysis focuses on key soil parameters which drive the simulation of evapotranspiration, namely the rooting depth, the soil moisture at saturation, the soil moisture at field capacity and the soil moisture at wilting point. The simulations achieved with the standard values of these parameters are compared to those achieved with the in situ values. The portability of the ISBA pedotransfer functions is evaluated over a typical Mediterranean crop site. Various in situ estimates of the soil parameters are considered and distinct parametrization strategies are tested to represent the evapotranspiration dynamic over the crop succession.

This work shows that evapotranspiration mainly results from the soil evaporation when it is continuously simulated over a Mediterranean crop succession. The evapotranspiration simulated with the standard surface and soil parameters of the model is largely underestimated. The deficit in cumulative evapotranspiration amounts to 24 % over 12 years. The bias in daily daytime evapotranspiration is $-0.24\,\mathrm{mm\,day^{-1}}$. The ISBA pedotransfer estimates of the soil moisture at saturation and at wilting point are overestimated which explains most of the evapotranspiration underestimation. The overestimation of the soil moisture at wilting point causes the underestimation of transpiration at the end of the crop cycles. The overestimation of the soil moisture at saturation triggers the underestimation of the soil evaporation during the wet soil periods. The use of field capacity values derived from laboratory retention measurements leads

to inaccurate simulation of soil evaporation due to the lack of representativeness of the soil structure variability at the field scale. The most accurate simulation is achieved with the values of the soil hydraulic properties derived from field measured soil moisture. Their temporal analysis over each crop cycle provides meaningful estimates of the wilting point, the field capacity and the rooting depth to represent the crop water needs and accurately simulate the evapotranspiration over the crop succession. We showed that the uncertainties in the eddy-covariance measurements are significant and can explain a large part of the unresolved random differences between the simulations and the measurements of evapotranspiration. Other possible model shortcomings include the lack of representation of soil vertical heterogeneity and root profile along with inaccurate energy balance partitioning between the soil and the vegetation at low LAI.

1 Introduction

Land surface models (LSMs) are relevant tools to analyze and predict the evolution of the water balance at various spatial and temporal scales. They describe water, carbon and energy fluxes between the surface and the atmosphere at hourly time scale. Most LSMs consist of 1-D column models describing the non-saturated soil (mainly the root-zone), the vegetation and the surface/atmosphere interaction processes. The LSM complexity mainly differs in (1) the number of sources involved in the surface energy balance, (2) the representation of water and thermal soil transfers, (3) the representation of stomatal conductance (see reviews in Olioso et al., 1999; Arora, 2002; Pitman, 2003; Overgaard et al., 2006; Bonan, 2010). For example, the original version of the Interactions between Soil, Biosphere, and Atmosphere (ISBA, Noilhan and Planton, 1989) computes a single energy budget assuming an unique “big leaf” layer. It is a simple bucket model based on the force-restore method with two or three soil layers. The stomatal conductance is simply represented by the Jarvis (1976) empirical formulation. More advanced LSMs resolve a double-source energy budget (e.g. Sellers et al., 1987) and implement a multi-layer soil diffusion scheme (e.g. Braud et al.,

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1995b). They also explicitly simulate photosynthesis and its functional coupling with plant transpiration and they represent vegetation dynamic (Calvet et al., 2008; Egea et al., 2011). Progress in LSMs led to more accurate estimations of energy and water fluxes. This resulted in more realistic simulations of air temperature and humidity of the surface boundary layer in atmospheric models (Noilhan et al., 2011). The improvement of the surface water budget in hydrological models permitted more accurate streamflow forescast (Habets et al., 2008) and drought monitoring (Vidal et al., 2010b). LSMs also proved their usefulness for agronomy application such as irrigation monitoring (Olioso et al., 2005).

This work focuses on the evaluation of evapotranspiration (ET) simulated from a land surface model over a crop site for a long period of time. ET has been recognized as one of the most uncertain term in the surface water balance (Dolman and de Jeu, 2010; Mueller and Seneviratne, 2014). Uncertainties in simulated ET may propagate large errors in both LSM-atmosphere and LSM-hydrological coupled models. ET uncertainties can arise from (1) errors in the large-scale datasets used to force LSMs, (2) shortcomings in the model structure and (3) errors in the parameter values. Since LSMs were originally designed to be coupled with atmospheric or hydrological models over large areas, their parametrization is generally parsimonious and their spatial integration is generally based on coarse resolution (∼ 1–10 km) maps of parameters. Surface parameters drive a large part of LSM uncertainties and explain most discrepancies between models (Chen et al., 1997; Gupta et al., 1999; Olioso et al., 2002; Boone et al., 2004). The representation of cropland and its temporal dynamic over long period of time need to be improved in LSMs (Lafont et al., 2011; Bonan and Santanello, 2013). Past evaluation studies focused on particular crop types for limited periods of time. They disregarded the succession of crop and inter-crop periods and its impact on the simulated water balance over a long period of time.

In this study, the ISBA-A-gs version (Calvet et al., 1998) of the ISBA LSM (Noilhan and Planton, 1989) is considered. ISBA-A-gs includes a coupled stomatal conductance-photosynthesis scheme. Local site studies demonstrated that ISBA

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(Noilhan and Mahfouf, 1996) and ISBA-A-gs (Gibelin et al., 2008) are able to correctly simulate the diurnal and seasonal time courses of energy fluxes and soil water content, over contrasted soil and vegetation types. Lower performances were obtained by Olioso et al. (2002) over wheat fields with a marked underestimation of ET.

The uncertainties in soil hydraulic properties can be large due to significant spatiotemporal variability (Braud et al., 1995a), uncertainties in the estimation method (Baroni et al., 2010; Steenpass et al., 2011) and spatial scale mismatch between the local measurements and the operational scale of the model (Mertens et al., 2005). Errors in soil hydraulic properties can have significant impact on LSM simulations of ET and soil water content (Jacquemin et al., 1990; Braud et al., 1995a; Cresswell and Paydar, 2000). Their impact on the model can be larger than the structural model uncertainties (Workmann and Skaggs, 1994; Baroni et al., 2010). Since the soil hydraulic properties are rarely known over large areas, they are generally derived from empirical pedotransfer functions (PTF) which relate the soil hydrodynamic properties to readily available variables such as soil texture and bulk density (Cosby et al.,1984; Vereecken et al., 1989; Schaap et al., 2000). These functions may not be accurate enough to describe the spatial variability of the soil hydrodynamic characteristics across soil types and their impact on LSM simulations need to be assessed locally (Espino et al., 1996; Baroni et al., 2010).

The objectives of this paper consist in:

1. evaluating the ISBA-A-gs simulations of ET over a 12 year Mediterranean crop succession,

2. assessing the impacts of errors in the soil hydraulic parameters on ET simulated over a long period of time.

ET simulations are assessed over the Avignon "Remote Sensing and Fluxes" crop site. 14 arable crop cycles and 14 inter-crop periods were monitored over this site through continuous measurements of soil water content and surface fluxes. The approach followed in this paper consists in evaluating the model in its standard implementation.

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The latter relies on the use of the ECOCLIMAP-II dataset for the surface parameters (Faroux et al., 2013) and the ISBA PTFs for the soil properties (Noilhan and Laccarère, 1995). No local calibration of the parameters is achieved to test the portability of the model parameters over a typical Mediterranean crop site (Olioso et al., 2002). The goal is to assess the capability of ISBA-A-gs to represent ET over a 12 yr Mediterranean crop succession and to identify the shortcomings in the physical process representation. The main originality of this work consists in representing the succession of crop cycles and inter-crop bare soil periods in the simulations and assessing its impact on the dynamic of simulated and measured evapotranspiration over a long period of time. The model performances are thoroughly quantified for a large range of surface and atmospheric states. The impact of the propagation in time of errors in soil moisture is investigated. The analysis focuses on key soil parameters which drive the simulation of ET, namely the rooting depth, the soil moisture at saturation, the soil moisture at field capacity and the soil moisture at wilting point. The simulations achieved with the standard values of these parameters are compared to those achieved with in situ values. The portability of the ISBA PTFs is evaluated. Various in situ estimates of the soil parameters are considered and distinct parametrization strategies are investigated to represent the ET dynamic over the crop succession. We tested field capacity values inferred from laboratory and field measurements. The use of crop-varying values of wilting point and rooting depth is compared to the use of constant values over the crop succession. The impact of reducing the soil reservoir depth on the soil evaporation is assessed over the inter-crop periods. Finally, we discussed our results with respect to the uncertainties in the soil parameters and the model structure. The errors in the ET measurements are quantified to put into perspective the performances of the model.

