Authors response to Reviewer 1

Comment: The paper presents and evaluates a land-surface energy flux model (SPARSE) based on the Two-Source Energy Balance (TSEB) modelling scheme. The differences between the original TSEB model and SPARSE (and their justifications) are generally well presented. However, the paper contains gaps in the description of the proposed SPARSE model (i.e. it is not clear how some of the terms were derived) and there is some confusion between the "patch" SPARSE and "parallel" TSEB implementations. Additionally, the comparison of the performance of SPARSE and original TSEB models (and therefore the evaluation of the improvements introduced by SPARSE) needs to be more robust. For example, there is no discussion of TSEB model in section 3 even though the testing of the first guess assumptions of canopy transpiring at the potential in the TSEB model (as well as in SPARSE) is listed among the main objectives of this paper in the end of section 1.

Reply: The main objective of the paper is to describe the SPARSE model and assess its limits with respect to theoretical limitations, measurements as well as simulations by a selection of published versions of TSEB. We have rephrase the sentence P4L154 in order to focus the paper on SPARSE rather than TSEB and to avoid any misunderstanding in the intended level of intercomparison with TSEB.

There are two associated grounding elements (hypotheses) in both SPARSE and TSEB models: 1- that the first guess assumption is a potential transpiration rate and 2- that if the vegetation is experiencing water stress the evaporation is at a minimum rate (null flux in general). Section 3 is mostly illustrating the limit of such assumptions in a fully synthetic and consistent framework, i.e. by using the same model in forward ("prescribed") and inverse ("retrieval") modes. The parameterization used by SPARSE is different from that used by TSEB, but a "prescribed" mode is clearly defined in SPARSE, contrarily to TSEB.

It is not possible to use a combination of SPARSE and TSEB in Section 3, as suggested below, because it would not be possible to interpret the results, i.e. to warranty that inconsistencies are due to the limit of the underlying assumptions and not the parameterization differences between SPARSE and TSEB. A prescribed mode could be built on the basis of TSEB, but it is beyond the scope of the study.

In Section 3, we mostly explain why the retrieval using the two core/grounding hypotheses is sometimes deficient, illustrate it with a synthetic case, and find out that for this particular case the retrieval with the parallel version is less robust. This is consistent with findings by Li et al. 2005 and Morillas et al. 2008 (see below) but brings a new light on the source of the lack of robustness for the parallel model.

The following sentence has been included P13L468: "This test has been carried out using SPARSE due to the possibility the model offers to combine both modes in a consistent synthetic experiment. Its outcomes are illustrated for this model and a single set of vegetation and climatic conditions. We don't claim that the differences between series and parallel retrieval capacities also fully apply to TSEB but since they share the same strong underlying assumptions and differ mostly by the parameterization of the fluxes, we're convinced that similar differences would be found with TSEB if TSEB could be run in a prescribed mode."

Comment: Additionally, in section 4.2 only one statistical parameter (root mean square error) is used in the evaluation, the implementation details and parameterization of the TSEB model are not presented and the discussion is brief and does not always reflect the results presented in figures and tables.

Reply:

Again, the TSEB model implementation is not the core of the paper but is rather an additional estimate of the energy balance components from a related model, to compare SPARSE's outputs to. Parameterization of TSEB is that of the publications referred to, with default values of the parameters, otherwise the same inputs are used for both TSEB and SPARSE. Since both models are uncalibrated, raw performances and subsequent comparisons should be treated with care, we draw main tendencies rather than absolute rankings of both models. The fact that both model applications are done with "default" (uncalibrated) parameters is emphasized in the revised manuscript P17L617-620.

Specific comments:

Comment: P7129 L27: Series model is more robust in case of SPARES but not in case of TSEB so this statement should be more precise.

Reply: Yes, modified ("SPARSE" mentioned).

Comment: P7130 L2: Should "globally" be "generally"?

Reply: Yes, modified.

Comment: P7131 L11-12: Dual source energy balance models allow deriving of both composite and component (vegetation and soil) water stress, not just the latter.

Reply: Sentence "They also provide an estimate of the climate-controlled and moisture-limited soil evaporation rates." inserted P2L74.

Comment: P7131 L15-16: Even though there is currently no operational satellite with dual-view land surface temperature (LST) observations, the soon to be launched Sentinel-3 mission will have such capability (Donlon et al., 2012). This might be worth mentioning.

Reply: Yes, sentence inserted P3L79.

Comment: P7132 L18-19: Provide reference for the study which introduced incremental decrease of transpiration efficiency. Also what does bulk retrieval mean in this context?

Reply: The iterative procedure is mentioned along the net radiation improvement in Kustas et al. 1999 and is initially a way to solve for the unknowns Ts an Tc iteratively (Page 27: "Therefore an iteration procedure will compute LEC values below estimates given by Eq. (A.19) until values of TC and TS used in Eq. (A.1) agree with the measured TR(¢)"). The respective sentence is modified to link both improvements.

The following sentence in brackets ("bulk retrieval") is unnecessary and has been suppressed.

Comment: P7133 L2-3: It should be made more clear "classical resistance scheme" refers to Penman-Monteith formulation and that this formulation (as well as Priestley-Taylor equation) are used just to obtain the first guess of plant transpiration.

Reply: Yes, modified as suggested.

Comment: P7134 L1-3: I am not sure how T can be above the potential level since it is initially assumed to be at potential level and later can be reduced if the model doesn't obtain plausible results (i.e. E < 0) but is never increased.

Reply: It can be above the potential level when there is a strong "micro-oasis" effect. The following sentence has been included P4L144: "Indeed, transpiration can be above its potential level when there is a strong coupling between the soil and the vegetation through conditions at aerodynamic level (stability correction notably): maximum transpiration for a plant surrounded by very dry bare soil is increased above the potential transpiration rate as computed in a fully wet environment. This coupling might be excessive and a potential transpiration of a wet environment is an interesting baseline to assess excess in this coupling."

Comment: P7134 L15-16: The first guess assumptions of the TSEB model are not tested in this study since section 3 deals only with SPARSE model. It would be interesting to evaluate the performance of the original TSEB formulations in retrieving the transpiration and evaporation efficiencies. Possibly it could be done by running SPARSE in prescribed mode, then using the resulting temperature as input to TSEB model and estimating the efficiencies by dividing LE_s and LE_v by their respective potential values.

Reply: This could be interesting, but then it would not be possible to evaluate whether retrieved efficiencies (simulated using a combination of SPARSE and TSEB) are different to the prescribed ones (simulated by SPARSE) because of the differences between SPARSE and TSEB, or only due to the TSEB algorithm.

Comment: P7134 L21 – P7135 L2: It would be more clear if the order of the equations presented here corresponded to the order in which those equations are introduced in sections 2.1.1 and 2.1.2 and mentioned on P7144 L5-6 (i.e. latent heat flux equations, followed by energy budget of soil and vegetation and finally relating radiative surface temperature to the temperatures of soil and vegetation).

Reply: Agreed, this has been changed accordingly.

Comment: P7137 L15-16: More details of the iterative procedure should be given. This is its only mention in the whole manuscript.

Reply: This is an alternative version only, its mention has been suppressed for the sake of clarity.

Comment: P7139 L17: How is R_atm obtained in this study? Was it measured (there is no mention of that in section 4.1), estimated from T_a or obtained in another way?

Reply: R_atm was estimated from T_a (Brutsaert clear sky R_atm equation provided P23L842).

Comment: P7140 L4: T_rad is often observed from angles other than nadir and becomes T_rad(theta) where theta is the view zenith angle. How is the view zenith angle ac- counted for in eq. 17? In appendix A2 there is a vegetation cover fraction (f_c) parameter but there is no explanation of how it is derived and I couldn't see any parameter taking theta into account.

Reply: Equation provided P23L841, also it is specified that we use data acquired at nadir (P13L482).

Comment: P7141 L5-L9: Why are the stability correction factors not estimated separately if T_0s and T_0v are known?

Reply: This is explained P7131 L28-P7132 L12: vegetation and soil patches are linked, liked in TSEB, only though their common stability conditions with a common Surface Boundary Layer.

Comment: In appendix A1 z_om,s is already estimated and d could also be estimated thus r_a and Richardson number could also be estimated separately for soil and vegetation. What would be the expected effect of estimating r_a,s and r_a,v separately?

Reply: Again, cf. P7131 L28-P7132 L12: this would mean that there are two SBLs above the soil and the vegetation, which, given the size of the respective areas, is not realistic.

Comment: P7141 L12: Again, how is f_c estimated.

Reply: cf supra.

Comment: P7141 L15-18: The "patch" representation of SPARSE model consists of two independent flux networks (one for vegetation and one for soil) which are combined using the fraction of sub-pixel the source of each flux occupies. In this approach the fluxes represent current densities if the resistance networks are considered in electrical terms (Sanchez et al. 2008). In the "parallel" TSEB implementation the interaction between the canopy and soil fluxes is still minimal but the two component fluxes are added up to obtain the total flux. This implies that the fluxes are treated as currents in electronic networks since currents are additive when two parallel branches meet. Therefore, even though both approaches ("patch" and "parallel") are correct based on the assumption they make, they are not directly comparable and the interchangeable use of "patch" and "parallel" terms when describing SPARSE might be confusing when the "parallel" TSEB term is also used in the manuscript. Therefore the difference between the two approaches should be clearly described and taken into account when analysing TSEB and SPARSE model results.

Reply: The differences between the translations of the "patch approach" into the parallel algorithm of TSEB and other formalisms have been detailed in Lhomme and Chehbouni (1999) and re-assessed in Lhomme et al. (2012) who refer to the latter earlier comment. The way the total turbulent heat fluxes are computed from the soil and vegetation components is not very different in fine between both models: in TSEB, each component flux (Hs or Hv) is directly expressed for the whole surface once the available energy has been partitioned into a soil and a vegetation patch according to fc, therefore the total flux is the simple arithmetic sum of both (Equation 7 of Norman et al. 1995). In SPARSE, we describe each flux density of each patch, i.e. one for the soil and one for the vegetation. Therefore the partitioning is computed once the individual flux is computed after solving the surface energy balance for each patch, and the total is therefore computed as a weighted sum and no longer a simple sum. It seems to us that this choice is more consistent with the “patch approach” defined by Lhomme et al. (2012) and schematized in Figure 1

Comment: P7147 L28: In the figure the indicated efficiency is 0.6

Reply: Yes, corrected.

P7148 – Section 3: What would be the effect of incrementally reducing B_v and re- running the model in case of negative evaporation instead of setting B_s immediately to 0? You mention this technique as an improvement to original TSEB on P7132 P18-19 so why not implement it in SPARSE. Also, the performance of TSEB should also be assessed in this section (see comment related to P7134 L15-16).

Reply: In SPARSE, all variables are solved simultaneously, including Ts and Tv, therefore the iterative procedure to reduce B_v to reach convergence is not useful.

Comment: P7149 L3: Was LST acquired from nadir? If it was acquired at a different view zenith angle then how was this taken into account?

Reply: It was acquired at nadir, it’s now specified P13L482.

Comment: P7149 L8: Does residual method mean that residual energy was assigned to LE or H? Also maybe consider the approach from the study of Ingwersen et al. (2015).

Reply: In this experiment, there was clearly a problem with the fast response psychrometer, but we’ll keep your suggestion in mind for closure analysis in the future evaluations of SPARSE.

