ISBA Transpiration fix under dry conditions

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Contents

1 Transpiration fix for ISBA for dry conditions

1.1 Identification of the problem

Owing to semi-arid simulations using ISBA within SURFEX during the AMMA campaign, a problem with ISBA transpiration during very dry conditions has been identified. This problem was first noted by T. Pellarin as a decrease in soil moisture in offline mode using ISBA for semi-arid sites within the AMMA region, even for very dry soil conditions (defined as when the root zone average soil moisture is below the permanent wilting point, w_{wilt}). Theoretically, E_{tv} should go to zero under such conditions (physically). But the problem was masked to some extent owing to the baresoil component (which can continue to extract soil water below wilting point). J. Démarty later noted this during simulations for Niger supersites: he even imposed zero water content and noted transpiration, E_{tr}, above 0 (and in fact, daily values reaching on the order of 25 W m^{-2} at times for this academic case). A. Boone then performed further academic tests to find results consistent with Démarty. It should be noted that such problems are noticeable when the soil becomes very dry and *veg* is above 0. The issue becomes very problematic over a long timescale since eventually the remaining soil water is exhausted (given a long enough dry down period) but E_{tv} continues, thus leading to water budget closure errors as the ground becomes an infinite source of water vapor for the atmosphere (removal of water correctly ceases as the soil becomes completely dry, but the atmospheric vapor flux continues unabated). The conditions where such errors become readily visible are, in fact, not so unusual for semi-arid regions such as over West Africa. A simple proposal to correct this problem is described herein. It should be noted that the proposed corrections relate to explicit coefficients, and therefore have no impact on the implicit numerical resolution of the system and involve literally just a few lines of code in SURFEX.

1.2 Illustration using scaling

Very dry conditions here are defined as $F2 = 0$, where $F2$ is defined as the water stress (e.g. Noilhan and Mahfouf, 1996)

$$F_2 = \sum_{k=1}^{N_g} \gamma_{r,k} \frac{w_{g,k} - w_{wilt,k}}{w_{fc,k} - w_{wilt,k}} \qquad (0 \leq F_2 \leq 1) \tag{1}$$

where γ_r represents the root zone distribution function, N_g is the number of soil layers, and the other symbols have their usual meaning. Note that for ISBA-2L or 3L Force-Restore soil options, $\gamma_{r,2} = 1$ and is zero for all other values of k. So it is obvious that $F2 = 0$ implies that the average root zone water content is below the permanent wilting point, w_{wilt}. $F2$ is used in the computation of the stomatal resistance, R_s.

The problem can be quite simply illustrated by considering the relation for the latent heat flux from transpiration in ISBA

$$LE_{tv} = \frac{veg\,\rho_a L_v}{R_a + R_s} (q_{sat} - q_a) \tag{2}$$

where the symbols have the usual meaning (see Noilhan and Mahfouf, 1996). Note that $q_{sat} = q_{sat}\left(T_{g,1}\right)$ (the saturation vapor pressure computed using the uppermost soil/vegetation temperature).

For very hot dry conditions ($F2 = 0$), R_s attains it's maximum value ($R_{s\,max}$, which is currently defined as 5000 s m^{-1}), and assuming $\rho_a = 1$ and unstable conditions so that R_a becomes small compared to R_s. Finally, for hot dry conditions q_{sat} can become much larger than q_a in semi-arid or desert regions, so that the mixing ratio difference above can approach the value of q_{sat}. Using these scaling arguments, we finally approximate Eq. 2 as

$$LE_{tv} \approx 500\, veg\, q_{sat} \tag{3}$$

Eq. 3 implies that $LE_{tv} > 0$ during daytime conditions independent of soil dryness below w_{wilt} (since R_s is limited, rather than going to infinity). It is easy to see that one could expect values on the order of 10's of W m^{-2} depending on the value of *veg*, which is hardly negligible.

This is illustrated for an academic case in the left panel of Fig. 1. The forcing is from HAPEX-MOBILHY, initialized with a soil water content of 0.01 m m^{-3} and assuming $veg = 1$ and that input rainfall is zero. Non-zero E_r values are indeed physical (especially because the atmosphere at this site is not as dry as West Africa, so condensation then subsequent evaporation occur). But despite the fact that $F2 = 0$ always, E_{tr} attains values of over 25 W m^{-2} fairly often, especially during summer. This eventually leads to water balance errors, in addition to non-physical behavior.