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2 Site and measurements

2.1 Site characteristics

The "Remote sensing and flux site" of INRA Avignon[1] (France, 4.8789° E, 43.9167° N; alt = 32 m a.s.l.) is characterized by a Mediterranean climate with a mean annual temperature of 14 °C and a mean annual precipitation of 687 mm. It is a flat agricultural field oriented north–south in the prevailing wind direction. The 12 year period (Table 1) consists in a succession of winter arable crops (wheat, peas) and summer arable crops (sorghum, maize, sunflower). Periods between two consecutive crop cycles lasted ∼ 1–1.5 month in the case of a summer crop followed by a winter crop and ∼ 9–10 months in the reverse case. During inter-crop periods, the soil is mostly bare. Limited wheat regrowths occurred over short periods of time.

2.2 Field measurements

2.2.1 Soil measurements

A 0–190 cm soil moisture profile at 10 cm resolution was measured every ∼ 10 days using 4 neutron probes implemented at different locations in the field. Near-surface volumetric soil moisture was continuously measured within a 5 cm soil layer. Surface ground heat flux (G) was derived from 4 heat flux plate measurements located at 5 cm depth and heat storage estimates within the 5 cm layer.

2.2.2 Plant measurements

Crop characteristics (leaf area index (LAI), height, biomass) were regularly measured at selected phenological stages. Vegetation height was linearly interpolated on a daily

[1] https://www4.paca.inra.fr/emmah_eng/Facilities/In-situ-facilities/Remote-Sensing-Fluxes.

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basis. Daily interpolation of LAI was achieved using a functional relationship between LAI and the sum of degree-days (Duveiller et al., 2011).

2.2.3 Micrometeorological measurements

Half-hourly observations of precipitation, air temperature and humidity, wind speed, atmospheric pressure, radiations, energy fluxes, were continuously performed over the 12 year period. The net radiation (RN) was computed from the measured shortwave and longwave upwelling and downwelling radiations. Sensible (H) and latent (LE) heat fluxes were computed from an eddy-covariance system. The latter was composed of a 3-D sonic anemometer set up in 2001 and of an open-path gas (H_2O, CO_2) analyzer set up in November 2003. The system was monitored following the state of the art guidelines for cropland sites (Rebmann et al., 2012; Moureaux et al., 2012). Fluxes were computed on 30 min intervals using the EDIRE software[2] The flux data processing included spike detection on raw data and standard eddy-covariance corrections (coordinate rotation, density fluctuations, frequency-loss). The ECPP[3] software (Beziat et al., 2009) was used to discard spurious flux (e.g. friction velocity and footprint controls) and to apply the Foken et al. (2004) quality control tests on the temporal stationarity and the development of turbulence conditions. In this work, only the best quality class of data (Mauder et al., 2013) was used. An additional threshold of 100 W m^{-2} on the energy balance non-closure was applied to eradicate very inconsistent fluxes. For LE, the percentage of valid data was 47 % over the 20 November 2003–18 December 2012 period (55 % if we consider only daytime). For the 2001–2003 period, LE estimates were derived as the residue of the energy balance (LE = RN – G – H). Cumulative ET in mm was derived from LE over given period of time.

[2]Robert Clement, ©1999, University of Edinburgh, UK, http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe.

[3]Eddy Covariance Post Processing, Pierre Béziat, CESBIO, Toulouse, France.

2.3 Soil properties

Table 2 presents the values of the soil parameters averaged over the 0–1.2 m soil layer, where most of the root-zone processes occurred. The soil moisture at saturation (w_{sat}) was derived from soil bulk density measurements performed at different field locations over the 12 year period. The soil moisture at field capacity (w_{fc}) and wilting point (w_{wp}) were estimated using the two following methods:

1. A Brooks and Corey (1964) retention curve model was adjusted over soil matric potential (h) and soil water content laboratory measurements. These measurements were obtained from the Richard pressure plate technique in laboratory (Bruckler et al., 2004). w_{wp} was computed for $h = -150$ m. Most studies agree on this definition (Boone et al., 1999; Olioso et al., 2002). The agronomic definition of w_{fc} corresponds to $h = -3.3$ m (Olioso et al., 2002). In hydrological applications, the threshold $K = 0.1$ mm day^{-1} can be used (Wetzel and Chang, 1987; Bonne et al., 1999). w_{wp} and w_{fc} estimates are reported in Table 2.

2. w_{fc} and w_{wp} can be inferred from the field measurements of soil moisture. The time evolution of the root-zone (0–1.2 m) soil moisture is analyzed over each crop cycle. Under Mediterranean climate, the root-zone soil moisture starts from a upper-level which generally approximates w_{fc}. It reaches a lower-level at the end of the growing season which often approaches w_{wp}. The estimates of w_{fc} and w_{wp} are recorded for each crop cycle in Table 3. w_{wp} value varies from one crop to another, but its mean value is close to the one derived from the retention curve. w_{fc} shows lower temporal variability but its mean value differs from the retention curve estimates.

The rooting depth (d_2) was estimated from the analysis of the time evolution of the vertical profiles of soil moisture field measurements. d_2 was approximated by the depth at which the soil moisture change in time vanishes (Table 3). We assumed that at a given depth, the time variations in soil moisture due to the vertical diffusion and gravitational drainage are smaller than those generated by the plant water uptake (Olioso et al., 2002). This is a reasonable hypothesis for low hydraulic conductivity soil as the one under study.

3 The ISBA-A-gs model

3.1 Model description

The ISBA model (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996) is developed at the CNRM/Météo France within the SURFEX surface modeling platform (Masson et al., 2013). In this study, we used the version 6.1 of SURFEX. ISBA relies on a single surface energy budget of a soil-vegetation composite. The surface temperature is simulated using the Bhumralkar (1975) and Blackadar (1976) force restore scheme for heat transfers. An horizontal soil/snow/ice/vegetation surface partitioning is used to simulate the evapotranspiration. The soil water transfers are simulated using a force-restore scheme adapted from Deardoff (1977) with three reservoirs: the 0.01 m superficial layer designed to regulate the soil evaporation, the root-zone and the deep reservoir. The force restore coefficients were parameterized as a function of the soil hydrodynamic properties which were derived from the Brooks and Corey (1966) retention model. w_{fc} and w_{wp} are defined for $K = 0.1\,\mathrm{mm\,day}^{-1}$ and for $h = -150\,\mathrm{m}$, respectively. The soil parameters are derived from clay and sand fractions using the ISBA pedotransfer functions. The latter were built upon on the Clapp and Hornberger, 1978 soil texture classification using statistical multiple regressions (Noilhan and Laccarère, 1995). The force-restore equations and coefficient formulas are given in Boone et al. (1999). Regarding the vegetation processes, we used the A-gs version of ISBA (Calvet et al., 1998, 2008). It simulates the photosynthesis and computes the stomatal conductance as a function of the net assimilation of CO_2. The simulation of the plant response to drought relies on distinct evolutions of the water use efficiency (Calvet et al., 2000,

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2012). It is parameterized as a function of the maximum root-zone water stock available for the plant which is defined as:

$$\mathrm{MaxAWC} = d_2(w_{\mathrm{fc}} - w_{\mathrm{wp}}). \quad (1)$$

In this work, the model does not simulate the vegetation dynamic and is forced by in situ LAI and vegetation height. The model is parametrized through 12 generic land surface patches using the ECOCLIMAP-II database which provides the ISBA surface parameters for ~ 273 distinct land cover types over Europe (Faroux et al., 2013).

3.2 Model implementation at the Avignon site

ISBA-A-gs was run at a 5 min time step and 30 min outputs of the state variables were analyzed. Continuous simulations were performed from 25 April 2001 up to 18 December 2012. The 12 year period was split into sub-simulations corresponding to crop and inter-crop periods. The simulation was initialized once on 25 April 2001 using in situ soil temperature and soil moisture measurements for each soil layer. To ensure the continuity between 2 contiguous sub-simulations, each sub-simulation was initialized using the simulated soil moisture and soil temperature of the last time step of the previous sub-simulation. The C3 crop patch was used to represent wheat, pea and sunflower. The C4 crop patch was used for maize and sorghum. Inter-crop periods are represented by the bare soil patch. ISBA-A-gs was driven by local meteorological observations. It was forced by in situ LAI and vegetation height measurements averaged over 10 days. Crop irrigation was not simulated by the model and the actual amount of irrigation water was added to the local rainfall.