Comment: P7149 L18-19: In Section 4.2 it is often not clear which models are being discussed. The original TSEB model implementations should be listed here and not only in the caption of Table 1. Why are different references used for the parallel and series versions of TSEB? Cammalleri et al. (2010) were looking at different representations of wind profile in the canopy but did not present any modifications to the actual TSEB formulations. So is one of the wind profile models presented in Cammalleri et al. (2010) used in the series version of TSEB but not in the parallel? What would be the justification for that and which wind profile model was used? Also implementation and parameterization details of the TSEB model should be clearly stated. For example, what default value of alpha_PT was used, was clumping factor used, was fraction of vegetation that is green (f_g) set to 1 or varied during senescence. In particular it would be interesting to look at the effects of varying or not varying f_g estimate in the TSEB model as it has a large effect on the estimated fluxes and is available in this study since hemispherical photography and destructive sampling were used to estimate LAI.

Reply: We’ve used the TSEB series and parallel versions of Kustas et al., (1999), i.e. the Goudriaan (1977) wind profile. We mentioned Cammalleri et al. (2010) because it is a more recent and complete description of the series model including choices of parameter default values for the resistance ras. it is therefore not necessary to refer to it if parameter values are specified and we keep the Kustas et al. 1999 reference for the model. We also specify that Alpha_PT was set to its classical value 1.26. Green and total LAI index are shown.

Comment: P7150 L1: If the model is designed to be routinely applied with remote sensing data then it should be explained how the view zenith angle of the LST observations is taken into account.

Reply: Yes, cf supra.

Comment: P7150 L5-6: More thorough statistical analysis should be performed and presented in Table 1 (and Table 2).

Reply: Yes, cf. supra.

Comment: The effect of bounding LE estimates should be explored by looking not only at RMSE but also other statistical parameters, for example (but not necessarily limited to) bias, correlation or coefficient of variation. During what conditions do the outputs have to be bound? Is it mainly during plant growth stage or senescence?

Reply: It is mostly important in selected dates, the following sentence has been included P15L553: "Without bounding, values of evaporation and transpiration above potential levels are obtained for the series version during vegetation growth, and some negative values of transpiration are found during late maturity and beginning of senescence".

Comment: P7150 L6-13: The description in this paragraph does not reflect the results presented in Table 1. For example, the RMSE of parallel and series versions of SPARSE are not "almost similar" as stated on L7 (see difference between non-bounded models in irrigated wheat),

Reply: We agree, but since the model is uncalibrated differences must be described with special care. We replaced change "almost similar" by "of similar order of magnitudes".

Comment: The reduction in RMSE stated on L9 is only true for SPARSE model and the statements on L9-13 are only true for bounded versions of the models. I would suggest rewriting this paragraph (after further statistical measures have been included in Table 1) and being more clear about which version of the model (SPARSE/TSEB, parallel/series, bounded/unbounded) is being discussed.

Reply: Agreed and specified accordingly.

Comment: P7150 L14-15: Are any fluxes recalculated after LE_s and LE_v are bounded? If not, then wouldn't the estimates for H, G and Rn be the same for bounded and unbounded case?

Reply: Yes, the following sentence is added: "For consistency, if LE_x is limited by $LE_x(\beta_s{=}1, \beta_v{=}1)$, all fluxes of the corresponding component energy balance (Rn_x, H_x and G) are set to their values obtained by the "prescribed" mode in potential conditions, i.e. $Rn_x(\beta_s{=}1, \beta_v{=}1)$, $H_x(\beta_s{=}1, \beta_v{=}1)$ and $G(\beta_s{=}1, \beta_v{=}1)$."

Comment: P7150 L18: Be more clear in what exactly is consistent with Li et al. (2005) and Morillas et al. (2013). What did those studies show?

Reply: Those studies indicate that the series model tend to provide more robust and slightly better results, but that the parallel model does not always show significantly worse statistical criteria. This will be made explicit.

Comment: P7151 L20-23: On L20, should it be “little to no stress” instead of “little to no evaporation”? Furthermore in top-right Figure 3 (low evaporation efficiency) the most accurate retrieval of evapotranspiration efficiency for parallel SPARSE model is for high transpiration efficiencies (small vegetation stress values) which is contradictory with the statement on L22-23.

Reply: We’re referring to evaporation only, it has been specified.

Comment: P7152 L14: How is theta_sat estimated and what is its value?

Reply: It is obtained in-situ (values given).

Comment: P7153 L5-9: Can the temporal pattern of agreement be explained by the patch/layer representations present in parallel/series SPARSE model versions being more appropriate at different stages of vegetation development?

Reply: It was not possible to relate those patterns for sure to specificities of both model representations.

Comment: P7154 L3-5: Was this finding presented in the results section? P7154 L5-6: I do not understand this sentence.

Reply: This refers to section 3 findings only (it has been specified).

Comment: P7154 L17: It should be 0.2 not 0.1.

Reply: Agreed and changed accordingly.

Comment: P7154 L27-28: In the rainfed field senescence began around DOY 80 and vegetation was fully brown by around DOY 120 (Fig 3). Looking at Fig 10 the agreement between the soil evaporation efficiencies modelled with SPARSE and soil moisture data agree very well between DOY 120 and DOY 160. Therefore, at least at this site SPARSE models seems to be performing well over “low or senescent vegetation” (although be- tween DOY 80 and DOY 120 the agreement is not so good). This is not fully consistent with statement on L27-28.

Reply: As pointed out, there is a mismatch between observed and simulated soil efficiencies before DOY120 and after DOY160, on the basis of which this general comment is drawn. However, the good performance between DOY 120 and DOY160 is mentioned P7153 L7. On that basis the previous statement is softened in P7154 L28-29.

Comment: P7156 L4-5: How are d and z_om estimated?

Reply: Equations provided P23L826.

Comment: Table 1: Add more statistical measures as mentioned in comment P7150 L5-6.

Reply: Done (MAPE and correlation provided).

Comment: Table 2: Add more statistical measures to be consistent with Table 1. Also, why was the series TSEB model not included in this table?

Reply: Done (MAPE and correlation provided).

Comment: Table A1: There are some mistakes present in this table. For example r_a, r_as, r_av and r_w have the same definition. Double check the other parameters as well.

Reply: Yes, corrected.

Comment: Figure 2: This figure is too complicated. I would remove the input data for synthetic test and also the synthetic test branch (broken line) to improve clarity.

Reply: This line is useful for section 3, but has been dropped.

Comment: Figure 5: The shown plots appear to be for green LAI. It would be good to also show total LAI and possibly f_g, especially if the effect of varying f_g in the TSEB model during senescence is investigated as suggested in comment P7149 L18-19.

Reply: Done

Comment: Figures 7 and 9: The legend captions should be fixed.

Reply: Corrected.

Authors response to Reviewer 2

Comment:

Page 12 Eq. (7) & (8): How are Ts and Tv determined and is the view angle of the radiometer accommodated? I can't find an expression in the text that describes this.

Reply: In order to improve the clarity of the model's description, we have added explicitly the symbols Ts and Tv in the model's introduction to stress that it is derived by solving the system of equations (beginning of section 2.1).

Information about the radiometer view-angle (nadir, P13L482) and an equation to use Trad from a different view angle (this is also suggested by Reviewer 1) following the view angle dependent vegetation fraction cover have been added (P23L841).

Comment:

Page 15 Eq. (24): What is the physical basis for simply weighting the aerodynamic temperature estimated for the soil and vegetation? In addition, have two aerodynamic temperatures for the soil-canopy system is not physically plausible at the canopy/micrometeorological scale-this needs some explanation/discussion.

Reply: This section has been rewritten and is now: "For the parallel model, the sensible heat flux rate above each patch is:

$$H_s = \rho c_p \frac{T_s - T_a}{r_{as} + r_a} \quad (22)$$

for the soil, and

$$H_v = \rho c_p \frac{T_v - T_a}{r_{av} + r_a} \quad (23)$$

for the vegetation.

The value of the Leaf Area Index used for the parallel model is a "clump LAI" obtained by dividing the total LAI by the fraction cover of the vegetation f_c (Lhomme and Chehbouni, 1999). Total fluxes are the sum of the soil and vegetation components also weighted by their relative contribution, f_c for the vegetation and $1\text{-}f_c$ for the soil:

$$LE = (1 - f_c)LE_s + f_c LE_v \quad (24)$$

where LE_s is expressed according to (20) and LE_v to (21), and

$$H = (1 - f_c)H_s + f_c H_v \quad (25)$$

where H_s is expressed according to (22) and H_v to (23).

The stability correction for the aerodynamic resistance r_a depends on an average aerodynamic temperature computed from the total sensible heat flux H:

$$T_0 = T_a + \frac{H r_a}{\rho c_p} \text{ "}$$

Comment:

Page 17 Lines 5-9. It's unclear to me how the iterative procedure works
more clarification is needed.

Reply: This alternative way of solving the system of equations is not necessary and has been removed.

Comment:

Page 18 Lines 21-24. The discussion of realistic bounds for LEx based on Su (2002) seems to be a critical part of the modeling approach, but is not explained in any detail. Some further discussion is needed.

The paragraph has been rewritten: "Finally, in order to ensure that LE_x outputs are within realistic bounds, LE_x values obtained by running SPARSE in "retrieval" conditions are limited by the evapotranspiration components in potential conditions $LE_x(\beta_s=1,\ \beta_v=1)$ computed by SPARSE in prescribed potential conditions (Figure2). This procedure is the dual source equivalent of what is done in the single-source model SEBS (Su, 2002)."

Comment:

Page 19 Section 3.1/3.2. It's not clear to me if this simulation experiment/synthetic test is truly independent of the model structure. Why didn't the authors use a more complex SVAT that generates Trad, Ts and Tv and component fluxes to compare with SPARSE? Justification for this synthetic test needs to be made.

Reply: The synthetic test illustrates the theoretical limit of the 2 underlying assumptions of SPARSE, which are also the underlying assumptions of most TSEB versions. It builds on the existence of both modes (prescribed and retrieval) of SPARSE to test the capacity of the model to retrieve correctly the water status of both sources (represented in SPARSE by their respective efficiencies) when they are known. It is important to keep the same model and the same parameters for this test, because otherwise it would be impossible to know whether inconsistencies between the prescribed and the retrieved efficiencies are due to the model structure or represent the theoretical limit of the retrieval (absence of bijective relationships) due to its assumptions. The following sentences have been added:

P4L157: "The purpose of the simulation experiment is specifically to test the limits of the underlying first guess assumptions of SPARSE, which are identical to those used in most TSEB versions."

P13L468: "This test has been carried out using SPARSE due to the possibility the model offers to combine both modes in a consistent synthetic experiment. Its outcomes are illustrated for this model and a single set of vegetation and climatic conditions. We don't claim that the differences between series and parallel retrieval capacities also fully apply to TSEB but since they share the same strong underlying assumptions and differ mostly by their parameterization of the fluxes, we're convinced that similar differences would be found with TSEB if TSEB could be run in a prescribed mode."

Comment:

Page 23 Line 5. What was the closure values achieved by the eddy covariance system and what was done with the missing energy flux?

The following sentences are inserted P13L484: "For the rainfed wheat site, there was clearly a problem with the fast response psychrometer with an energy balance closure of 60 %. Thus for that site the closure was forced and the corrected LE was computed as Rn-H-G. For the irrigated site, the half hourly closure was of the order of 80%. For this site closure was achieved with the conservation of the Bowen ratio H/LE, thus the corrected LE was computed as (Rn-G)/(1+H/LE)."