1.3 Solution 1: $R_{s\,max}$ modification

We seek a solution which is simple (conceptually and numerically) and which will minimize any impact on existing results. We avoid simply imposing $E_{tv} = 0$ since this will cause budget problems owing to the implicit numerics: we seek a smooth continuous function to impose this constraint.

1.4 Solution 1a: Increase $R_{s\,max}$

Based on the scaling arguments in Eq. 3, the simplest proposition is to simply increase $R_{s\,max}$. An example of the impact is seen in the right hand panel of Fig. 1 where we have simply increased it by a factor of 10. A zoom over a typical several day period is shown in Fig. 2: indeed, as expected E_{tr} is decreased by an order of magnitude. But obviously a physical problem persists in that E_{tv} continues for soil moisture well below w_{wilt} can totally dry out the soil given a sufficiently long time period (although arguably quite long!). The logical extension would be to simply increase $R_{s\,max}$ until E_{tr} becomes acceptably small...but this poses 2 problems. i) E_{tr} would never be exactly zero (albeit it could become quite small), ii) But, the other potential problem with this can be seen in Eq. 2, this factor will affect results even outside of dry conditions for condensation, or other limiting conditions (atmospheric vapor pressure deficit, temperature deficit, light, etc...).

1.5 Solution 1b: Increase $R_{s\,max}$ as soil dries

An alternate approach could be to use an equation of the form

$$R_{s\,max} = R_{s\,max\,d} - \left(R_{s\,max\,d} - R_{s\,max\,0}\right) F5 \tag{4}$$

where $R_{s\,max\,0}$ is the default value of 5000, and $R_{s\,max\,d}$ is a larger value (10 or 100x larger for example). The dryness factor, $F5$ could be defined as

$$F5 = \left(\frac{w - \gamma_l\, w_{wilt}}{\gamma_u\, w_{wilt} - \gamma_l\, w_{wilt}}\right)^p \tag{5}$$

where $\gamma_u \geq 1 \geq \gamma_l$, and these parameters define the upper and lower limits of a soil moisture range about w_{wilt} over which $F5$ ranges from 0 to 1. The simplest form is to assume $p = 1$, $\gamma_u = 1$ and $\gamma_l = 0$ so that

$$F5 = \frac{w}{w_{wilt}} \tag{6}$$

But this still permits unphysical behavior ($E_{tr} > 0$ when $F2 = 0$). Another alternative would be to assume $F5 = F2$. But this could effect conditions for $F2 > 0$ as explained above, and for all of the above solutions, $E_{tr} > 0$ for $F2 = 0$ and can completely dry the soil (although again, the timescale might be extremely long).

1.6 Solution 2: h_v modification

An alternative modification is to force $E_{tv} = 0$ via h_v. For example, h_v can be expressed as

$$h_v = \delta + (1-\delta)\frac{R_a}{R_a + R_s} \tag{7}$$

where δ represents the fractional intercepted water coverage. The first term on the RHS of Eq. 7 corresponds to the E_r component, while the second term corresponds to E_{tr}. A simple constraint to