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4 Methodology

4.1 Experiment design

The first analysis consists in an overall evaluation of ET over the 12 year crop succession. The model is used in its standard implementation (simulation Sa). The vegetation parameters and the soil depths are provided by the ECOCLIMAP-II database (Gibelin et al., 2006; Faroux et al., 2013). ECOCLIMAP-II gives a d_2 value of 1.5 m which is equal to the mean d_2 estimate derived from the soil moisture vertical profiles (Table 3). The soil properties are derived from the local soil texture using the ISBA pedotransfer functions.

The second analysis aims at evaluating the impact of using in situ w_{sat}, w_{fc}, w_{wilt} and d_2 on ET simulated over a long period of time. The simulations Sb, Sc, Sd and Se were achieved using distinct in situ estimates of these soil parameters (Table 4). They are compared to Sa for which w_{sat}, w_{fc} and w_{wp} were derived from the ISBA pedotransfer functions. The following aspects are investigated:

- The impact of w_{wp} is assessed over the crop periods comparing Sa and Sd.
- The role of w_{sat} in the simulation of soil evaporation is investigated comparing Sa and Sd.
- The impact of the variability in in situ w_{fc} estimates induced by the estimation method is analyzed. We compare Sb achieved with the laboratory retention curve estimate of w_{fc} at $h = -3.3$ m, Sc performed with the laboratory retention curve estimate of w_{fc} at $K = 0.1\,\mathrm{mm\,day^{-1}}$ and Sd achieved with w_{fc} estimated from the field measurements of soil moisture.
- The impact of using crop-varying values of w_{wp} and d_2 over the crop succession is tested. w_{wp} and d_2 are two key drivers of MaxAWC. Constant values in time are generally used in LSM while they can vary with crop and climate conditions

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(Table 3). Se is achieved with d_2 and w_{wp} estimated from the soil moisture measurements for each crop cycle. It is compared to Sd which is performed with the mean estimates over the crop succession.

- The impact of reducing the soil reservoir depth on the soil evaporation is tested over the inter-crop periods. We compare Sd for which d_2 keeps a constant value of 1.5 m and Se for which d_2 is set to 0.5 m over the inter-crop periods.

4.2 Simulation performance metrics

The simulations were evaluated comparing measured and simulated ET cumulated over the 12 year period. Cumulative ET were concomitantly analyzed with the root-zone soil moisture (w_2) changes in time over selected crop cycle or inter-crop periods to identify the deficiencies in ET modeling. Cumulative values were computed over the time steps for which valid measurements were available. The latter represents 65 % of the 12 year period (77 % of daytime). Daily daytime ET (ET_d) were computed when 90 % of daytime measurements were valid for each day. The simulation performances were quantified using the Root Mean Square Error (RMSE), the bias (BIAS), the SD of the differences between simulations and measurements (SDD) and the correlation coefficient (r). These metrics were applied to half-hourly energy fluxes, w_2 and ET_d. For LE and ET_d, they were computed considering only the direct and valid LE measurements which represent 47 % of the 2003–2012 period.

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5 Results

5.1 Evaluation over the 12 year crop succession

5.1.1 Impact of crop succession on the evapotranspiration partition

Figure 1 illustrates the influence of the succession of crop and inter-crop periods on the temporal evolution of simulated and measured ET and root-zone soil moisture (w_2).

During the inter-crop periods and the early stages of the crop cycles, the cumulative rate of ET is slow. It is mostly influenced by soil evaporation. Daily ET generally keeps value lower than 3 mm day^{-1}. w_2 reaches its upper level during these periods which comprise fall and winter rains. Simulated soil evaporation represents 64 % of cumulative ET over 12 years. It comprises more than 50 and 95 % of daily ET for 80 and 60 % of the days, respectively.

Crop growing periods are marked by abrupt increases in ET which is related to plant transpiration. This is concomitant with the depletion of w_2 which usually reaches its lower level at the end of the crop cycles. Daily ET reaches its highest values at maximum LAI. While plant transpiration may generate significant daily ET, it concerns only short-time periods compared to soil evaporation.

This experiment shows the impact of the succession of crop periods and bare soil inter-crop periods on the water balance of the field. The low soil water content at the start of the inter-crop periods directly results from the plant water uptake during the previous crop cycle.

5.1.2 Evaluation of simulated evapotranspiration

Figure 1 shows large underestimation in simulated ET using the ISBA standard vegetation and soil parameters (simulation Sa). The deficit in cumulative ET computed over 65 % of the 12 year period amounts to 1490 mm (24 %). The overall bias in daily ET is −0.24 mm day^{-1}. The simulated w_2 has an overall positive bias of 0.029 m^3 m^{-3} which results from the underestimation of ET. The first row of Table 6 provides separate performance scores for crop and inter-crop periods. The bias and RMSE are lower for the inter-crop periods due to lower flux magnitude. The correlations for daily ET are 0.8 and 0.6 for crop and inter-crop periods, respectively.

For crop cycles, ET and w_2 are generally properly simulated during the early growing period. ET underestimation occurs during the water stress periods at the end of the crop cycles. The simulated ET shows an early decrease compared to the measurements and the resulting w_2 is overestimated at the end of most crop cycles.

For inter-crop periods, ET is mainly underestimated over wet bare soils. Over dry soils, the soil evaporation flux is small and falls within the range of measurements. The overestimation of w_2 at the end of the crop cycle can propagate through the subsequent inter-crop period as illustrated in 2004 and 2006 in Fig. 1. This bias in w_2 persists during the dry period and may affect locally the simulation of ET. But it generally vanishes during the rainy period.

5.1.3 Evaluation of energy fluxes

Table 5 shows the overall performances of simulated energy fluxes. RN is properly simulated ($r = 0.99$) with a low RMSE of $28\,\mathrm{W\,m^{-2}}$. The latter probably falls within the range of the expected measurement errors. H and LE show substantial RMSE ($56\,\mathrm{W\,m^{-2}}$ for H and $52\,\mathrm{W\,m^{-2}}$ for LE). LE has a negative bias of $-12\,\mathrm{W\,m^{-2}}$. H shows larger positive bias of $18\,\mathrm{W\,m^{-2}}$. G is markedly overestimated during daytime (daytime bias of $28\,\mathrm{W\,m^{-2}}$).

5.2 Impact of the soil hydraulic properties

The simulation Sa achieved with the ISBA pedotransfer estimates of w_{sat}, w_{fc}, w_{wp} is compared to the simulations Sb, Sc, Sd and Se achieved with distinct in situ values of the soil parameters (Table 4). The simulation performances are reported in Table 6.

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5.2.1 Impact of wilting point

Figure 2 shows the underestimation of ET and the concomitant overestimation of w_2 for Sa at the end of the crop cycle. The use of the lower in situ w_{wp} in Sd leads to higher cumulative ET and greater depletion in w_2 which are both in better agreement with the measurements. The ET underestimation in Sa is related to the overestimation of the pedotransfer estimate of w_{wp}. The resulting water stock available for the crop's growth (MaxAWC, Eq. 1) is underestimated which triggers an early water stress in the model and an early drop-off of the simulated plant transpiration. This effect is not observed for the irrigated crops (e.g. maize in Fig. 3) and the rainy crop cycles. In these cases, MaxAWC is larger than the crop water needs over the cycle. w_{wp} is not reached and no water stress occurs.

5.2.2 Impact of soil moisture at saturation

Figure 4 illustrates the underestimation of the soil evaporation for Sa over wet bare soil. For Sd, which is achieved with a lower in situ w_{sat}, the soil evaporation is increased and the slope of the w_2 depletion is steeper than for Sa (day 255 to 295 in Fig. 4). This in better agreement with the measurements. The improvement of the simulated soil evaporation is also illustrated at the start of the Maize crop cycle in Fig. 3. The underestimation of the soil evaporation is related to the overestimation of the pedotransfer estimate of w_{sat}. In the model, the soil evaporation depletes as the superficial soil moisture (w_1) drops below w_{fc}. The temporal dynamic of w_1 is mainly driven by the coefficient C_1 which is an inverse function of the hydraulic diffusivity and controls the moisture exchange between the superficial layer and the atmosphere (Noilhan and Planton, 1989). The use of the lower in situ w_{sat} in Sd decreases C_1 which tends to maintain higher w_1 and thus higher soil evaporation (Eq. A4 in Appendix A).