Page 23 Lines 26-27. The minimum stomatal resistance was set to 100 s/m, so what would happen if 50 m/s was chosen? This is certainly plausible for cereal crops.

The following sentence has been inserted P17L619: "If a value of rstmin=50 s/m is used, a value also reported for wheat crops in more temperate regions, RMSE on latent heat flux increases by 4 W/m2 in bounded conditions for the rainfed wheat site (62 W/m2) and 13 W/m2 for the irrigated wheat site (66 W/m2) for the series version. For the parallel model it increases by 12 W/m2 (82 W/m2) and 8 W/m2 (74 W/m2), respectively."

Comment:

Page 24 Lines 5-19. There is little explanation again on how the bounded versus unbounded model results were determined.

Reply: cf. supra.

Comment:

Also Tables 1 and 2 should include more statistics, such as mean of observed and modeled, also the mean absolute error statistic and a percentage difference.

Reply:

MAPE and correlation coefficient have added in both Tables, as requested by both Reviewer 1 and 2. Mean of observed and modeled fluxes are useful in the case of applications to individual surface temperature images, but represent a wide range of situations over the whole season, it would be difficult to extract additional information from these values if biases are mentioned.

Comment:

Moreover, I'm confused that the series TSEB model is based on a citation from Cammalleri et al (2010) while the authors use the citation for TSEB parallel version of Kustas and Norman (1999), even though I believe a series version is also developed in that paper. There needs to be an explanation as to what the differences are in TSEB formulations used in the 2 papers.

We now mention that in TSEB is run with a nominal (1.26) value for the PT coefficient (see also the Reply to Reveiwer 1 comments) and use the single reference Kustas et al., 1999 for both model versions.

Comment:

Page 28 Lines 5-8. So is the SPARSE model considered more reliable than the TSEB based on Table 1 and 2 results?

TSEB and SPARSE are run with default values corresponding to typical vegetation classes, as it is the case for routine applications of remote sensing energy balance models to lead to spatially distributed evapotranspiration products. They were not calibrated against in-situ data. It is thus difficult to conclude on their absolute respective reliability. We compare their relative performance with default values on 2 datasets only. We do not claim that SPARSE is more reliable than TSEB, but find that SPARSE with default values of the parameters performs better TSEB for those 2 datasets. The following sentence has been inserted P17L617: “This comparison must be treated with special care since both models are run with no prior calibration of the poorly known parameters such as the minimum stomatal resistance (for SPARSE) or the Priestly-Taylor coefficient (for TSEB)”.

Comment:

In larger scale applications, should the authors consider a lack of having reliable vapor pressure data and what impact this may have on models such as SPARSE which require this input?

Reply: The final sentence has been added: “SPARSE needs more input data than TSEB, for instance relative humidity. The impact of uncertainty on available meteorological data (reanalysis or remote-sensing meteorological products vs local meteorological stations network) on SPARSE model performance will also be assessed in the future.”

Marked-up MS version:

The SPARSE model for the prediction of water stress and evapotranspiration components from thermal infra-red data and its evaluation over irrigated and rainfed wheat.

G. Boulet*[1,2], B. Mougenot[1,2], J.-P. Lhomme[3], P. Fanise[1], Z. Lili-Chabaane[2], A. Olioso[4,5], M. Bahir[1,4,5], V. Rivalland[1], L. Jarlan[1], O. Merlin[1], B. Coudert[1], S. Er-Raki[6] and J.-P. Lagouarde[7]

[1] CESBIO - UMR 5126 UPS, CNRS, CNES, IRD, Toulouse, France

[2] Département Génie Rural des Eaux et Forêts, Institut National Agronomique de Tunisie Université de Carthage, Tunis, Tunisia

[3] IRD, UMR LISAH, Montpellier, France

[4] INRA, EMMAH – UMR1114, Avignon, France

[5] UAPV, EMMAH – UMR1114, Avignon, France

[6] LP2M2E, FST, Université Cadi Ayyad, Marrakech, Morocco

[7] INRA, UMR 1391 ISPA, 33140 Villenave d'Ornon, France

* Gilles.Boulet@ird.fr

Abstract

Evapotranspiration is an important component of the water cycle, especially in semi-arid lands. A way to quantify the spatial distribution of evapotranspiration and water stress from remote-sensing data is to exploit the available surface temperature as a signature of the surface energy balance. Remotely sensed energy balance models enable to estimate stress levels and, in turn, the water status of continental surfaces. Dual-source models are particularly useful since they allow deriving a rough estimate of the water stress of the vegetation instead of that of a soil-vegetation composite. They either assume that the soil and the vegetation interact almost independently with the atmosphere (patch approach corresponding to a parallel resistance scheme) or are tightly coupled (layer approach corresponding to a series resistance scheme). The water status of both sources is solved simultaneously from a single surface temperature observation based on a realistic underlying assumption which states that, in most cases, the vegetation is unstressed, and that if the vegetation is stressed, evaporation is negligible. In the latter case, if the vegetation stress is not properly accounted for, the resulting evaporation will decrease to unrealistic levels (negative fluxes) in order to maintain the same total surface temperature. This work assesses the retrieval performances of total and component evapotranspiration as well as surface and plant water stress levels by 1- proposing a new dual-source model named Soil Plant Atmosphere and Remote Sensing Evapotranspiration (SPARSE) in two versions (parallel and series resistance networks) based on the TSEB (Norman et al., 1995) model rationale as well as state of the art formulations of turbulent and radiative exchange, 2- challenging

the limits of the underlying hypothesis for those two versions through a synthetic retrieval test and 3- testing the water stress retrievals (vegetation water stress and moisture-limited soil evaporation) against in-situ data over contrasted test sites (irrigated and rainfed wheat). We demonstrated with those two datasets that the SPARSE series model is more robust to component stress retrieval for this cover type, that its performance increases by using bounding relationships based on potential conditions (Root Mean Square Error lowered by up to 11 W/m^2 from values of the order of 50-80 W/m^2), and that soil evaporation retrieval is ~~globally~~ generally consistent with an independent estimate from observed soil moisture evolution.

1. Introduction

Evapotranspiration is an important, yet difficult to estimate (Jasechko et al., 2013), component of the water cycle, especially in semi-arid lands. Its quantification is crucial for a sustainable management of scarce water resources. The recent development of remote sensing products and data assimilation methods have led to a new era in the use of remote sensing data in the various spectral domains to derive more robust estimates of evapotranspiration at various spatial scales (Crow et al., 2008; Olioso et al., 2005). Amongst those products, surface temperature provides access to a rough estimate of water stress. Indeed, moisture limited evapotranspiration triggers an increase in surface temperature above a theoretical equilibrium value in unstressed conditions (Amano and Salvucci, 1997; Boulet et al., 2007). Most algorithms based on the use of a remotely sensed surface temperature evaluate a total latent heat flux corresponding to the sum of the evaporation and the transpiration components: they're named "single-source models". Total latent heat flux representing the whole surface is derived as the residual term of the surface energy balance at the time of satellite overpass (Kalma et al., 2008). Single-source models require a method to relate the temperature at the aerodynamic level and the surface temperature obtained by remote sensing (Matsushima, 2005). It is very often based on an additional resistance term or kB^{-1} (Carlson et al., 1995, Verhoef, 1997) that is heavily parameterized. Even though the use of single-source models is widespread, dual-source models are particularly useful because they allow retrieving separate estimates of evaporation and transpiration. Those components are particularly needed for ecohydrological or agrohydrological applications (irrigation management, water stress detection...). Moreover, dual-source models provide a more realistic description of the main water and heat fluxes, even if the vegetation is seen as a single "big leaf" and the soil a single "big pore" (Kustas et al., 1996). This is especially true for sparse vegetation, when commonly used scalar profiles within the canopy no longer apply. It also avoids the use of a parameterized kB^{-1} (Kustas and Anderson, 2009).

Beyond evapotranspiration, estimating water stress is also important to infer the surface water status and the root zone soil moisture level (Hain et al., 2009). Water stress can be obtained for the surface as a whole by combining the simulated latent heat flux and the potential latent heat flux, i.e. the theoretical value of the latent heat in current climatic conditions if the surface was still undergoing stage one (unstressed) evapotranspiration (Lhomme, 1997). Dual-source energy balance models allow deriving a rough estimate of the water stress but of the vegetation instead of a soil-vegetation composite. They also provide an estimate of the climate-controlled and moisture-limited soil evaporation rates. Such frameworks use as input data either the component surface temperatures (e.g. soil and vegetation components retrieved from directional surface temperature data, Jia et al., 2003 or Colaizzi et al., 2012) or a single soil-vegetation composite surface skin temperature. For the former, there is no current operational satellite that offers estimates of temperatures at two contrasted view angles with a very small interval between both acquisitions, even though the soon to be launched Sentinel-3 mission will have such capability (Donlon et al., 2012). For the latter, the TSEB model proposes a realistic underlying assumption to downsize the number of unknowns from two (evaporation E and transpiration T) to one (E or T, Norman et al., 1995). The TSEB model assumes that in most eco- or agro-systems vegetation has access to enough water in the root zone to transpire at a potential rate, so that a modeled potential transpiration rate is a valid first guess estimate for T. This assumption implies that, if vegetation stress is not properly taken into account, the resulting evaporation will decrease to unrealistic levels (negative fluxes) in order to maintain the same total surface temperature, so that a retrieved negative evaporation is a good witness of plant water stress. This assumption is sometimes misleading, and we propose to study its limits.

The original version of TSEB (Norman et al., 1995) provides two algorithms to describe the soil-vegetation-atmosphere interactions, representing respectively the “patch” and the “layer” approaches following the terminology proposed by Lhomme et al. (2012). In the “layer” approach, one assumes that the air is well mixed within the canopy space so that air temperature at the aerodynamic level is rather homogeneous. The vegetation layer completely covers the ground and prevents the soil from interacting directly (in terms of radiation and turbulent heat transfer) with the atmospheric reference level: soil and vegetation heat sources are fully coupled through a resistance network organized in series (Figure 1). In the “patch” approach, soil and canopy sources are located side by side, and the soil interacts directly with the air above the canopy. There is a possible lateral gradient in air temperature around the aerodynamic level even though heat transfer around the canopy is associated to the same momentum transfer: soil and vegetation heat sources are thermally uncoupled and fluxes are computed with two parallel resistance schemes. In the original TSEB version, total net radiation is split into soil and vegetation components according to a simple Beer-Lambert law. Several improvements have been proposed later on and implemented in various TSEB versions. Amongst them, one can mention the development of a more complex net radiation scheme, with an initialization of soil and vegetation temperatures in separate formulations of the net radiation of the soil and the canopy ~~(Kustas and Norman, 1999) ~~or the use of an incremental decrease of a transpiration efficiency ~~instead of a bulk retrieval of the latent heat of the vegetation ~~(Kustas and Norman, 1999; it corresponds roughly to the ratio between the actual and the potential transpiration rates and matches the definition of the efficiency used in the present work). The TSEB rationale has been translated into several algorithms, with the possibility of using directional radiative temperatures (Kustas and Norman, 1997), day-night temperature difference (Guzinski et al., 2013; Norman et al., 2000), correcting for clumping effects in sparsely vegetated areas (Anderson et al., 2005), and finally by taking into account a Penman-Monteith formulation for potential transpiration (Colaizzi et al., 2012).