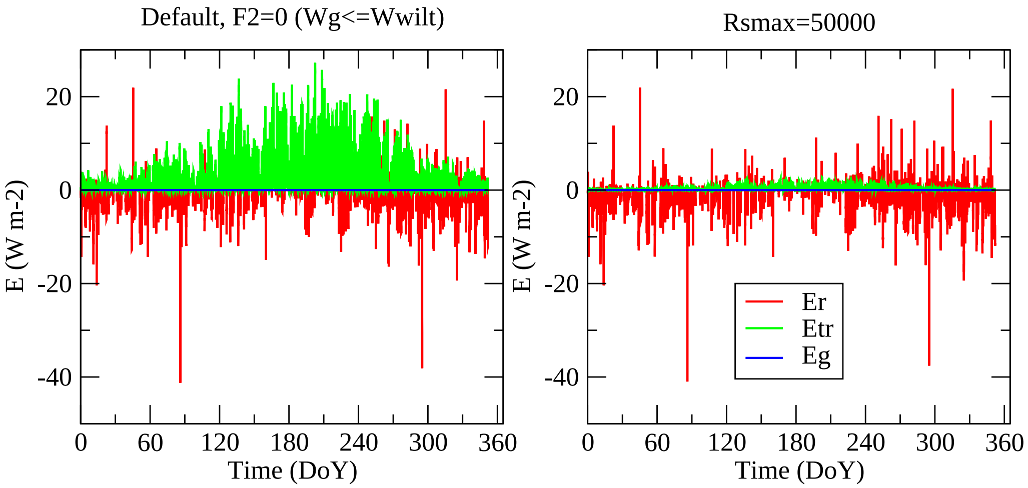

Figure 1: Evapotranspiration components for an academic test using HAPEX forcing and parameters with $veg = 1$, rainfall shut off and an initial soil water content of 0.01 m^3 m^{-3}. On the left, the default ISBA simulation. On the right, the same simulation but with 10xR_{smax}.

force $E_{tr} \rightarrow 0$ as $F2 \rightarrow 0$ (i.e. $R_s \rightarrow R_{s\,max}$) is to rewrite Eq. 7 as

$$h_v = \delta + (1-\delta) R_a \left(\frac{1}{R_a + R_s} - \frac{1}{R_a + R_{s\,max}} \right) \tag{8}$$

so that it is obvious that $E_{tr} = 0$ when $R_s = R_{s\,max}$. The above will alter the fluxes slightly when $F2 > 0$, but this can be minimized by simply writing

$$h_v = \delta + (1-\delta) R_a \left[\frac{1}{R_a + R_s} - \frac{(1-F5)}{R_a + R_{s\,max}} \right] \tag{9}$$

where $F5$ is one for wet conditions and approaches 1 as the soil dries. The simplest solution would be to set $F5 = F2$ for example. Different h_v values for $\delta = 0$ and 2 values of R_a (40 m^{-1}, unstable, and 100 m^{-1}, moderately unstable) are shown in Fig. 3 using Eq.s7-9 (assuming $F5 = F2$). One could minimize the effect further on h_v by defining

$$F5 = (F2)^p \qquad (0 \leq p \leq 1) \tag{10}$$

The smaller the value of p, the more sharp of a drop of E_{tr} as $F2 \rightarrow 0$. If p becomes too small then $F5$ might approach a step function which should be avoided.

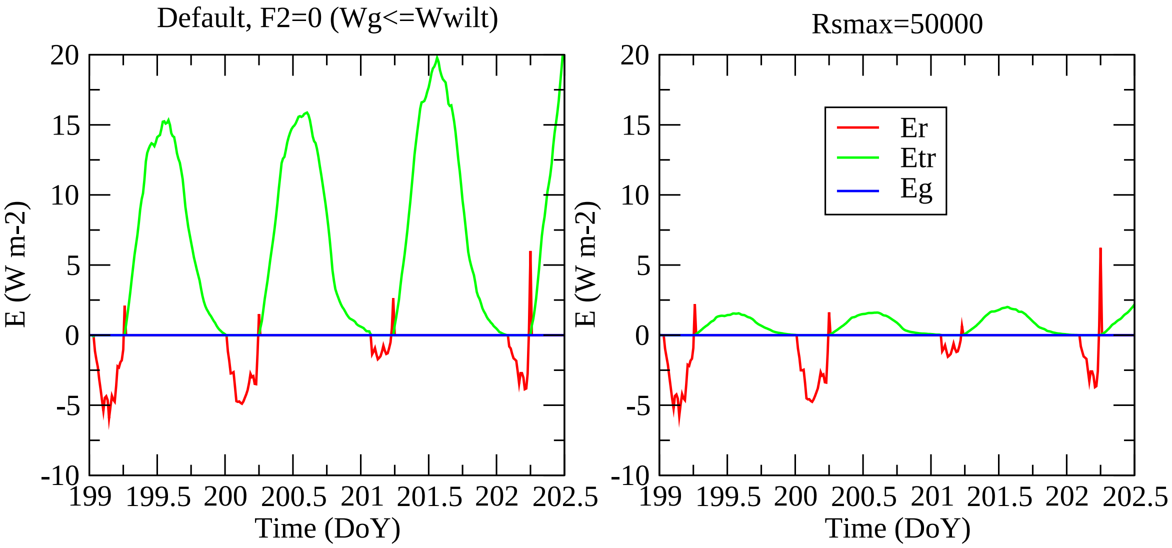

Figure 2: As in Fig. 1, except a zoom over a typical 3 day summertime period.