5.2.3 Impact of variability in w_{fc} in situ estimates

Impact of w_{fc} on simulated soil evaporation is assessed by comparing Sc, Sd and Sb which have increasing w_{fc} values. Figure 4a shows that the soil evaporation increases with increasing w_{fc}. w_2 tends to converge to the field capacity during the rainy periods (Fig. 4b). The differences in soil evaporation are related to differences in the simulated capillary rises which increase with w_2 (see Eq. A5 in Appendix A).

The high w_{fc} value estimated from the laboratory retention curve at $h = -3.3$ m and used in Sb leads to the overestimation of the soil evaporation (Fig. 4a). The performances of ET and w_2 simulations over inter-crop periods are decreased compared to Sa.

The low w_{fc} value estimated from the laboratory retention curve at $K = 0.1$ mm day^{-1} and used in Sc leads to underestimated ET (Fig. 4a and Table 6). The gain in w_1 triggered by the use of the in situ w_{sat} is partly canceled out by the reduction in the simulated capillary rises. The resulting soil evaporation keeps values close to the Sa ones (Fig. 4a). The low w_{fc} used in Sc triggers larger gravitational drainage than other simulations. This compensates for part of the ET underestimation and explains the reduced bias in simulated w_2 obtained for Sc over the inter-crop periods (Table 6).

The use of w_{fc} estimated from the soil moisture measurements in Sd leads to better agreement between simulated and measured soil evaporation (Fig. 4a and Table 6).

w_{fc} has also an impact on the transpiration through MaxAWC (Eq. 1). The low w_{fc} of Sc leads to insufficient MaxAWC and undertesimation of ET over most crop periods (Table 6).

5.2.4 Impact of crop-varying d_2 and w_{wp}

Se, where d_2 and w_{wp} were estimated from the soil moisture measurements for each crop cycle, is compared to Sd where mean d_2 and w_{wp} estimates are used over the crop succession. Sd and Se show similar cumulative ET over 12 years and close simulation performances (Table 6). The use of d_2 estimated for each crop cycle can locally improve

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the simulation of ET. This concerns Sorghum, Sunflower or dry wheat cycles (see Se in Fig. 2a) for which the rooting depth is greater than the 1.5 m mean value (Table 3). The use of w_{wp} estimated for each crop cycle has little impact. This is due to the low w_{wp} variability across the crop cycles (Table 3).

5.2.5 Impact of reduced d_2 during inter-crop bare soil periods

For the inter-crop periods, d_2 keeps the mean value of 1.5 m in Sd while it is reduced to 0.5 m in Se. The reduction in d_2 over bare soil slightly improves the performances of ET and w_2 simulations (Table 6). Locally, the reduced d_2 increases the amplitude of w_2 variations in time (Fig. 4b). This can impact the simulation of the soil evaporation through an increase or a decrease of the simulated capillary rises.

6 Discussion

We discuss the previous results to identify the possible sources of uncertainties affecting the simulation of ET over a long period of time.

6.1 Soil parameter uncertainties

The ISBA pedotransfer estimates of w_{wp} and w_{sat} are overestimated which explains most of the ET underestimation over 12 years. The use of their in situ values in the simulation Sd and Se substantially reduces the bias in LE, daily ET and w_2 (Table 6). w_{wp} is a key parameter of the water stock available for the crop (MaxAWC, Eq. 1) which drives the effect of water stress on plant transpiration. w_{sat} drives the simulation of the hydraulic diffusivity in the superficial layer which impacts the simulation of soil evaporation during wet bare soil periods.

Large discrepancies have been reported between pedotransfer functions (PTFs) which are prone to distinct sources of uncertainties (Espino et al., 1996; Baroni et al., 2010; Gijsman et al., 2013). The first shortcoming concerns their representativeness

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of soil property variability. The ISBA pedotransfer functions were established upon the Clapp and Hornberger (1978) database. These functions were calibrated using mean values of soil properties over few classes of soil texture and do not represent the variability within each soil class. The second source of uncertainty is related to the estimation method. PTFs were designed to be applied over readily available variables such as soil texture. Improvements of the prediction equations may require the use of additional predictors related to soil structure (Vereecken et al., 1989). Most PTFs are based on simple statistical regressions such as the ISBA ones (Noilhan and Laccarère, 1995). The more advanced ROSETTA PTF (Schaap et al., 2001) addresses the uncertainty in the predicted soil parameters through the use of an ensemble of functions calibrated over distinct soil datasets. Such model provides essential information on the variance and covariance of the hydraulic properties (Scharnagl et al., 2011) which are required to propagate the uncertainties in the LSM simulations.

The w_{fc} value at $h = -3.3$ m estimated from the adjustment of the retention curve over laboratory measurements is too high to be consistent with the field measurements of soil moisture during wet bare soil periods. It leads to the overestimation of the simulated soil evaporation. The w_{fc} estimate at $K = 0.1$ mm day^{-1}, as defined in ISBA, is too low and leads to the underestimation of both the transpiration and the soil evaporation. Various studies have questioned the use of hydraulic properties inferred from laboratory techniques to simulate water transfers at the field scale (Basile et al., 2003; Mertens et al., 2005; Scharnagl et al., 2010). Laboratory experiments may not be representative of field conditions. Gravimetric measurements can disturb the actual soil structure. Small soil samples cannot capture the spatial and vertical heterogeneity of the soil structure at the field scale which can be substantially influenced by macroporosity (Mertens et al., 2005). Single measurement cannot resolve the changes in soil structure caused by crop development and tillage operations (Baroni et al., 2010).

In this work, the best performances of ET simulations are achieved with d_2, w_{fc} and w_{wp} estimated from field measurements of soil moisture. The latter better resolve the intra-field spatial variability through 4 neutron probes compared to the laboratory

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measurements. The temporal analysis of the soil moisture vertical profiles provides meaningful estimates of the wilting point, the field capacity and the rooting depth over each crop cycle. Their mean values are representative of a range of crop and soil conditions over 12 years. This work shows that they are accurate enough to represent the crop water needs and simulate ET over the 12 year crop succession.

The reduction of the soil reservoir depth over the inter-crop bare soil periods induces little changes on the ET simulation performances over 12 years. Besides, the use of a constant d_2 for both crop and inter-crop periods is preferable to ensure the conservation of mass in the force-restore simulation of the water balance over a long period of time. Sd is thus selected as our best simulation with respect to the tested set of soil parameters.

The RMSE for LE and daily ET are not reduced in Sd compared to Sa. They mostly represent random differences between the measurements and the simulations. For Sd, the SD of these random differences amounts to 53 $W\,m^{-2}$. The following sections address additional sources of modeling and measurement uncertainties that may explain these remaining discrepancies.

6.2 Propagation of errors in soil moisture

We showed that the overestimation of w_2 induced by the underestimation of ET at the end of the crop cycle can propagate through the subsequent inter-crop period. The induced bias in w_2 can influence the simulation of soil evaporation through an overestimation or an underestimation of the capillary rises. It has an impact at a short time scale and it is generally removed at the rainy period. A control simulation was performed initializing each crop and inter-crop sub-simulation with in situ soil temperature and soil moisture measurements. While the performances of simulated w_2 were improved, the performances of simulated ET slightly change. The propagation of the bias in w_2 is not a prevailing source of uncertainties in ET simulated over a long period of time.