Here, we propose to revisit the “layer/series” and “patch/parallel” formulations in order to build a new model based on the same rationale that provides the foundation for all TSEB model versions.

First, we build on the statement by Colaizzi et al. (2012) that, in semi-arid lands, it is more relevant to use a ~~classical ~~resistance scheme based on a Penman-Monteith expression instead of the Priestley-Taylor equation, so that adiabatic exchanges are explicitly described. The most common value of the Priestley-Taylor coefficient (close to 1.3) has indeed been challenged for natural vegetation and sites with strong vapour pressure deficit values where root zone moisture is not limiting transpiration (Agam et al., 2010). According to Colaizzi et al. (2014), potential transpiration using Penman-Monteith equation showed better performances compared to the Priestley-Taylor equation. In particular, these authors showed a consistent underestimation of T and overestimation of E when using Priestley-Taylor formulation with the classical 1.3 coefficient, even if total evapotranspiration was similar for both models.

Second, since in the layer approach the vegetation is a semi-infinite cover overlaying the ground, it appears more consistent that this version of the model takes into account not only the soil-vegetation interactions of the turbulent fluxes, but also of the radiative fluxes. Conversely, in the patch approach there is no radiation exchange between the soil and the vegetation patches. This is achieved for the series model through a multiple reflections description between the soil and the overlaying vegetation cover in order to stick more closely to the patch and layer representations schematized in Figure 1.

Based on those studies, we propose a generalization of the TSEB model (named SPARSE: Soil Plant Atmosphere and Remote Sensing Evapotranspiration model) as a linearization of the full set of energy budget equations and the Choudhury and Monteith (1988) and Shuttleworth and Gurney (1990) expressions of the aerodynamic resistances. The series model is very close to the soil-plant-atmosphere interface of the SiSPAT model (Braud et al., 1995). The full set of equations can be solved either in prescribed conditions (for example, in fully stressed or potential conditions) to compute transpiration and evaporation rates for given stress levels, or in retrieval mode, identically to TSEB. In that case, stress levels are deduced from a known (observed) surface temperature. We propose a third improvement to the existing TSEB model versions, which is similar to what is done in a post-processing step in the single-source SEBS model (Su, 2002). It consists in bounding each retrieved individual flux component (T, E) by its corresponding potential level deduced from running the model in prescribed potential conditions. Indeed, transpiration can be above its potential level when there is a strong coupling between the soil and the vegetation through conditions at aerodynamic level (stability correction notably): maximum transpiration for a plant surrounded by very dry bare soil is increased above the potential transpiration rate as computed in a fully wet environment. This coupling might be excessive and a potential transpiration of a wet environment is an interesting baseline to assess excess in this coupling.

The main objective of the paper is twofold:

1- To describe the SPARSE model, evaluate it against in-situ data and ~~compare~~ relate its performance with those of the “patch/parallel” and “layer/series” TSEB model formulations, with a focus on the potential gain in robustness obtained when limiting evaporation and transpiration outputs by their corresponding potential rates derived from SPARSE.

2- Test the retrieval capacities of both “patch/parallel” and “layer/series” versions of the model, not only for total evapotranspiration as well as its components (soil evaporation and transpiration) but also for water stress, first with synthetic data (simulation experiment) and second with in-situ data collected over two wheat fields in semi-arid climate, one irrigated and one rainfed. The purpose of the simulation experiment is specifically to test the limits of the underlying first guess assumptions of ~~TSEB and~~ SPARSE, which are identical to those used in most TSEB versions.

2. Series and parallel versions of the SPARSE model

2.1. SPARSE system of equations

The SPARSE model computes the equilibrium surface temperatures of the soil (T_s) and the vegetation (T_v) at the meteorological time step as a signature of the energy budget equations of each source. Five main equations are solved simultaneously. The first two express the continuity (series version) or the summation (parallel version) of the latent and sensible heat fluxes from the soil and the canopy to the aerodynamic level and above ~~represent the energy budget of the soil and the vegetation~~, the third and the fourth represent the energy budget of the soil and the vegetation~~express the continuity (series version) or the summation (parallel version) of the latent and sensible heat fluxes from the soil and the canopy to the aerodynamic level and above~~, and the fifth describes the link between the radiative surface temperature T_{rad} and its two component temperature sources (soil T_s and vegetation T_v).

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Two versions are derived, which can be regarded as fully coupled (series) and fully uncoupled (parallel) soil–vegetation-air exchanges (Figure 1). This corresponds to (respectively) the "layer" and "patch" approaches described in Lhomme et al. (2012). However, the interpretation of the situations for which one or the other approach is valid differs between TSEB and Lhomme et al. (2012). In TSEB, both soil and vegetation patches share a common surface boundary layer (and therefore the same aerodynamic resistance from the aerodynamic level to the reference level) but the patch representation allows defining different aerodynamic temperatures at the aerodynamic level over the soil and the vegetation. As pointed out by Lhomme et al (2012), the patch representation should in theory only apply to patches large enough to develop different surface boundary layers, e.g. fallow fields amongst wetter and taller vegetated areas rather than bare soil patches even few meters large. Here, we keep the TSEB assumption for our parallel version and assume that the wind profile above the aerodynamic level in the canopy and above the soil surface are identical in both versions. ~~The main difference lies therefore in the lateral gradient in aerodynamic temperature: in the series version, a single aerodynamic temperature is computed, while in the parallel version two different aerodynamic temperatures are computed above the soil and the canopy, allowing a small departure of the temperature profiles above the soil and the canopy level from the standard mean profile.~~

The various aerodynamic resistances are computed according to Choudhury and Monteith (1988), Shuttleworth (1985) and Shuttleworth and Gurney (1990) while the stomatal resistance is modelled according to Braud et al. (1995) for all environmental control factors except water stress which is replaced by a transpiration efficiency β_v, and the moisture limited evaporation which is governed by an evaporation efficiency β_s (Mahfouf and Noilhan, 1991). Definitions of β_s and β_v are given just below.

2.1.1. The series model version

In the series model the latent heat flux components for the soil (LE_s) and the vegetation (LE_v) are representative averages for the surface as a whole:

$$LE_s = \frac{\rho c_p}{\gamma} \beta_s \frac{e_{sat}(T_s) - e_0}{r_{as}} \tag{1}$$

$$LE_v = \frac{\rho c_p}{\gamma} \beta_v \frac{e_{sat}(T_v) - e_0}{r_{vv}} \tag{2}$$

where ρc_p is the product of air density and specific heat, γ the psychrometric constant, r_{as} the soil to aerodynamic level resistance and r_{vv} the minimum total resistance for latent heat exchange between the vegetation and the aerodynamic level (see Annex A1); $e_{sat}(T_x)$ is the saturated vapour pressure at temperature T_x (x refers to “s” for soil, “v” for vegetation) and e_0 is the partial pressure of vapour at the aerodynamic level; T_s and T_v are the soil and the vegetation temperatures respectively.

This formulation is different from that of the most common TSEB algorithms which use the Priestley-Taylor relationship to derive a first estimate of LE_v. Efficiencies β_x are functionally equivalent to surface resistances (again, x referring “s” for soil, “v” for vegetation and is left blank for the total evapotranspiration flux). Their range of validity is [0, 1]: if β_v=1 then the vegetation transpires at potential rate, and if β_s =1 the soil evaporation rate is that of a saturated surface, while β_v=0 or β_s =0 correspond to a non-transpiring or a non-evaporating surface, respectively. Scaling between those extremes depends on the soil moisture content around the root zone (for β_v) or in the top few centimetres (for β_s). Here, r_{vv}/β_v represents a total canopy resistance including stomatal processes while r_{as}/β_s corresponds to a total soil evaporation resistance, both in actual conditions. There is no minimum resistance to vapour extraction from the soil porous medium, therefore resistances above the soil are the same for sensible and latent heat transfers.

In order to reduce the computational cost of solving the system for all unknown variables including T_s and T_v, all non-linear expressions are linearized though Taylor expansion around air temperature so that the model can be solved through a simple matrix inversion. This is a requirement if one wants to run the model for a large number of pixels~~. A non-linear model version using optimization routines of the commercial software Matlab™ has been implemented to check the relevance of the linearization, but its computational cost is of course much higher~~. Eqs. 1 and 2 are converted to Eqs. 3 and 4:

$$LE_s \approx \frac{\rho c_p}{\gamma} \beta_s \frac{e_{sat}(T_a) + \Delta(T_s - T_a) - e_0}{r_{as}} \tag{3}$$

$$LE_v \approx \frac{\rho c_p}{\gamma} \beta_v \frac{e_{sat}(T_a) + \Delta(T_v - T_a) - e_0}{r_{vv}} \tag{4}$$

where Δ is the slope of the saturation vapour curve at air temperature T_a.

The only non-linear term that is kept in either version is the dependence of the aerodynamic resistance to the stability correction. The latter depends on the difference between the aerodynamic temperature and the reference air temperature (Richardson number, cf. Annex A1). Aerodynamic temperature is updated iteratively until convergence.

According to the layer representation in Figure 1, total fluxes (net radiation, sensible heat flux, latent heat flux, soil heat flux) are computed as the sum of the soil and vegetation components. The continuity of the latent heat flux below and above the aerodynamic level implies:

$$LE = LE_s + LE_v = \frac{\rho c_p}{\gamma}\frac{e_0 - e_a}{r_a} \quad (5)$$

where LE_s is expressed in (3) and LE_v in (4).

Continuity of the sensible heat reads:

$$H = H_s + H_v = \rho c_p \frac{T_0 - T_a}{r_a} \quad (6)$$

where T_0 is the aerodynamic temperature and

$$H_s = \rho c_p \frac{T_s - T_0}{r_{as}} \quad (7)$$

$$H_v = \rho c_p \frac{T_v - T_0}{r_{av}} \quad (8)$$

(r_a and r_{av} are the aerodynamic level to reference level and vegetation to aerodynamic level aerodynamic resistances, resp., see Annex A1 for their complete expression)

Net radiation depends on the greybody emissions of the soil and vegetation surfaces at temperature T_s and T_v. Taylor expansion for those emission terms in the net radiation estimates leads to:

$$\sigma T_x^4 \approx \sigma T_a^4 + \rho c_p \frac{4\sigma T_a^3}{\rho c_p}(T_x - T_a) = \sigma T_a^4 + \rho c_p \frac{T_x - T_a}{r_{rad}} \quad (9)$$

where σ is the Stefan-Boltzman constant and r_{rad} represents a “radiative resistance”.

Net radiation is computed according to the radiative transfer scheme of Merlin and Chehbouni (2004) which takes into account the multiple reflections between the soil and the vegetation layer in the shortwave and the longwave domains. Application of Eq. 9 on the various equations of this scheme leads to a forcing term depending on the incoming shortwave and longwave radiations, A_x, and a linear expression of the unknown surface temperatures T_s and T_v divided by the appropriate radiative resistances r_{radx} (for the expression of those terms, see Annex A2). For the soil, this leads to:

$$R_{ns} = A_{ss} - \rho c_p \frac{T_s - T_a}{r_{radss}} - \rho c_p \frac{T_v - T_a}{r_{radsv}} \quad (10)$$

and for the canopy:

$$R_{nv} = A_{vv} - \rho c_p \frac{T_s - T_a}{r_{radvs}} - \rho c_p \frac{T_v - T_a}{r_{radvv}} \quad (11)$$

The total flux is:

$$R_n = R_{ns} + R_{nv} \quad (12)$$

The soil heat flux G is a fraction ξ of the net radiation available for the whole the soil surface ($G = \xi R_{ns}$). If the model is run at the same time of the day, for instance with surface temperatures acquired with a sun-synchronous satellite, ξ depends mostly on the bare soil fraction cover. For diurnal variations of G, a time-dependent expression (e.g. Santanello and Friedl, 2003) should be preferred.