An example using Eq. 8 is shown in the right hand side of Fig. 4 (the default case is shown once again on the left). It is seen that E_{tv} is completely shut off, only condensation and evaporation of the interception reservoir continue (and water balance is maintained with a gradual net soil moistening, not shown). A zoom over the same period from Fig. 2 is shown in Fig. 5. The impact on condensation is quite small and $E_{tr} = 0$.

It should be noted that in SURFEX, a delta function is actually included in the computation of h_v (δ_{hv}: it is 0 when condensation occurs, 1 otherwise) and in the code (DRAG.F90) it is expressed as

$$h_v = 1 - \delta_{hv} \left(1 - \delta\right) \frac{R_s}{R_a + R_s} \tag{11}$$

After a good deal of algebra, one can express the above equation in the same form as in Eq. 9 as

$$h_v = \delta + \left(1 - \delta\right) \left[R_a + R_s \left(1 - \delta_{hv}\right)\right] \left[\frac{1}{R_a + R_s} - \frac{\delta_{hv}(1 - F5)}{R_a + R_{s\,max}}\right] \tag{12}$$

The impact of using Eq. 12 with $F5 = 0$ is shown in Fig. 6 for all of France for a one year simulation (using ISBA-Ags with the NIT option). This run is a good test since there is a full feedback between the vegetation and the soil moisture. It can be seen that the impact is fairly small, not not negligible. The simulation was repeated with $F5 = F2$, and the results are shown in Fig. 7. It can be seen that the impact is reduced further, while still preventing errors.

In another test, the impact of using Eq. 12 with $F5 = F2$ is shown in Fig. 8 for all of France for the present climate (the AST option is used: LAI is prescribed from ECOCLIMAP). This run is of interest since is covers a fairly long time period. Again, the impact is overall fairly small, but it is

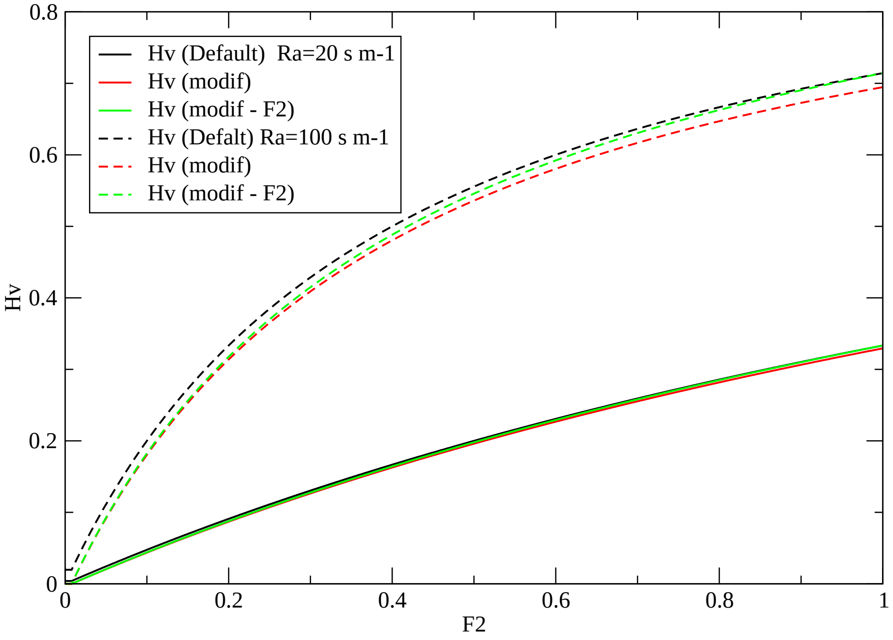

Figure 3: h_v from Eq.s7-9 (assuming $F5 = F2$) for 2 different values of R_a and assuming $\delta = 0$.

relatively largest in areas where one would expect: semi-arid zones or areas with vegetation which can experience significant drying in summer. The effect on the transpiration component is shown in Fig. 9.