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6.3 Structural model uncertainties

A first shortcoming of the force-restore scheme concerns the lack of description of soil vertical heterogeneity. Attempts to account for soil property stratification were achieved through re-scaling functions of the force-restore coefficients (Montaldo and Albertson, 2001; Decharme et al., 2006). The increase in hydraulic conductivity at saturation (K_{sat}) generally observed in the ~ 0–0.4 m soil layer of crop fields can be represented in SURFEX using a decreasing exponential profile of K_{sat} between the surface and the bottom of the root-zone (Decharme et al., 2006). The use of a K_{sat} exponential profile in the simulation Sd decreases the performances of LE and daily ET simulations (see $Sd_{K_{sat}}$ in Table 6). It increases the hydraulic diffusivity which results in a frequent overestimation of the soil evaporation. A second shortcoming of the force-restore is the lack of root profile. This could particularly affect the representation of the effect of water stress on plant transpiration (Desborough et al., 1997; Braud et al., 2005; Fan et al., 2006). A multi-layer diffusion scheme can explicitly represent the soil vertical heterogeneity and the interactions between plant and soil more accurately (Decharme et al., 2011). However, the performances of such detailed models rely on accurate parametrization of root profile and soil vertical heterogeneity which may not be available at large-scale (Olioso et al., 2002; Demarty et al., 2004). Further works are needed to evaluate whether such model improves the simulation of the water balance over a crop succession.

Substantial differences in simulated soil evaporation between LSMs have been attributed to differences in soil evaporation formulations and representation of the soil resistance to water diffusion (Mahfouf and Noilhan, 1991; Desborough et al., 1996). In ISBA, a bulk aerodynamic formulation is used. The potential soil evaporation is weighted by a surface relative humidity coefficient parametrized as a function of the superficial soil moisture (Eq. A2 in Appendix A). This may not be accurate enough to describe the resistance of a drying soil to water vapor diffusion which depends on both soil structure and texture (Kondo et al., 1990; Merlin et al., 2011).

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The remaining underestimation in ET during the crop senescence despite the use of the in situ soil hydraulic parameters (e.g. Maize in 2001 in Fig. 4b) could be attributed to inaccurate partitioning between soil evaporation and transpiration at low LAI (Olioso et al., 2002). This could be related to unrealistic decrease of the vegetation cover which is a function of LAI in the model while the senescent crop is covering a non negligible soil fraction and has radiative and aerodynamic impacts. The use of a single source energy balance can also impact ET partitioning (Olioso et al., 2002). Other factors related to the parametrization of photosynthesis, canopy conductance and water stress could also cause transpiration underestimation.

6.4 Uncertainties in eddy covariance measurements

Random errors in eddy covariance measurements arise from turbulence sampling errors, instrument errors and flux footprint uncertainties (Richardson et al., 2006). While random errors are likely to cancel out when the measurements are cumulated over long period of time, their magnitude can be substantially large at half-hourly time scale. An overall random error of $15\,\mathrm{W\,m^{-2}}$ is obtained for LE measurements in our dataset following the Richardson et al. (2006) method (Appendix B).

The non closure of the measured energy balance (EB) is a critical source of uncertainties when these measurements are compared to LSM estimates. Reasons for EB non-closure include footprint mismatch between the eddy fluxes and the other energy fluxes, horizontal and vertical advection, unresolved low frequency turbulence, inaccuracies in the eddy covariance processing (Foken, 2008; Leuning et al., 2012). The application of an energy imbalance threshold of $100\,\mathrm{W\,m^{-2}}$ minimized the magnitude of the EB non-closure of our dataset. The mean and the SD of the absolute value of the EB non-closure are 28 and $22\,\mathrm{W\,m^{-2}}$, respectively. This is comparable to the non-closure reported for cropland in Wilson et al. (2002), Hendricks et al. (2010) and Ingwersen et al. (2010). The EB non-closure is further assessed comparing the direct measurement of LE with two other estimates. The first estimate is computed as the residue of the energy balance assuming that H is error-free. The second estimate is

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derived from the bowen ratio (ratio between H and LE) assuming that the bowen ratio is correctly estimated (Twine et al., 2000). The SD of the differences between these LE estimates falls between 24 and 36 $\mathrm{W\,m^{-2}}$ (Table 7).

The uncertainties in the eddy-covariance measurements of ET are thus significant and can explain a large part of the unresolved random differences between the simulations and the measurements of ET.

7 Summary

In this study, the SURFEX/ISBA-A-gs simulations of evapotranspiration (ET) are assessed at local scale over a 12 year Mediterranean crop succession. The model is evaluated in its standard implementation which relies on the use of the ISBA pedotransfer estimates of the soil properties. The originality of this work consists in explicitly representing the succession of crop cycles and inter-crop bare soil periods in the simulations and assessing its impact on the dynamic of simulated and measured evapotranspiration over a long period of time. The analysis focuses on key soil parameters which drive the simulation of ET, namely the rooting depth, the soil moisture at saturation, the soil moisture at field capacity and the soil moisture at wilting point. The simulations achieved with the standard values of these parameters are compared to those achieved with the in situ values. The portability of the ISBA PTF is evaluated over a typical Mediterranean crop site. Various in situ estimates of the soil parameters are considered and distinct parametrization strategies are tested to represent the evapotranspiration dynamic over the crop succession.

Evapotranspiration mainly results from the soil evaporation when it is simulated over a succession of crop cycles and inter-crop periods for Mediterranean croplands. The crop transpiration generates high ET over short-time periods while the soil evaporation represents more than 50 % of ET for 80 % of the days. Accounting for crop succession in LSM is thus essential to accurately estimate ET amount and ET temporal dynamic which are both critical to properly represent land-surface atmosphere interactions.

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ET simulated with the standard surface and soil parameters of the model is largely underestimated. The deficit in cumulative ET amounts to 24 % over 12 years. The bias in daily daytime ET and root-zone soil moisture are $-0.24\,\mathrm{mm\,day^{-1}}$ and $0.029\,\mathrm{m^3\,m^{-3}}$. The shortcomings in the representation of ET over the crop succession concern the representation of (i) water stress period which is mainly driven by the soil moisture at wilting point and (ii) soil evaporation during wet periods which is influenced by the soil moisture at saturation. These parameters are overestimated by the ISBA PTFs, which explains most of the ET underestimation. The overestimation of the wilting point triggers the underestimation of the water stock available for the crop's growth which depletes the simulated plant transpiration at the end of the crop cycle. The overestimation of the soil moisture at saturation triggers an underestimation of the water diffusivity in the superficial layer which reduces the soil evaporation. The field capacity value at $h = -3.3\,\mathrm{m}$ derived from laboratory retention measurements triggers frequent overestimation of the simulated soil evaporation which is related to the lack of representativeness of the soil structure variability at the field scale. The field capacity estimate at $K = 0.1\,\mathrm{mm\,day^{-1}}$ is too low and leads to the underestimation of evapotranspiration. The most accurate simulation is achieved with the values of the soil hydraulic properties derived from field measurements of soil moisture. The latter better resolve the intra-field spatial variability. Their temporal analysis over each crop cycle provides meaningful estimates of the wilting point, the field capacity and the rooting depth to represent the crop water needs and accurately simulate ET over the crop succession. The use of crop-varying rooting depth and wilting point and the reduction of the soil reservoir depth during the inter-crop periods have little impact on the ET simulation performances over 12 years.

We showed that the uncertainties in the eddy-covariance measurements are significant and can explain a large part of the unresolved random differences between the simulations and the measurements of ET. Other modeling uncertainties could concern the lack of soil vertical heterogeneity and root profile representation in the force-restore water transfer scheme, inaccurate ET partitioning between the soil and the vegetation at low LAI, inaccurate representation of the soil resistance in the soil evaporation

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formulation and shortcomings in the representation of vegetation processes (e.g. photosynthesis).

This work highlights the great impact of errors in soil properties on multi-year simulation of ET. Accounting for the uncertainties in the soil hydrodynamic properties is of paramount importance for the spatial integration of land surface models and their use in climatic change scenarios. Bayesian inverse modelling (Vrugt et al., 2009) are appropriate methods to translate the variability in the soil hydraulic properties into uncertainties in the predicted fluxes (Mertens et al., 2004; Scharnagl et al., 2011). Both vegetation and soil parameters should be analysed to identify their possible interactions. All sources of modelling errors (forcing, parameters and model structure) can be adequately incorporated in the analysis. Our results will serve as a basis for such complementary work in order to provide a comprehensive analysis of the sources of uncertainties which affect the simulation of ET over cropland.