The resulting energy balance for the soil ($R_{ns} - G = H_s + LE_s$) and the canopy ($R_{nv} = H_v + LE_v$) for the series model can be written as follows:

$$(1-\xi)A_{ss} = (1-\xi)\rho c_p \frac{T_s - T_a}{r_{radss}} + (1-\xi)\rho c_p \frac{T_v - T_a}{r_{radsv}} + \rho c_p \frac{T_s - T_0}{r_{as}} + \frac{\rho c_p}{\gamma}\beta_s \frac{e_{sat}(T_a) + \Delta(T_s - T_a) - e_0}{r_{as}} \quad (13)$$

for the soil and

$$A_{vv} = \rho c_p \frac{T_s - T_a}{r_{radvs}} + \rho c_p \frac{T_v - T_a}{r_{radvv}} + \rho c_p \frac{T_v - T_0}{r_{av}} + \frac{\rho c_p}{\gamma} \beta_v \frac{e_{sat}(T_a) + \Delta(T_v - T_a) - e_0}{r_{vv}} \quad (14)$$

for the vegetation.

Finally, the link between the radiative surface temperature T_{rad} and the net longwave radiation components is:

$$\sigma T_{rad}^4 = R_{atm} - R_{an} \quad (15)$$

where R_{atm} is the incoming atmospheric radiation and R_{an} is the net longwave radiation of the whole surface, which depends on T_s and T_v and can be expressed as follows:

$$R_{an} = A_{atm} - \rho c_p \left(\frac{1}{r_{radss}} + \frac{1}{r_{radvs}}\right)(T_s - T_a) - \rho c_p \left(\frac{1}{r_{radvv}} + \frac{1}{r_{radsv}}\right)(T_v - T_a) \quad (16)$$

The forcing term for the net longwave radiation A_{atm} is given in Annex A2.

The equation relating the radiative surface temperature T_{rad} and the surface temperatures T_s and T_v is thus:

$$\sigma T_{rad}^4 + A_{atm} - R_{atm} = \rho c_p \left(\frac{1}{r_{radss}} + \frac{1}{r_{radvs}}\right)(T_s - T_a) + \rho c_p \left(\frac{1}{r_{radvv}} + \frac{1}{r_{radsv}}\right)(T_v - T_a) \quad (17)$$

2.1.2. The parallel model version

For the parallel model, all fluxes are representative of each patch (Figure 1). The total resistance is the sum of the aerodynamic resistance r_a and the surface resistances r_{as} (for the soil) or r_{vv} (for the canopy). The transpiration rate of the vegetated subpixel (in W/m^2) is thus:

$$LE_v = \frac{\rho c_p}{\gamma} \beta_v \frac{e_{sat}(T_v) - e_a}{r_{vv} + r_a} \quad (18)$$

while for the separate patch of bare soil the evaporation rate is:

$$LE_s = \frac{\rho c_p}{\gamma} \beta_s \frac{e_{sat}(T_s) - e_a}{r_{as} + r_a} \quad (19)$$

After linearization, we have:

$$LE_s \approx \frac{\rho c_p}{\gamma} \beta_s \frac{D_a + \Delta(T_s - T_a)}{r_{as} + r_a} \quad (20)$$

$$LE_v \approx \frac{\rho c_p}{\gamma} \beta_v \frac{D_a + \Delta(T_v - T_a)}{r_{vv} + r_a} \quad (21)$$

where $D_a = e_{sat}(T_a) - e_a$ is the vapour pressure deficit at reference level.

For the parallel model, the sensible heat flux rate above each patch is:

$$H_s = \rho c_p \frac{T_s - T_a}{r_{as} + r_a} \quad (22)$$

for the soil, and

$$H_v = \rho c_p \frac{T_v - T_a}{r_{av} + r_a} \qquad (23)$$

for the vegetation.

The value of the Leaf Area Index used for the parallel model is a "clump LAI" obtained by dividing the total LAI by the fraction cover of the vegetation f_c (Lhomme and Chehbouni, 1999). Total fluxes are the sum of the soil and vegetation components also weighted by their relative contribution, f_c for the vegetation and $1-f_c$ for the soil:

$$LE = (1 - f_c)LE_s + f_c LE_v \qquad (24)$$

where LE_s is expressed according to (20) and LE_v to (21), and

$$H = (1 - f_c)H_s + f_c H_v \qquad (25)$$

where H_s is expressed according to (22) and H_v to (23).

The stability correction for the aerodynamic resistance r_a depends on an average aerodynamic temperature computed from the total sensible heat flux H:

$$T_0 = T_a + \frac{H r_a}{\rho c_p}$$

(26)~~For the parallel model, the sensible heat flux rate and the related continuity of the flux through the aerodynamic level above each patch leads to the following equations:~~

$$H_s = \rho c_p \frac{T_s - T_a}{r_{as} + r_a} = \rho c_p \frac{T_s - T_{0s}}{r_{as}} \qquad (22)$$

~~for the soil, and~~

$$H_v = \rho c_p \frac{T_v - T_a}{r_{av} + r_a} = \rho c_p \frac{T_v - T_{0v}}{r_{av}} \qquad (23)$$

~~for the vegetation, where T_{0s} is the aerodynamic temperature above the soil and T_{0v} is the aerodynamic temperature above the canopy.~~

~~In the parallel model, fluxes from the soil and the vegetation components are computed independently except again for the stability correction for the transfer resistance between the aerodynamic level and the reference level, which depends on an average aerodynamic temperature computed as a weighted average of T_{0s} and T_{0v}:~~

$$T_0 = (1 - f_c)T_{0s} + f_c T_{0v} \qquad (24)$$

~~Values of T_{0s} and T_{0v} can be derived from (22) and (23) once T_s and T_v are known. The value of the Leaf Area Index used for the parallel model is a "clump LAI" obtained by dividing the total LAI by the fraction cover of the vegetation f_c (Lhomme and Chehbouni, 1999). Total fluxes are the sum of the soil and vegetation components also weighted by their relative contribution, f_c for the vegetation and $1-f_c$ for the soil:~~

$$LE = (1 - f_c)LE_s + f_c LE_v \qquad (25)$$

~~where LE_s is expressed according to (20) and LE_v to (21), and~~

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$$H = (1 - f_c)H_s + f_c H_v \quad (26)$$

where H_s is expressed according to (22) and H_v to (23).

For the parallel model, incoming solar and atmospheric radiations are fully available for each source. The net radiation components are solved independently and, like the turbulent fluxes, summed according to their respective cover fraction. The radiative transfer scheme is simpler than for the series model. The Taylor expansion of the net radiation expression for the soil writes:

$$R_{ns} = A_s - \rho c_p \frac{T_s - T_a}{r_{rads}} \quad (27)$$

and for the vegetation:

$$R_{nv} = A_v - \rho c_p \frac{T_v - T_a}{r_{radv}} \quad (28)$$

where A_s and A_v are the radiation forcing terms for the soil and the vegetation, respectively (See Annex A2 for their numerical expression).

The total flux is:

$$R_n = (1 - f_c)R_{ns} + f_c R_{nv} \quad (29)$$

The soil heat flux G is a fraction ξ of the net radiation available on the bare soil patch ($G = (1 - f_c)\ \xi R_{ns}$).

Finally, the respective energy balance equations for the soil and the vegetation patches of the parallel model are:

$$(1 - \xi)A_s = (1 - \xi)\rho c_p \frac{T_s - T_a}{r_{rads}} + \rho c_p \frac{T_s - T_a}{r_{as} + r_a} + \frac{\rho c_p}{\gamma}\beta_s \frac{D_a + \Delta(T_s - T_a)}{r_{as} + r_a} \quad (30)$$

and

$$A_v = \rho c_p \frac{T_v - T_a}{r_{radv}} + \rho c_p \frac{T_v - T_a}{r_{av} + r_a} + \frac{\rho c_p}{\gamma}\beta_v \frac{D_a + \Delta(T_v - T_a)}{r_{vv} + r_a} \quad (31)$$

For the parallel version, the net longwave radiation has also a simpler expression than for the series model:

$$R_{an} = (1 - f_c)\left[\varepsilon_s(R_{atm} - \sigma T_a^4) - \rho c_p \frac{T_s - T_a}{r_{rads}}\right] + f_c\left[\varepsilon_v(R_{atm} - \sigma T_a^4) - \rho c_p \frac{T_v - T_a}{r_{radv}}\right] \quad (32)$$

The equation relating the radiative surface temperature T_{rad} and the surface temperatures T_s and T_v is thus:

$$\sigma T_{rad}^4 - R_{atm} + [(1 - f_c)\varepsilon_s + f_c\varepsilon_v][R_{atm} - \sigma T_a^4] = (1 - f_c)\rho c_p \frac{T_s - T_a}{r_{rads}} + f_c \rho c_p \frac{T_v - T_a}{r_{radv}} \quad (33)$$

2.2. “Prescribed” and “retrieval” modes

The system of five equations to be solved simultaneously consists in Eqs. 5, 6, 13, 14 and 17 for the series model, and Eqs. 2524, 2625, 30, 31 and 33 for the parallel model. This system can be solved in

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a forward mode for which the surface temperature is an output, and an inverse mode when the surface temperature is an input. The SPARSE model combines both modes (cf. Figure 2).

If the soil and the vegetation efficiencies are known (for example through an ancillary two compartments water budget model) then the model is run in a forward mode from prescribed water stress conditions (from fully stressed to potential). In that case the system is solved for the following unknowns: T_{rad}, T_s, T_v, e_0 and T_0. T_{rad} in this prescribed mode is then an output of the system computed from Eqs. 17 and 33 after solving for T_s, T_v, e_0 and T_0 in the other four equations. This mode has two direct applications. It can be used independently from the retrieval mode to generate an equilibrium surface temperature at the time of the satellite overpass in order to assimilate surface temperature measurements from known β_s and β_v values computed at the daily or subdaily timesteps from a hydrological model (e.g. Er-raki et al., 2008). It is also implemented as a final step in the retrieval mode to provide theoretical limits corresponding to maximum reachable levels of sensible heat (fully stressed conditions) or latent heat (potential conditions) for each component (the soil and the vegetation). Output fluxes from the retrieval run are bounded by those limiting cases. In full potential conditions, $\beta_s=\beta_v=1$ while in fully stressed conditions $\beta_s=\beta_v=0$.