1.7 Summary

A simple modification to cause E_{tr} to go to zero during very dry conditions (soil water below w_{wilt}) has been proposed. The solution is simple, and has been proposed such the impact when $F2 > 0$ is small and so that implicit numerics are not impacted. The final proposed solution is

$$h_v = \delta + (1-\delta)R_a \left[\frac{1}{R_a + R_s} - \frac{(1-F2)}{R_a + R_{s\,max}} \right] \tag{13}$$

An additional advantage of Eq. 13 is that no new parameters are introduced. Other solutions are perhaps also possible, but these seem to be the two most direct. Both proposals imply changing literally 1 to 3 lines of code in the ISBA routines of SURFEX.

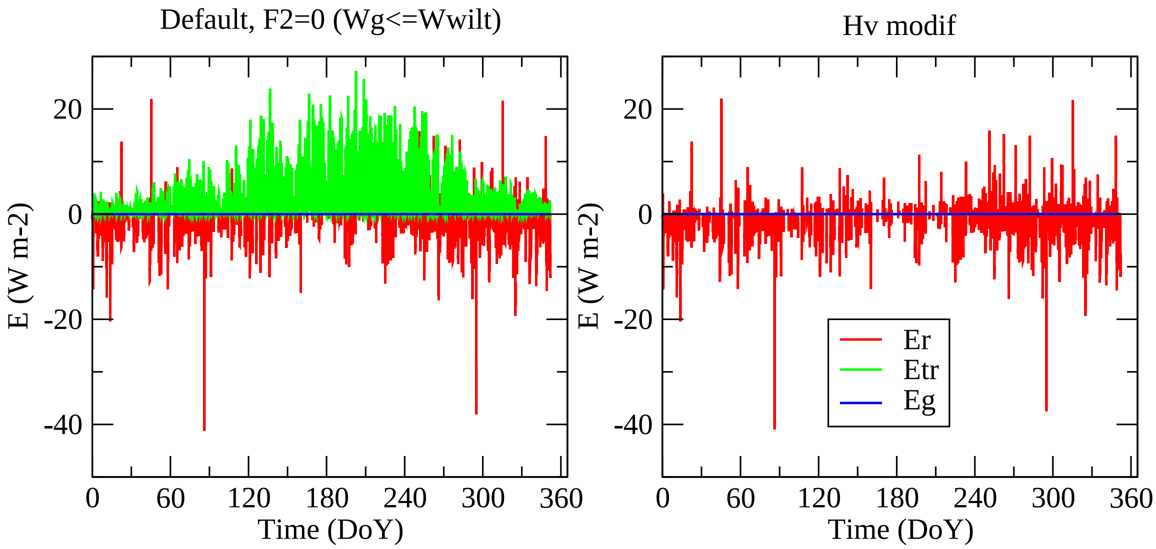

Figure 4: As in Fig. 1, except using the modified h_v formulation.

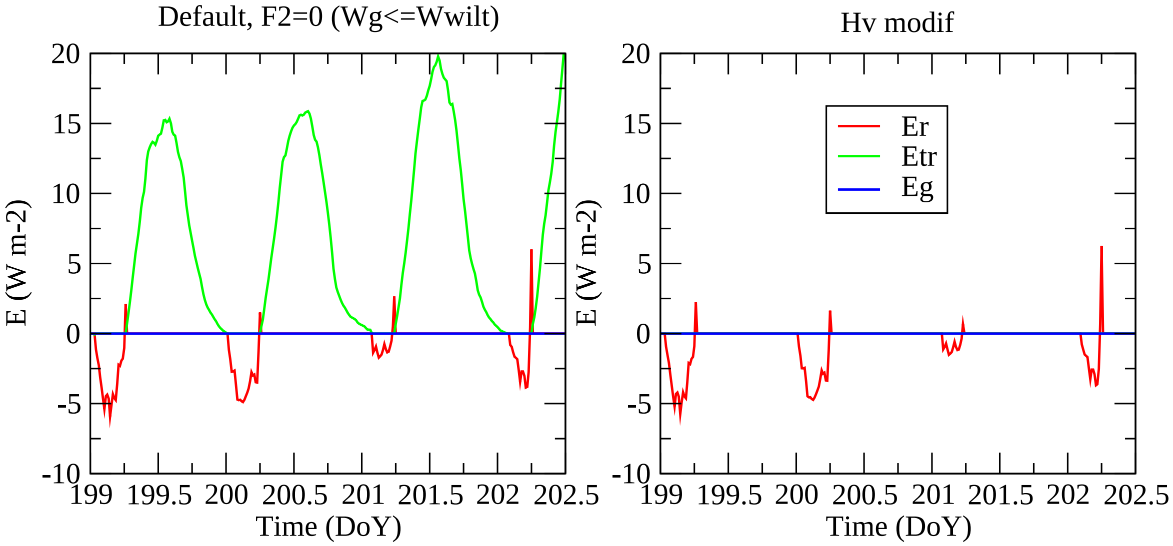

Figure 5: As in Fig. 4, except a zoom over a typical 3 day summertime period.