Appendix A: The soil evaporation in the force-restore scheme

The ISBA soil evaporation (ES) is given by

$$\mathrm{ES} = (1-\mathrm{veg})\rho_a C_H V[h_u q_{sat} - q_a] \tag{A1}$$

where veg is the fraction of vegetation cover, ρ_a is the dry air density, C_H is the drag coefficient, V is the wind speed, q_{sat} is the surface specific humidity at saturation and q_a is the air specific humidity at the reference height. h_u is the air relative humidity at the surface and is computed as:

$$h_u = 0.5\left[1-\cos\left(\min\left(\frac{w_1}{w_{fc}},1\right)\pi\right)\right] \tag{A2}$$

where w_1 is the superficial soil moisture and w_{fc} is the field capacity. ES is at its potential rate when $w_1 > w_{fc}$ ($h_u = 1$). It depletes as w_1 drops below w_{fc}. For $h_u \cdot q_{sat} < q_a$, if $q_{sat} < q_a$ a dew flux is triggered and if $q_{sat} > q_a$ the soil evaporation is set to zero.

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The time course of w_1 is given by the force-restore equation:

$$\frac{\partial w_1}{\partial t} = \frac{C_1}{\rho_w d_1}(P - \mathrm{ES}) - \frac{C_2}{\tau}(w_1 - w_{eq}). \tag{A3}$$

In Eq. (A3), ρ_w is the liquid water density, P is the flux of water reaching the surface and τ is the restore constant of one day.

The coefficient C_1 is driving the moisture exchange between the surface and the atmosphere. It is an inverse function of the hydraulic diffusivity (Noilhan and Planton, 1989; Eq. A4).

$$C_1 = C_{1sat} d_1 \left(\frac{w_{sat}}{w_1}\right)^{0.5b+1} \tag{A4}$$

In Eq. (A4), C_{1sat} is the value at saturation (in m^{-1}) calibrated as a function of clay fraction and b is the slope of the Brooks and Corey (1964) retention curve. C_1 is minimum at saturation and increases as the soil surface dries out. It reaches its maximum for $w_1 = w_{wp}$. For w_1 lower than w_{wp}, water vapor phase transfers are prevailing. C_1 is represented by a gaussian formulation (Giordani et al., 1993; Giard and Bazile, 1996) and decreases with increasing soil temperature and decreasing soil moisture.

The second term in the right-hand side of Eq. (A3) represents the vertical water diffusion between the root-zone and the superficial layer. It is ruled by the diffusion coefficient C_2 (Eq. A5) which quantifies the rate at which the soil moisture profile between layer 1 and 2 is restored to the equilibrium w_{eq} (water content at the balance between the gravity and the capillary forces).

$$C_2 = C_{2ref}\left(\frac{w_2}{w_{sat} - w_2 + w_l}\right) \tag{A5}$$

In Eq. (A5), w_l is a numerical constant. C_{2ref} is the mean value of C_2 for $w_2 = 0.5 w_{sat}$ and is computed as a function of clay fraction. C_2 is an increasing function of w_2.

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In ISBA, the force-restore water transfer scheme and the resulting soil evaporation strongly depend on soil texture (Jacquemin et al., 1990). Coarse soil texture are characterized by high soil hydraulic diffusivity and conductivity which is represented in the model by low C_1 and high C_2, respectively. For sandy soil, low value of C_1 reduces the depletion of w_1 due to soil evaporation and high C_2 enhances the supply of w_1 by capillary rises. The resulting daily variations of w_1 are low and the values of w_1 are frequently higher than w_{fc}. The resulting soil evaporation is frequently at its potential rate. Conversely, clay soils have higher C_1 and lower C_2. This leads to more rapid depletion of w_1 which keeps lower values compared to sandy soil. The subsequent soil evaporation drops since it is more rapidly limited by the soil water supply.

Appendix B: Characterization of the random errors in the eddy covariance measurements

The Richardson et al. (2006) method to assess the random errors in eddy-covariance measurements consists in selecting 24 h apart pairs of measurement acquired under equivalent environmental conditions. The latter are defined by differences in vapor pressure deficit within 0.2 kPa, wind speed within $1\,\mathrm{m\,s^{-1}}$, air temperature within 3 °C and photosynthetic photon flux within $75\,\mathrm{\mu mol\,m^{-2}\,s^{-1}}$. Compared to the original method, additional criteria were implemented: wind direction within ±15°, footprint within 30 %, surface soil moisture within $0.05\,\mathrm{m^3\,m^{-3}}$, incoming solar radiation within $50\,\mathrm{W\,m^{-2}}$. The differences in flux value between paired measurements are assumed to be solely attributed to random errors. The random error is estimated as the SD of the paired flux differences. The overall random error obtained for the LE measurements in our dataset is $\sigma_R = 15\,\mathrm{W\,m^{-2}}$. The variance of the error (σ_R^2) represents 8 % of the variance of the differences between simulated LE and measured LE obtained for the Sd simulation.

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Table 1. 2001–2012 crop succession. The first sunflower in 2003 ([1]) was stopped and replaced by a new one. The 2009 maize ([2]) was stopped and replaced by sorghum because the emergence of maize was too heterogeneous. T and Rain are the mean temperature and cumulative precipitation, respectively, over the crop cycle.

Year	Crop	Sowing date	Harvest date	Irrigation (mm)	Rain (mm)	T (°C)
2001	Maize	25 Apr 2001	28 Sep 2001	375	232.0	20.7
2002	Wheat	23 Oct 2001	2 Jul 2002	0	399.0	11.6
2003	Sunflower[1]	16 Apr 2003	26 May 2003	40	68.0	17.1
2003	Sunflower	2 Jun 2003	19 Sep 2003	225	68.5	24.8
2004	Wheat	7 Nov 2003	28 Jun 2004	0	422.0	11.2
2005	Peas	13 Jan 2005	22 Jun 2005	100	203.5	11.9
2006	Wheat	27 Oct 2005	27 Jun 2006	20	256.0	10.7
2007	Sorghum	10 May 2007	16 Oct 2007	80	168.5	20.6
2008	Wheat	13 Nov 2007	1 Jul 2008	20	502.5	11.7
2009	Maize[2]	23 Apr 2009	15 Jun 2009	80	110.5	19.2
2009	Sorghum	25 Jun 2009	22 Sep 2009	245	89.0	23.6
2010	Wheat	19 Nov 2009	13 Jul 2010	0	446.5	11.6
2011	Sorghum	22 Apr 2011	22 Sep 2011	60	268.5	21.4
2012	Wheat	19 Oct 2011	25 Jun 2012	0	437.0	12.0

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Table 2. Mean soil properties over the 0–1.2 m soil profile. Density is the soil bulk density. w_{sat} is the soil moisture at saturation derived from bulk density measurements. w_{wp}, w_{fc} are the soil moisture at wilting point and field capacity, respectively. They were derived from the laboratory adjustment of the Brooks and Corey (1964) retention curve for given hydraulic conductivity (K) or matric potential (h) levels. The second and third rows represent the vertical (σ_V) and the spatio-temporal (σ_{ST}) variability of these measurements, respectively.

	clay (%)	sand (%)	density ($g\,cm^{-3}$)	w_{sat} ($m^3\,m^{-3}$)	w_{wp} ($h = -150$ m) ($m^3\,m^{-3}$)	w_{fc} ($h = -3.3$ m) ($m^3\,m^{-3}$)	w_{fc} ($K = 0.1\,mm\,day^{-1}$) ($m^3\,m^{-3}$)
Mean	33.15	13.95	1.57	0.390	0.170	0.344	0.268
σ_V	0.58	1.14	0.16	0.056	0.011	0.021	0.027
σ_{ST}	na	na	0.05	0.019	na	na	na

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Table 3. Estimated values of the rooting depth (d_2), the soil moisture at field capacity (w_{fc}) and the soil moisture at wilting point (w_{wp}) derived from the time evolution of vertical profiles of field-measured soil moisture. MaxAWC (mm), defined as $(w_{fc} - w_{wp}) \cdot d_2$, represents the maximum root-zone water stock available for the crop. When no measurements were available, the mean value (in bold) from similar crop type was used. The last two rows are the mean and the SD computed over all crop cycles. The 1.85 m d_2 obtained for wheat in 2006 can be related to the dryness of the crop period (256 mm of rain). The shallower d_2 (1.0 m) obtained for wheat in 2008 can be related to the wetness of the crop period (500 mm of rain).