In retrieval conditions (inverse mode), T_{rad} is known and is derived from satellite observations or in-situ measurements in the thermal infra red domain. In order to compute the various fluxes of the energy balance, the full set of five equations must be solved simultaneously by inverting ~~the~~ the same matrix corresponding to Eqs. 5, 6, 13, 14 and 17 for the series model and Eqs. ~~25~~24, ~~26~~25, 30, 31 and 33 for the parallel model. In that case however, contrarily to the prescribed mode, the problem is initially ill-posed since the system contains six unknowns: evaporation LE_s and transpiration LE_v, surface temperature components T_s and T_v, and aerodynamic level conditions e_0 and T_0. LE_s and LE_v values are directly converted into stress levels β_s and β_v using Eqs. 3 and 4 (series model) or 20 and 21 (parallel model). In order to downsize the number of unknowns, SPARSE carries out the same rationale than the TSEB model: as a first guess, the vegetation is supposed to transpire at potential rate, therefore β_v is set to 1, and the system is solved for unknown LE_s (thus β_s), Ts, Tv, e_0 and T_0. If a negative LE_s is obtained, then the assumption of an unstressed canopy proves to be inconsistent with the observed surface temperature level. In that case, one assumes that the vegetation is suffering from water stress. This means that root zone soil moisture is depleted under critical levels, and that, most probably, the soil surface is already long dry. Therefore, β_s is set to 0 and the system is solved for LE_v (thus β_v) instead of LE_s. Finally, if LE_v is negative, fully stressed conditions are imposed for both the soil and the vegetation independently from T_{rad}. Of course, inconsistent positive values of LE_s corresponding to slightly stressed vegetation conditions can occur when one assumes that the vegetation is unstressed, but in that case the model won't be able to detect this inconsistency. The limit of this hypothesis will be assessed in Section 3 through a synthetic case study.

Finally, in order to ensure that LE_x outputs are within realistic bounds, LE_x values obtained by running SPARSE in "retrieval" conditions are limited by the evapotranspiration components in potential conditions $LE_x(\beta_s=1, \beta_v=1)$ computed by SPARSE in prescribed potential conditions (Figure2). This procedure is the dual source equivalent of what is done in ~~in a similar way to~~ the single-source model SEBS (Su, 2002). For consistency, if LE_x is limited by $LE_x(\beta_s=1, \beta_v=1)$, all fluxes of the corresponding component energy balance (Rn_x, H_x and G) are set to their values obtained by the "prescribed" mode

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in potential conditions, i.e. $Rn_x(\beta_s=1, \beta_v=1)$, $H_x(\beta_s=1, \beta_v=1)$ and $G(\beta_s=1, \beta_v=1)$. The impact of limiting LE_x outputs on the model performance will be assessed in Section 4.

Also, an arbitrary minimum positive value of LE_s = 30 W/m^2 is used as the threshold for vegetation stress detection instead of 0, in order to take into account the contribution of vapour transfer from within the topsoil porous network (Boulet et al., 1997).

3. Assessing the retrieval properties of SPARSE through a synthetic case study

3.1. Principles of the simulation experiment

The strong underlying assumptions behind SPARSE are (i) in a first guess the vegetation is supposed to be unstressed, and (ii) water stress of the vegetation is always concomitant to a non evaporative soil. This simplification of the soil-vegetation-atmosphere continuum impacts not only the total evapotranspiration retrieval but also its resulting partition between transpiration and soil evaporation. It is thus important to assess the limits of both assumptions. To do so, a synthetic simulation experiment is proposed.

The rationale of the synthetic test is as follows: for each combination of known water stress levels affecting either the transpiration or the evaporation of the soil, one can simulate through the energy budgets of the soil and the vegetation the resulting component temperatures T_s and T_v and the surface temperature of the whole surface (synthetic T_{rad}). If one assumes that the satellite is actually measuring this temperature, it can be used as input data to get back to the soil evaporation and transpiration levels and their corresponding efficiencies through the retrieval mode. If there was a unique bijective relationship between the component temperatures and the temperature of the whole surface, the retrieved stress levels would correspond to the exact combination of the stress levels used to generate the synthetic T_{rad}. Of course this is not the case and many different combinations of soil and vegetation efficiency values will correspond to the same equilibrium surface temperature. However, one expects that the whole surface energy balance is well constrained by the knowledge of T_{rad}, i.e. that each value of T_{rad} corresponds to only one surface stress level (or total efficiency). In other words, we expect that SPARSE will not always partition accurately total ET in E and T, but will retrieve the ET value relatively satisfactorily.

The objective of the synthetic stress is to assess the inconsistencies of the decision tree that distributes acceptable stress values between the soil and the vegetation, as well as its impact on the component and total evapotranspiration retrieval performances.

3.2. Set-up of the synthetic test

In this simulation experiment, the SPARSE model is run sequentially in its two operating modes: the "prescribed" or "forward" mode to generate an estimate of the radiative surface temperature from prescribed β_s and β_v efficiencies, and the "retrieval" or "inverse" mode to retrieve β_s and β_v efficiencies using as input data the surface temperature obtained previously through the "prescribed" mode ("synthetic test" branch of Figure 2). The test consists therefore in computing a mixed surface radiative temperature (T_{rad}), soil evaporation (LE_s), transpiration (LE_v) and evapotranspiration (LE) for each possible combination of soil evaporation ($\beta_s \in [0,1]$) and transpiration ($\beta_v \in [0,1]$) efficiencies in 0.1 increments with the SPARSE model in prescribed mode, then forcing the SPARSE model with T_{rad} to retrieve new LE_s, LE_v and total evapotranspiration *LE* values as well as the corresponding efficiencies (β_s, β_v and β for the total). β is deduced as the ratio between two total evapotranspiration estimates: one with actual β_s and β_v and one with β_s=β_v=1. In order to assess the limits of the model assumptions for each version, the prescribed and the retrieval modes are run for the same version (series or parallel): the surface temperature obtained by each combination of β_s and β_v for the series model (resp. the parallel model) in prescribed conditions is used as input for the series model in retrieval mode (resp. the parallel model). The retrieval performance is then assessed by comparing these new retrieved β_s, β_v and β values and the ones used to generate T_{rad}. If the retrieval is fully consistent, those efficiencies must match. The test is carried out for average dry climate conditions (R_g=800 W/m^2, *RH*=50%, u_a=2m/s, T_a=25°C) and a Leaf Area Index characteristic of maximum development stage of a cereal cover in dry climates (LAI=3).

3.3. Results

Results for the total evapotranspiration efficiency retrieval are illustrated in Figure 3. One expects rather good performances (albeit some bias) close to the first guess assumptions (transpiration close to potential conditions, i.e. $\beta_v \cong 1$ and low soil evaporation i.e. $\beta_s \cong 0$) with a degradation when soil evaporation is high and transpiration is low. In Figure 3, retrieved total efficiency is compared to the prescribed total efficiency for various incremental values of β_v for two discrete levels of β_s (0.6 and 0.2, top plots), and for incremental values of β_s for two discrete levels of β_v (0.8 and 0.4, bottom plots).

Total evapotranspiration and its corresponding β efficiency value is well retrieved for each [β_s, β_v] combination for the series model formulation (blue points all aligned along the [1:1] line), while for the parallel model β is reasonably well retrieved for situations close to the model assumptions, i.e. a low β_s and a high β_v. For extreme stress values when the assumption underlying SPARSE algorithms is challenged (low transpiration and non negligible soil evaporation) the parallel model tends to overestimate β.

In Figure 4, the performance of transpiration (top plots) and evaporation (bottom plots) efficiency retrievals are assessed separately. Since the first guess of SPARSE is that the vegetation is unstressed, the model will tend to overestimate β_v. This is the case for all transpiration efficiency values, with, as expected, a larger difference close to a fully transpiring canopy when the inconsistency in β_s retrieval is not yet detected. Indeed, for β_v values close to 1, the initial guess of an unstressed canopy leads to assign a fix value of 1 to β_v. The vegetation temperature is therefore underestimated, and the soil temperature that matches the total surface radiative temperature is overestimated. In turn, sensible heat over the soil is overestimated, the soil net radiation is underestimated, and the resulting soil evaporation computed as a residual term is underestimated. As long as this underestimation does not lead to a negative value of β_s, the model does not detect the discrepancy. Consequently, especially for a wet soil (top plot on the left hand side, β_s =0.~~8~~6), β_v retrievals match poorly the prescribed values, and β_v values cling to the unstressed boundary, except for very high prescribed stress levels (β_v below 0.4 for the series model, 0.2 for the parallel one).

Despite this overestimation, β_v retrievals are relatively consistent if the soil is very dry (top plot on the right hand side, β_s =0.2). Once again β_v retrievals by the series model are closer to the prescribed values than those of the parallel model. Conversely, soil evaporation retrievals (bottom plots) show, as expected, a slight underestimation when the vegetation is close to unstressed (left hand plot, β_v =0.8). Its amplitude is fairly constant and mirrors the overestimation of the transpiration efficiencies when the soil is dry. In that case, blue dots (series) and red squares (parallel) of the retrievals are close to the [1:1] line for all β_s levels.

For conditions far from the initial assumption, e.g. low transpiration efficiencies, soil evaporation is largely underestimated. One must note that this is the case for both models and all β_s values. Again, moderately stressed vegetation and a low level soil evaporation rate will always be interpreted in terms of composite surface temperature as a dry soil and fully transpiring vegetation. As a consequence, very small rain events on an otherwise dry soil will most probably be interpreted as a dry soil surface with slightly stressed vegetation. Those cases, not very frequent but not rare either, must be treated with care in a data assimilation perspective.

All those biases should be kept in mind when interpreting results from all dual-source models based on the same rationale: the fact that the total flux is well simulated does not always means that the component fluxes are consistent, let alone realistic. This has been shown for this particular synthetic dataset.

This test has been carried out using SPARSE due to the possibility the model offers to combine both modes in a consistent synthetic experiment. Its outcomes are illustrated for this model and a single set of vegetation and climatic conditions. We don't claim that the differences between series and parallel retrieval capacities also fully apply to TSEB but since they share the same strong underlying assumptions and differ mostly by their parameterization of the fluxes, we're convinced that similar differences would be found with TSEB if TSEB could be run in a prescribed mode.

4. Application over irrigated and rainfed wheat

4.1. Datasets

Two datasets were used to assess the performance of the series and parallel versions of the SPARSE model over a whole growing season. The first experimental dataset was collected over a rainfed wheat with green Leaf Area Index values up to 2 and the second over an irrigated wheat with green LAI up to 4. Both have been grown in a semi-arid climate (central Tunisia and Morocco). Surface temperature data were acquired with ~~an~~ a nadir-looking Apogee thermoradiometer, while energy fluxes were measured according to classical FLUXNET recommendations (Baldocchi et al., 2001) with Campbell™ CSAT sonic anemometers and Krypton fast response hygrometers. Observed and simulated latent heat flux values (half hourly averages in W/m^2) are compared at midday (local standard time) in all sky conditions. For the rainfed wheat site, there was clearly a problem with the fast response psychrometer with an energy balance closure of 60 %. Thus for that site the closure was forced and the corrected LE was computed as Rn-H-G. For the irrigated site, the half hourly closure was of the order of 80%. For this site closure was achieved with the conservation of the Bowen ratio H/LE, thus the corrected LE was computed as (Rn-G)/(1+H/LE). ~~Bowen ratio and the residual method~~

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~~have been used to close the energy balance for the irrigated and rainfed wheat sites, respectively, due to the fast response hygrometer failures of the latter site~~. Data for the irrigated wheat site have been acquired during the 2004 growing season (B124 site, Boulet et al., 2012), while the experiment for the rainfed wheat took place in 2012.

Leaf Area Index was estimated with hemispherical photography every 2 to 3 weeks depending on the phenological cycle, validated by destructive measurements during key stages (growth and full cover). Vegetation height was measured at the same dates. Temporal interpolation of Leaf Area Index for both sites is shown in Figure 5.