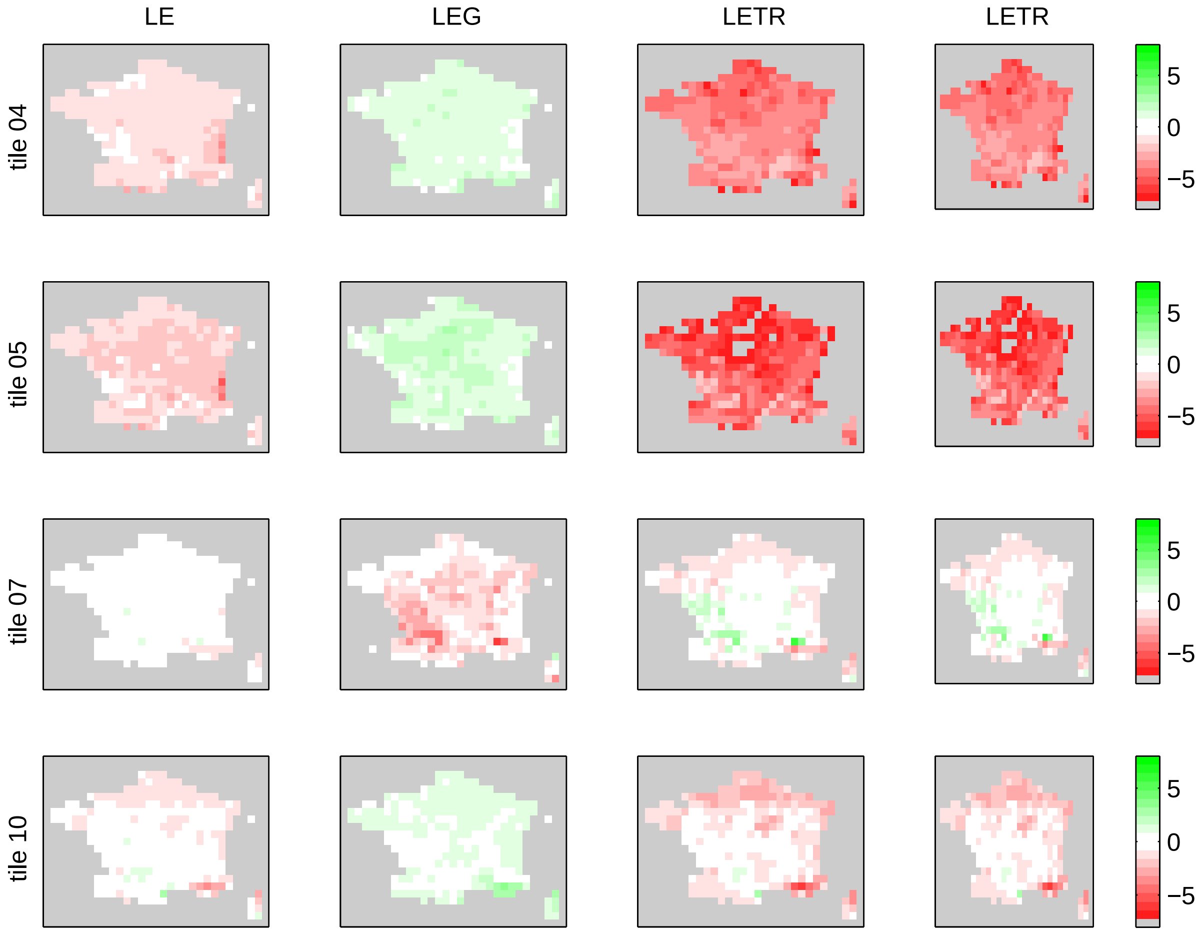

Figure 6: The map shows the relative difference of LE and its components over France after one year of simulation between the modified simulation and the reference simulation (SURFEX-V7.0). These results use Eq. 8 (i.e. no additional $F2$ factor). The row represents four different patches (top to bottom : deciduous forest, coniferous forest, C3 crops and grassland). ISBA-Ags is used to compute the photosynthesis (the NIT option is used). Figure from S. Lafont.