Crop	Year	d_2 (m)	w_{fc} ($m^3\,m^{-3}$)	w_{wp} ($m^3\,m^{-3}$)	MaxAWC (mm)
Maize	2001	1.45	0.320	0.174	212
Wheat	2002	1.55	0.314	0.126	291
Sunflower	2003	1.80	0.311	0.209	184
Wheat	2004	1.65	0.314	0.183	216
Peas	2005	1.00	0.308	0.218	90.0
Wheat	2006	1.85	0.309	0.179	241
Sorghum	2007	1.65	0.306	0.183	203
Wheat	2008	1.00	0.279	0.202	77.0
Maize	2009	**1.45**	**0.320**	**0.174**	**212**
Sorghum	2009	**1.65**	**0.306**	**0.183**	**203**
Wheat	2010	1.75	0.327	0.182	254
Sorghum	2011	**1.65**	**0.306**	**0.183**	**203**
Wheat	2012	**1.50**	**0.309**	**0.174**	**203**
mean		1.50	0.310	0.184	189
SD		0.30	0.012	0.025	56.0

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Table 4. Values of the soil parameters used in the simulations. Sa corresponds to the standard implementation of the model achieved with the ECOCLIMAP-II rooting depth (d_2) and the ISBA pedotransfer estimates (1) of the wilting point (w_{wp}), the field capacity (w_{fc}) and the saturation (w_{sat}). Distinct in situ estimates of these parameters are used in the Sb–Se simulations. They are defined as follows: (2) field-measured w_{sat}, (3) laboratory retention curve estimate of w_{fc} at $h = -3.3$ m, (4) laboratory retention curve estimate of w_{wp} at $h = -150$ m, (5) laboratory retention curve estimate of w_{fc} at $K = 0.1$ mm day^{-1}, (6) mean values of d_2, w_{fc} and w_{wp} estimated from the field measurements of soil moisture over the crop cycles; (7): CV: crop-varying values of d_2 and w_{wp} estimated from the field measurement of soil moisture for each crop cycle (see Table 3). MawAWC is the the maximum root-zone water stock available for the crop.

	Simulation cases				
Soil parameters	Sa	Sb	Sc	Sd	Se
w_{sat} ($m^3\,m^{-3}$)	0.479$^{(1)}$	0.390$^{(2)}$	0.390$^{(2)}$	0.390$^{(2)}$	0.390$^{(2)}$
w_{fc} ($m^3\,m^{-3}$)	0.303$^{(1)}$	0.344$^{(3)}$	0.268$^{(5)}$	0.310$^{(6)}$	0.310$^{(6)}$
w_{wp} ($m^3\,m^{-3}$)	0.214$^{(1)}$	0.170$^{(4)}$	0.170$^{(4)}$	0.184$^{(6)}$	CV$^{(7)}$
d_2 crop periods (m)	1.5	1.5$^{(6)}$	1.5$^{(6)}$	1.5$^{(6)}$	CV$^{(7)}$
MaxAWC (mm)	134	261	147	189	CV$^{(7)}$
d_2 inter-crop periods (m)	1.5	1.5	1.5	1.5	0.5

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Table 5. Performances of the simulated energy fluxes for the simulation Sa. RN is the net radiation. H, LE and G are the sensible, latent and ground heat fluxes. The metrics were computed over the valid measurements available for each variable. For LE, only the 2004–2012 period is used. N and r are the number of samples and the correlation coefficient, respectively.

RN ($W m^{-2}$)				H ($W m^{-2}$)				LE ($W m^{-2}$)				G ($W m^{-2}$)			
N	r	RMSE	BIAS	N	r	RMSE	BIAS	N	r	RMSE	BIAS	N	r	RMSE	BIAS
197 255	0.99	27.7	0.2	103 886	0.85	56.2	17.6	96 214	0.80	52.4	−11.8	191 619	0.88	46.9	−1.3

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Table 6. Performances of the simulated latent heat flux (LE), daily daytime evapotranspiration (ET_d) and root-zone soil moisture (w_2). ET_d was computed when 90 % of daytime measurements were valid for each day. Sa corresponds to the standard implementation of the model achieved with the pedotransfer estimates of the soil parameters. The rest of the simulations were achieved with distinct set of in situ soil parameters as defined in Table 4. $Sd_{K_{sat}}$ corresponds to the Sd simulation performed with the exponential vertical profile of K_{sat}. N is the number of samples used to evaluate each variable. Meas is the mean value of the measured variable.

	CROP CYCLE						INTER-CROP					
	LE ($W\,m^{-2}$)		ET_d ($mm\,day^{-1}$)		w_2 ($m^3\,m^{-3}$)		LE ($W\,m^{-2}$)		ET_d ($mm\,day^{-1}$)		w_2 ($m^3\,m^{-3}$)	
N	52 260		944		241		43 954		853		173	
Meas	70.1		1.64		0.255		35.6		0.85		0.247	
	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS
Sa	61.6	−14.3	1.07	−0.30	0.037	0.026	38.6	−8.9	0.58	−0.17	0.043	0.034
Sb	63.3	5.0	1.02	0.21	0.036	0.028	45.2	3.7	0.71	0.19	0.050	0.042
Sc	60.7	−11.8	1.03	−0.24	0.028	−0.011	37.7	−7.6	0.55	−0.14	0.026	−0.004
Sd	61.8	- 0.3	1.00	0.07	0.027	0.015	40.7	−0.2	0.60	0.06	0.036	0.025
Se	61.3	1.0	1.00	0.10	0.028	0.018	38.8	−1.2	0.55	0.04	0.032	0.024
$Sd_{K_{sat}}$	67.1	2.7	1.13	0.18	0.026	−0.007	50.6	6.9	0.84	0.30	0.030	0.008

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Table 7. Comparison of the direct measurement of LE (Direct), the energy balance residue estimate of LE (Residue) and the bowen ratio estimate of LE (Bowen). RMSD is the root mean square of the differences between the LE estimates. SDD is the SD of the differences between the LE estimates. MD is the mean difference between the LE estimates (for Y vs. X, the difference is computed as $Y - X$).

	Bowen vs. Direct	Residue vs. Direct	Bowen vs. Residue
RMSD ($W\,m^{-2}$)	25.0	36.3	29.3
MD ($W\,m^{-2}$)	7.5	3.2	4.3
SDD ($W\,m^{-2}$)	23.9	36.2	28.9

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Table A1. Definition of the main symbols.

BIAS	Mean difference between simulated and measured values
d_2	Rooting depth (m)
EB	Energy balance
ES	Soil evaporation (mm)
ET	Cumulative evapotranspiration (mm)
ET_d	Daily daytime evapotranspiration (mm day^{-1})
G	Ground heat flux (W m^{-2})
h	Matric potential (m)
H	Sensible heat flux (W m^{-2})
K	Hydraulic conductivity (m s^{-1})
K_{sat}	Hydraulic conductivity at saturation (m s^{-1})
LE	Latent heat flux (W m^{-2})
MaxAWC	Maximum root-zone water stock available for the crop (mm)
Meas	Measurement
MD	Mean difference
PTF	Pedotransfer function
RN	Net radiation (W m^{-2})
RMSE	Root mean square error between simulated and measured values
RMSD	Root mean square difference between two simulations or two measurements
SDD	SD of the differences between two simulations or two measurements
TR	Transpiration flux (mm)
w_{fc}	Volumetric soil moisture at field capacity (m^3 m^{-3})
w_{sat}	Volumetric soil moisture at saturation (m^3 m^{-3})
w_{wp}	Volumetric soil moisture at wilting point (m^3 m^{-3})
w_1	Superficial volumetric soil moisture (0–0.01 m) (m^3 m^{-3})
w_2	Root-zone volumetric soil moisture (0–d_2) (m^3 m^{-3})