4.2. Evapotranspiration estimates

Two sets of SPARSE simulations are derived for each model version (series or parallel): in the set the most faithful to the original TSEB, outputs are not limited by potential heat flux values; in the second set, outputs are, like in SEBS, bounded by the potential and fully stressed flux rates considered at absolute maximum and minimum reachable values for evaporation as well as transpiration, whatever the "oasis" or micro-advection heat transfer might be. Again, this is legitimate for the parallel version, but for the series version one must inquire if local advection effects do not enhance latent heat flux values over the total potential value of a uniformly wet surface. No calibration is performed, the minimum stomatal resistance value is arbitrarily set to a realistic level for herbaceous vegetation (100 s/m, Gentine et al., 2007) and the G/Rn_s ratio ξ is set to 40% (value often encountered around midday for bare soils in arid climates). This is consistent with the potential use of this model which is designed to estimate ET routinely from remote sensing data, based on surface properties derived per land use type in a similar way to most SVATs applied to continental scales. Those values are of course less sensitive than the uncertainty on the input variable T_{rad} (not shown). In order to relate those first guess results to those obtained by the series and parallel Kustas et al. (1999) TSEB versions, TSEB is also applied with a default value for the Priestley-Taylor coefficient (1.26).

Total flux values are shown in Figures 6 and 7 for the bounded sets and RMSE values for both bounded and unbounded sets are reported in Table 1. In both cases (series and parallel versions) the RMSE values are of similar order of magnitude~~almost similar~~ and consistent with values found in the literature (cf. Li et al., 2005). The bounded series outputs display the best performances, with RMSE values lowered by 4 to more than 10 W/m^2. Without bounding, values of evaporation and transpiration above potential levels are obtained for the series version during vegetation growth, and some negative values of transpiration are found during late maturity and beginning of senescence. RMSE values for the parallel TSEB version of Kustas et al. (1999) are very close to that of the SPARSE parallel version while RMSE values for the TSEB series model ~~built from Cammalleri et al. (2010)~~ are similar to the RMSE values displayed by both parallel versions.

Retrieval performances of the other energy balance components in the bounded case have also been assessed. Statistics are shown in Table 2. The series model shows slightly better retrieval performances for soil heat flux for both sites, but only for net radiation for the irrigated wheat and for sensible heat for the rainfed wheat site. This is consistent with Li et al. (2005) and Morillas et al. (2013) who showed that the series TSEB version was more robust than the parallel version, also their relative performances were close.

4.3. Water stress estimates

Low RMSE values for the total latent heat flux do not warranty that total water stress is correctly simulated. Indeed, if moisture availability in the root zone is large enough to maintain ET at potential levels, the prescribed model in potential conditions can already explain a very large amount of the information content within the observed time series, and the added value of TIR data might be limited. It is thus important to assess the amount of information introduced by the surface temperature itself, i.e. information on moisture limited evaporation and transpiration rates (i.e. second stage evaporation, cf. Boulet et al., 2004). Water stress is usually defined as the complementary part to 1 of the ratio between the actual and the potential evapotranspiration rates. It is expected to scale between 0 (unstressed surface) and 1 (fully stressed surface). Retrieved and observed surface water stress values have been estimated from potential evapotranspiration rates generated with the SPARSE model in prescribed conditions ($\beta_s=\beta_v=1$). Simulated and observed water stress values are computed as $1-LE/LE_p$ and $1-LE_{obs}/LE_p$ respectively, where LE_{obs} is the instantaneous observed latent heat flux while LE and LE_p are the simulated latent heat flux in actual and potential conditions respectively. Total stress is thus functionally equivalent to $1-\beta$. Results are shown in Figure 8 and 9. As expected, surface stress is much higher for the rainfed than for the irrigated wheat field. The scatter is quite large, therefore showing the intrinsic limit of stress retrieval from naturally noisy TIR data as already pointed out by numerous studies (Gentine et al., 2010; Katul et al., 1998; Lagouarde et al., 2013, 2015). However, broad tendencies are well reproduced, with most points located within a confidence interval of 0.2 indicated by dotted lines along the 1:1 line. This is encouraging in a data assimilation perspective. One must also note that it includes small LE and LE_p values for which measurement uncertainty can be as large as the flux itself. To scale those stress values back to potential evapotranspiration, the LE_p order of magnitude is indicated as marker size in Figure 8 and 9. Most outliers have smaller LE_p values while the points with the largest LE_p fall within the space delimited by the two dotted lines of the confidence interval.

Some points with little to no evaporation attest the difficulty to represent accurately the conditions close to the potential levels and might be related to the theoretical limit of the model for small vegetation stress values illustrated in figure 3, especially at low evaporation efficiencies.

4.4. Soil evaporation efficiency

As shown in the previous sections as well as many previous studies on soil-vegetation-atmosphere interactions in the literature (Li et al., 2005; Morillas et al., 2013), series and parallel versions have fairly similar performances in total flux retrieval even though the series version shows slightly better values for the selected statistical criterion. However, as illustrated with the synthetic case, it might not be the case for component flux retrieval. In order to check the consistency of component flux retrieval, one needs a measurement of either soil evaporation or transpiration. In neither sites transpiration data have been collected: measuring transpiration for a cereal cover is quite challenging. On the other hand, surface soil moisture data (at a depth of around 5 cm) are available at both sites. Of course, soil moisture at 5 cm does not always react to small rainfall events, but it is a good driver of soil evaporation despite its influence by shallow roots.

We therefore decided to compare the retrieved soil evaporation efficiency to a fairly independent evaluation noted β_{s_e} derived from the observed time series of soil moisture in the top 5 cm ($\theta_{0\text{-}5cm}$) instead of using TIR data. We used the efficiency model of Merlin et al. (2011) to derive β_{s_e}:

$$\beta_{s\_e} = \left[0.5 - 0.5\cos\left(\pi\frac{\theta_{0-5cm}}{\theta_{sat}}\right)\right]^p \qquad (34)$$

Where θ_{sat} is the in-situ water content at saturation (0.30 for the rainfed site and 0.48 for the irrigated wheat) and *p* is fixed to 1 for the loamy site (rainfed wheat) and 0.5 for the clay site (irrigated wheat) according to 1-LE/LE_p observations at the beginning and the end of the growing season when the soil is almost bare.

Since the surface temperature (and thus the partition between LE_s and LE_v) reacts immediately to atmospheric turbulence (Lagouarde et al., 2015) or very small rainfall events, β_s instantaneous retrievals by SPARSE show larger fluctuations than β_{s_e}. Indeed, the latter reacts mostly to the largest rainfall events (wetting of the entire 5 cm topsoil). Meteorological forcing can vary quickly and impact the potential soil evaporation rate LE_{sp}, but the latter is less sensitive to turbulence than T_{rad}. In order to smooth out the quick fluctuations of β_s retrievals by SPARSE, we compare 5 days running averages of β_s and β_{s_e}.

The resulting β_s and β_{s_e} evaporation efficiencies are shown on Figure 10 (rainfed wheat) and 11 (irrigated wheat). For both sites, increasing and decreasing trends of β_s and β_{s_e} are mostly synchronous, although their amplitude varies throughout the growing season. Due to irrigation, β_s values are on average higher for the irrigated than the rainfed wheat site.

For the rainfed site, both models simulate fairly large values of β_s compared to β_{s_e} at the beginning of the season. The parallel model agrees well with β_{s_e} towards the end of the growing stage (DOY 30-70) while the series model matches very closely β_{s_e} at maximum cover and early senescence (reduction of β_s from DOY 70 to DOY 100). Both models agree well with β_{s_e} at the end of the season (DOY 120-170) except for the last ten days. The small rainfall event around DOY 125 is not sufficient to impact β_{s_e} but affects β_s in both model versions, whereas the soil moisture increase around DOY 105 is mostly missed out by either version.

For the irrigated wheat, soil evaporation is mostly in the energy limited stage for the first half of the observation period, and β_s remains close to 1. This is due to the complement irrigation up to the middle of the maturation phase. The magnitude of both drying events around DOY 40 and DOY 100 is very well retrieved by the series model and somewhat less by the parallel model. Again, β_s reacts more strongly to the small rainfall event around DOY90 than what is indicated from soil moisture.

At the very end of the season both model versions differ greatly from the β_{s_e} estimates and remain close to the potential rate for both sites.

5. Discussion and conclusion

A new model based on the TSEB rationale, SPARSE, has been presented. Innovation lies mostly in the formulation of the energy balance equations and the use of complementary modes (prescribed and retrieval) which allow to bound the outputs by realistic limiting flux values which ensure increased robustness. We demonstrated with two datasets that using bounding relationships based on potential conditions decreases the Root Mean Square Error by up to 11 W/m^2 from values of the order of 50-80 W/m^2. Theoretical limitations of the performance of the evapotranspiration components (evaporation and transpiration) retrievals from a single radiative surface temperature have been inferred over rainfed and irrigated wheat fields at seasonal scales, as well as through a theoretical simulation exercise. ~~For very high vegetation stress levels~~According to results obtained in Section 3, it is almost impossible to retrieve a non-zero soil evaporation at medium to large LAI values for very high vegetation stress levels. Also, and by construction, transpiration tends to be overestimated in most ranges but specifically when only slightly stressed. Within these limits, the SPARSE model shows good retrieval performances of evapotranspiration compared to the original TSEB. This comparison must be treated with special care since both models are run with no prior calibration of the poorly known parameters such as the minimum stomatal resistance (for SPARSE) or the Priestly-Taylor coefficient (for TSEB). If a value of r_{stmin}=50 s/m is used, a value also reported for wheat crops in more temperate regions, RMSE on latent heat flux increases by 4 W/m^2 in bounded conditions for the rainfed wheat site (62 W/m2) and 13 W/m^2 for the irrigated wheat site (66 W/m^2) for the series version. For the parallel model it increases by 12 W/m^2 (82 W/m^2) and 8 W/m2 (74 W/m^2), respectively.

As expected for cereal covers whose homogeneity is usually well represented by a “layer” approach, the series version provides in general better estimates in both real and synthetic cases tested. Those cases are representative of cereals typically grown in semi-arid lands in irrigated and non-irrigated areas. Both models should be tested for other conditions of heterogeneity (sparse crops, orchards, row crops) whose geometrical features are closer to the “patch” description.

Estimates of water stress have also been looked at. Water stress is an interesting variable that can be assimilated in all hydrological or SVAT models in order to compute moisture-limited evapotranspiration rates. Even if the points in the simulated vs observed scatterplots have a significant number of outliers, i.e. points outside the 0.~~1~~ 2 range along the 1:1 line in Figures 8 and 9, the results indicate that the information retrieved from TIR data is useful in a data-assimilation perspective since the broad tendencies are well reproduced.

Estimates of soil evaporation efficiency have been evaluated against a reconstructed time series relying on observed soil moisture at the soil surface and therefore independent from any surface temperature measurement. This reconstruction is of course model-dependent (Merlin et al., 2011 in our case) and must be considered with care, but despite this we found that both efficiency values are consistent, except at the beginning and the end of the season, partly due to very small rainfall events, but also probably to the poor understanding of turbulence processes over low or senescent vegetation. It seems that the transpiration of the quasi-senescent vegetation encountered at this period of the year is not always well simulated by the model even if total and green LAI values seem realistic. This could be related to the change in soil-vegetation radiation exchange and drag partition in a drying vegetation with shrinking leaves and standing straw. In order to smooth out the scale differences between the information provided by soil moisture (a time-continuous variable) and that of surface temperature (influenced by high frequency turbulent fluctuations) we compared 5 days moving averages. This is consistent with the potential data assimilation method of β or *LE* estimated from TIR data that one could use in a SVAT model for example: a smoother is more likely to outperform a sequential assimilation algorithm for short observation windows since the former will naturally smooth-out the high order fluctuations due to high order fluctuations of T_{rad}. Simpler models would perhaps provide similar performances of soil evaporation efficiencies, for instance in

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rainfed agriculture where surface soil moisture is well constrained by rainfall, but in irrigated areas it is interesting to get proper timing of water inputs and this can be achieved with relatively good confidence with this model provided that TIR information is available frequently enough.

Future work will assess the potential use of microwave data (radar) to infer topsoil moisture and constraint the inversion procedure using a first guess efficiency value generated from topsoil moisture estimates. Current work is directed towards assessing the model performance over other crops, including orchards, and other climates.

SPARSE needs more input data than TSEB, for instance relative humidity. The impact of uncertainty on available meteorological data (reanalysis or remote-sensing meteorological products vs local meteorological stations network) on SPARSE model performance will also be assessed in the future.

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Annex A1: Expression of the various resistances according to Shuttleworth and Gurney (1990)

$$r_a = \frac{Ln\left(\frac{z-d}{z_{om}}\right)^2}{k^2 u_a (1+Ri)^m}$$

$$r_{as} = \frac{z_v e^{n_{SW}} Ln\left(\frac{z-d}{z_{om}}\right)\left(e^{\frac{-n_{SW} z_{om,s}}{z_v}} - e^{\frac{-n_{SW}(d+z_{om})}{z_v}}\right)}{n_{SW} k^2 u_a (z_v - d)}$$

$$r_{av} = \left(\frac{w}{u_a}\frac{Ln\left(\frac{z-d}{z_{om}}\right)}{Ln\left(\frac{z_v-d}{z_{om}}\right)}\right)^{0.5} \frac{n_{SW}}{4\alpha_0 LAI(1-e^{-0.5 n_{SW}})}$$

$$r_{vv} = r_{av} + \frac{r_{stmin} \prod f}{LAI_g \sout{LAI}}$$

Where u_a is the wind speed measured at height z, z_v the vegetation height, d the displacement height, z_{om} the roughness length for momentum exchange, n_{SW}=2.5, w the width of the leaves (in cm), α_o=0.005, r_{stmin} the minimum stomatal resistance and $z_{om,s}$=0.005m is the roughness length for momentum exchange over bare soil. $Ri = \frac{5g(z-d)(T_0-T_a)}{T_a u_a^2}$ is the stability correction (Richardson number); m=0.75 in unstable conditions and m=2 in stable conditions. Πf represent the product of weighting stress functions related to environmental factors affecting the stomatal resistance (temperature, solar radiation, vapour pressure deficit) and are taken from Braud et al. (1995). The rule of thumb applies: z_{om}=0.13*z_v and d=0.66*z_v.

Mis en forme : Indice

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Annex A2: Forcing terms and radiative resistances of the net radiation model for the series and the parallel versions of SPARSE.

For the series version:

$$A_{ss} = (a_{rads} + b_{rads})\sigma T_a^4 + c_{rads}$$

$$r_{radss} = -\frac{\rho c_p}{4\sigma T_a^3 a_{rads}}$$

$$r_{radsv} = -\frac{\rho c_p}{b_{rads} 4\sigma T_a^3}$$

$$A_{vv} = (a_{radv} + b_{radv})\sigma T_a^4 + c_{radv}$$

$$r_{radvs} = -\frac{\rho c_p}{a_{radv} 4\sigma T_a^3}$$

$$r_{radvv} = -\frac{\rho c_p}{b_{radv} 4\sigma T_a^3}$$

$$A_{atm} = (a_{rads} + b_{rads} + a_{radv} + b_{radv})\sigma T_a^4 + c_{ratms} + c_{ratmv}$$

where

$$a_{rads} = -\frac{\varepsilon_s[(1-f_c) + \varepsilon_v f_c]}{1 - f_c(1-\varepsilon_s)(1-\varepsilon_v)}$$

$$b_{rads} = a_{radv} = \frac{\varepsilon_v \varepsilon_s f_c}{1 - f_c(1-\varepsilon_s)(1-\varepsilon_v)}$$

$$c_{ratms} = \frac{(1-f_c)\varepsilon_s R_{atm}}{1 - f_c(1-\varepsilon_s)(1-\varepsilon_v)}$$

$$c_{rads} = \frac{R_g(1-\alpha_s)(1-f_c)}{1 - f_c \alpha_s \alpha_v} + c_{ratms}$$

$$b_{radv} = -f_c \varepsilon_v \left[1 + \frac{\varepsilon_s + (1-f_c)(1-\varepsilon_s)}{1 - f_c(1-\varepsilon_s)(1-\varepsilon_v)}\right]$$

$$c_{ratmv} = f_c \varepsilon_v R_{atm} \left[1 + \frac{(1-f_c)(1-\varepsilon_s)}{1 - f_c(1-\varepsilon_s)(1-\varepsilon_v)}\right]$$

$$c_{radv} = R_g(1-\alpha_v) f_c \left[1 + \frac{\alpha_s(1-f_c)}{1 - f_c \alpha_s \alpha_v}\right] + c_{ratmv}$$

(α_s and ε_s are the albedo and the emissivity of the soil, α_v and ε_v are the albedo and the emissivity of the canopy, and R_g is the global incoming radiation, $f_c = 1 - e^{-0.5LAI/\cos\varphi}$ where the view zenith angle φ=0° for both datasets; $R_{atm} = 1.24(e_a/T_a)^{1/7}\sigma T_a^4$)

For the parallel version:

$$A_s = (1-\alpha_s)R_g + \varepsilon_s(R_{atm} - \sigma T_a^4)$$

$$A_v = (1-\alpha_v)R_g + \varepsilon_v(R_{atm} - \sigma T_a^4)$$

$$r_{rads} = \frac{\rho c_p}{4\varepsilon_s \sigma T_a^3}$$

$$r_{radv} = \frac{\rho c_p}{4\varepsilon_v \sigma T_a^3}$$

Annex A3 : Symbols

a_{rads}	Coefficient in r_{radss}, A_{atm} and A_{ss}
a_{radv}	Coefficient in r_{radvs}, A_{atm} and A_{vv}
A_s	Forcing term of the soil net radiation for the parallel model (W m^{-2})
A_v	Forcing term of the vegetation net radiation for the parallel model (W m^{-2})
A_{ss}	Forcing term of the soil net radiation for the series model (W m^{-2})
A_{vv}	Forcing term of the vegetation net radiation for the series model (W/m^2)
b_{rads}	Coefficient in r_{radss}, A_{atm} and A_{ss}
b_{radv}	Coefficient in r_{radsv}, A_{atm} and A_{vv}
c_p	Specific heat of air at constant pressure (Jkg^{-1}K^{-1})
c_{rads}	Coefficient in A_{ss}
c_{radv}	Coefficient in A_{vv}
c_{ratms}	Coefficient in A_{atm}
c_{ratmv}	Coefficient in A_{atm}
d	Displacement height (m)
e_a	Air vapour pressure at reference level (Pa)
e_0	Air vapour pressure at the aerodynamic level (Pa)
$e_{sat}(T_x)$	Saturated vapour pressure at temperature Tx (Pa)
f_c	Vegetation cover fraction
G	Soil heat flux (W/m^2)
g	Gravitational constant (m s^{-2})
H	Total sensible heat flux (W m^{-2})
H_s	Sensible heat flux from the soil (W m^{-2})
H_v	Sensible heat flux from the canopy (W m^{-2})
LAI	Total Leaf Area Index
LAI_g	Green Leaf Area Index
LE	Total latent heat flux (W m^{-2})
LE_p	Total latent heat flux in potential conditions (W m^{-2})
LE_s	Latent heat flux from the soil (W m^{-2})
LE_{sp}	Latent heat flux from the soil in potential conditions (W m^{-2})
LE_v	Latent heat flux from the canopy (W m^{-2})
LE_{vp}	Latent heat flux from the canopy in potential conditions (W m^{-2})
m	Coefficient of the stability function
n_{sw}	Coefficient in r_{av}
r_a	Aerodynamic resistance between the aerodynamic level and the reference level (s m^{-1})
R_{an}	Longwave net radiation (W m^{-2})
r_{as}	Aerodynamic resistance between the soil~~aerodynamic level~~ and the aerodynamic level~~reference level~~ (s m^{-1})

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Mis en forme : Indice

R_{atm}	Incoming atmospheric radiation (W m^{-2})
r_{av}	Aerodynamic resistance between the vegetation~~aerodynamic level~~ and the aerodynamic level ~~reference level~~ (s m^{-1})
R_g	Incoming solar radiation (W m^{-2})
Ri	Richardson number
R_n	Total net radiation (W m^{-2})
R_{ns}	Net radiation over the soil (W m^{-2})
R_{nv}	Net radiation over the canopy (W m^{-2})
r_{rad}	Radiative resistance (s m^{-1})
r_{rads}	Soil radiative resistance for the parallel model (s m^{-1})
r_{radv}	Canopy radiative resistance for the parallel model (s m^{-1})
r_{radss}	Soil radiative resistance for the soil net radiation in the series model (s m^{-1})
r_{radsv}	Canopy radiative resistance for the soil net radiation in the series model (s m^{-1})
r_{radvs}	Soil radiative resistance for the vegetation net radiation in the series model (s m^{-1})
r_{radvv}	Canopy radiative resistance for the vegetation net radiation in the series model (s m^{-1})
r_{stmin}	Minimum stomatal resistance (s m^{-1})
r_{vv}	~~surface~~ Surface resistance between the aerodynamic level and the reference level (s m^{-1})
T_0	Aerodynamic temperature (K)
~~T_{0s}~~	~~Aerodynamic temperature over the soil patch (K)~~
~~T_{0v}~~	~~Aerodynamic temperature over the vegetation patch (K)~~
T_a	Air temperature at reference level (K)
T_{rad}	Radiative surface temperature (K)
T_s	Soil surface temperature (K)
T_v	Vegetation surface temperature (K)
u_a	Horizontal wind speed at reference level (s m^{-1})
w	Leaf width (cm)
z	~~Referecne~~ Reference height where air forcing variables are measured (m)
z_{om}	Roughness height (m)
z_{oms}	Equivalent roughness length of the underlying bare soil in absence of vegetation (m)
z_v	Vegetation height (m)
α_0	Coefficient in r_{av}
α_s	Soil albedo
α_v	Vegetation albedo
β	Evapotranspiration efficiency
β_s	Evaporation efficiency
β_{s_e}	Merlin et al. (2011) evaporation efficiency
β_v	Transpiration efficiency
ε_s	Emissivity of the soil
ε_v	Emissivity of the vegetation
Δ	Slope of the vapour pressure deficit at T_a (Pa K^{-1})
γ	Psychrometric constant (Pa K^{-1})
ρ	Air density (kg m^{-3})
σ	Stefan-Boltzmann constant (W m^{-2} K^{-4})
$\theta_{0\text{-}5cm}$	Integrated volumetric soil moisture in the top 5 cm
θ_{sat}	Volumetric soil moisture at saturation
[illegible]	View zenith angle (rad)

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