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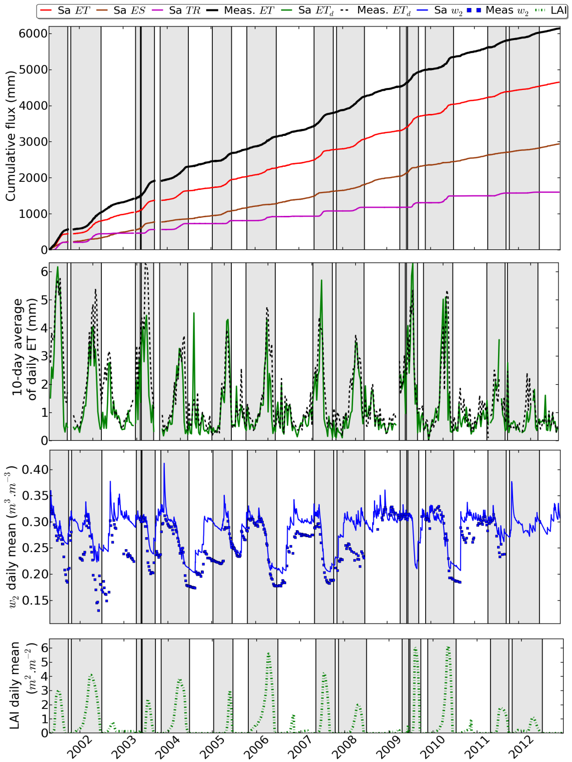

Figure 1. Evolution of simulated and measured evapotranspiration (ET), simulated soil evaporation (ES), simulated plant transpiration (TR), simulated and measured daily daytime ET (ET_d), simulated and measured daily root-zone soil moisture (w_2), daily in situ LAI over the 2001–2012 period. Cumulative values were computed over the time steps for which valid ET measurements were available. ET_d was computed when 90 % of valid daytime measurements were available for each day. Average of ET_d over 10 days is displayed here. The simulation corresponds to the standard implementation of the model (Sa). Crop and inter-crop periods are represented by grey and white background, respectively.

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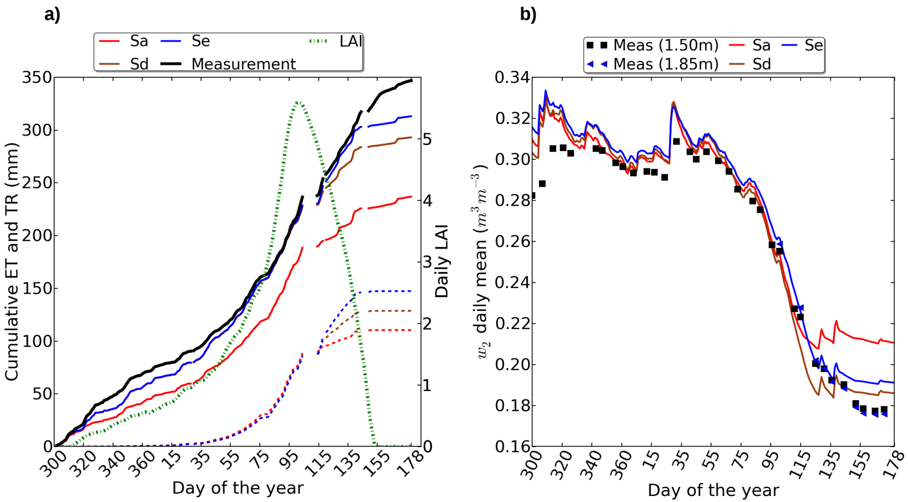

Figure 2. Evolution of **(a)** measured and simulated evapotranspiration ET and **(b)** measured and simulated root-zone soil moisture w_2, over the wheat cycle in 2006. Sa is the standard simulation achieved with the pedotransfer estimates of the soil parameters (w_{wp} = 0.214) and the ECOCLIMAP-II value of d_2 (1.5 m). Sd is achieved with the mean w_{wp} (0.184) and d_2 (1.5 m) in situ estimates derived from the soil moisture measurements. Se was achieved with w_{wp} (0.179) and d_2 (1.85 m) estimated over the 2006 wheat cycle. In **(a)**, the simulated transpirations are represented by dashed lines. The LAI cycle is represented by green dash-dot lines. In **(b)**, measured w_2 over a soil reservoir depth of 1.50 and 1.85 m are provided.

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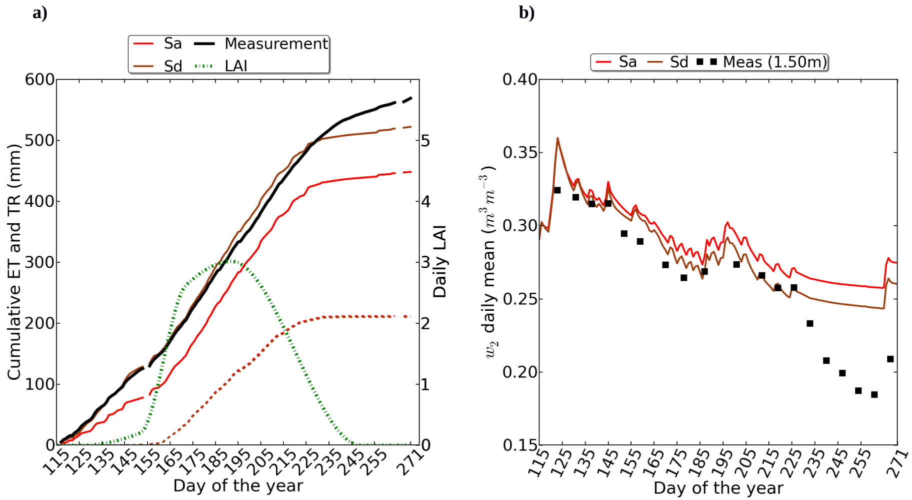

Figure 3. Evolution of **(a)** measured and simulated evapotranspiration ET and **(b)** measured and simulated root-zone soil moisture w_2, over the irrigated maize in 2001. Sa is the standard simulation based on the pedotransfer estimates of the soil parameters (w_{wp}=0.214) and the ECOCLIMAP-II value of d_2 (1.5 m). Sd is achieved with the mean w_{wp} (0.184) and d_2 (1.5 m) in situ estimates derived from the soil moisture measurements. In **(a)**, the simulated transpirations are represented by dashed lines. The LAI cycle is represented by green dash-dot lines. In **(b)**, measured w_2 over a soil reservoir depth of 1.50 m is provided.

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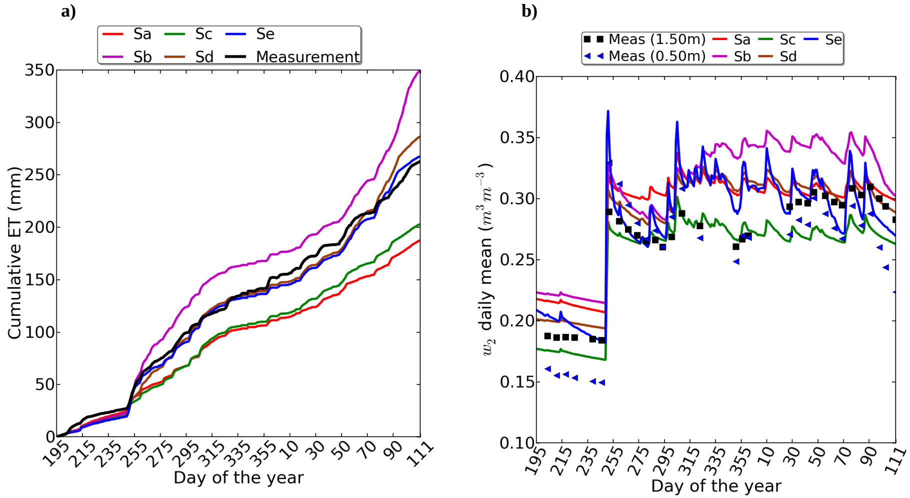

Figure 4. Evolution of **(a)** measured and simulated evapotranspiration ET and **(b)** measured and simulated root-zone soil moisture w_2, over the inter-crop period in 2010. Sa is the standard simulation based on the ISBA pedotransfer estimates of the soil parameters (w_{fc} = 0.303 and w_{sat} = 0.479). Sb, Sc and Sd were achieved with the in situ estimate of w_{sat} (0.390). Sb and Sc were achieved with the laboratory retention curve estimates of w_{fc} at $h = -3.3$ m (0.344) and $K = 0.1$ mm day^{-1} (0.268), respectively. Sd and Se were achieved with w_{fc} (0.310) derived from the field measured soil moistures. The soil reservoir depth d_2 is equal to 1.5 m in Sa, Sb, Sc, Sd and Sd. It is reduced to 0.5 m in Se. In **(b)**, measured w_2 over a soil reservoir depth of 1.50 and 0.50 m are provided.

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