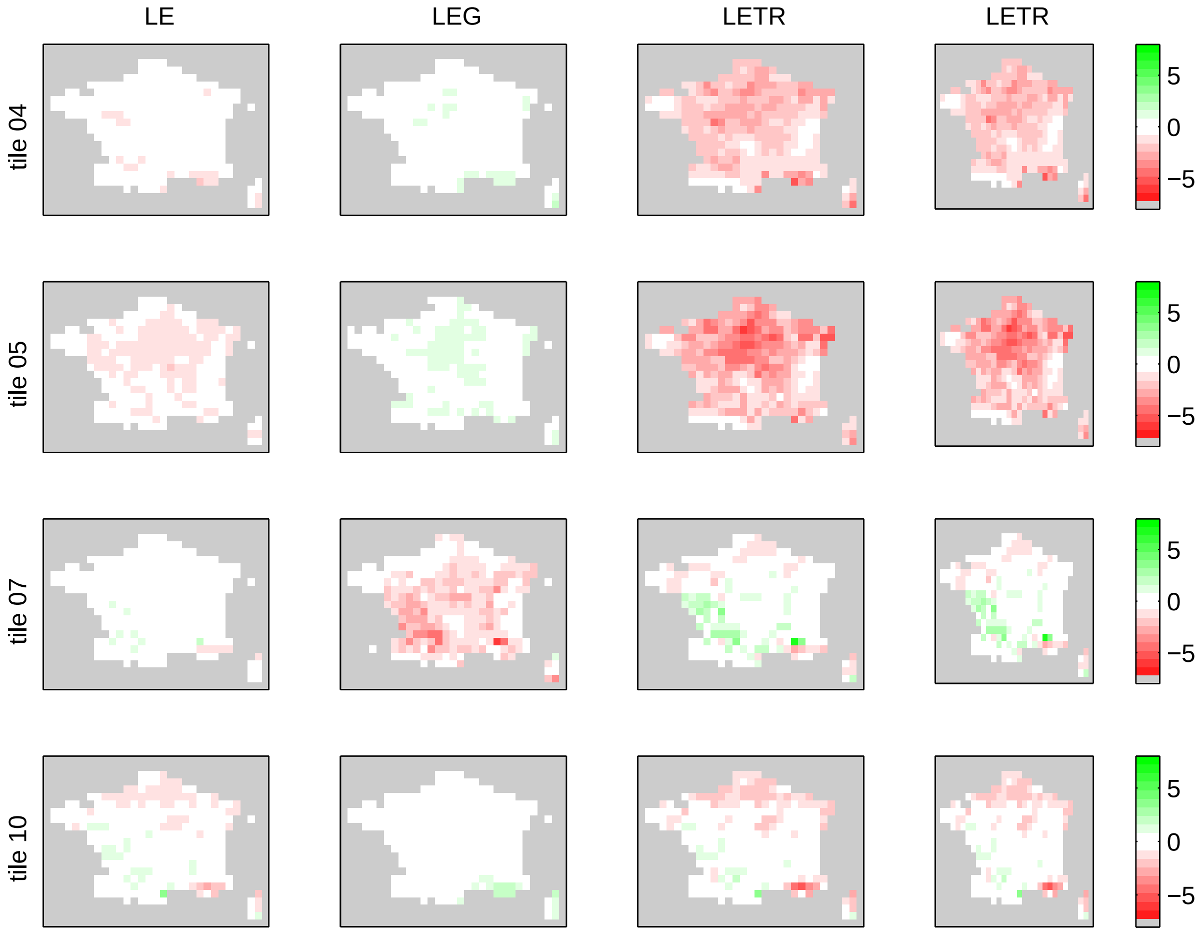

Figure 7: As in Fig. 6, except Eq. 13 is used. The use of the additional $F2$ factor reduces the impact of the modification further, while still retaining the main desired effect (no transpiration below wilting point).

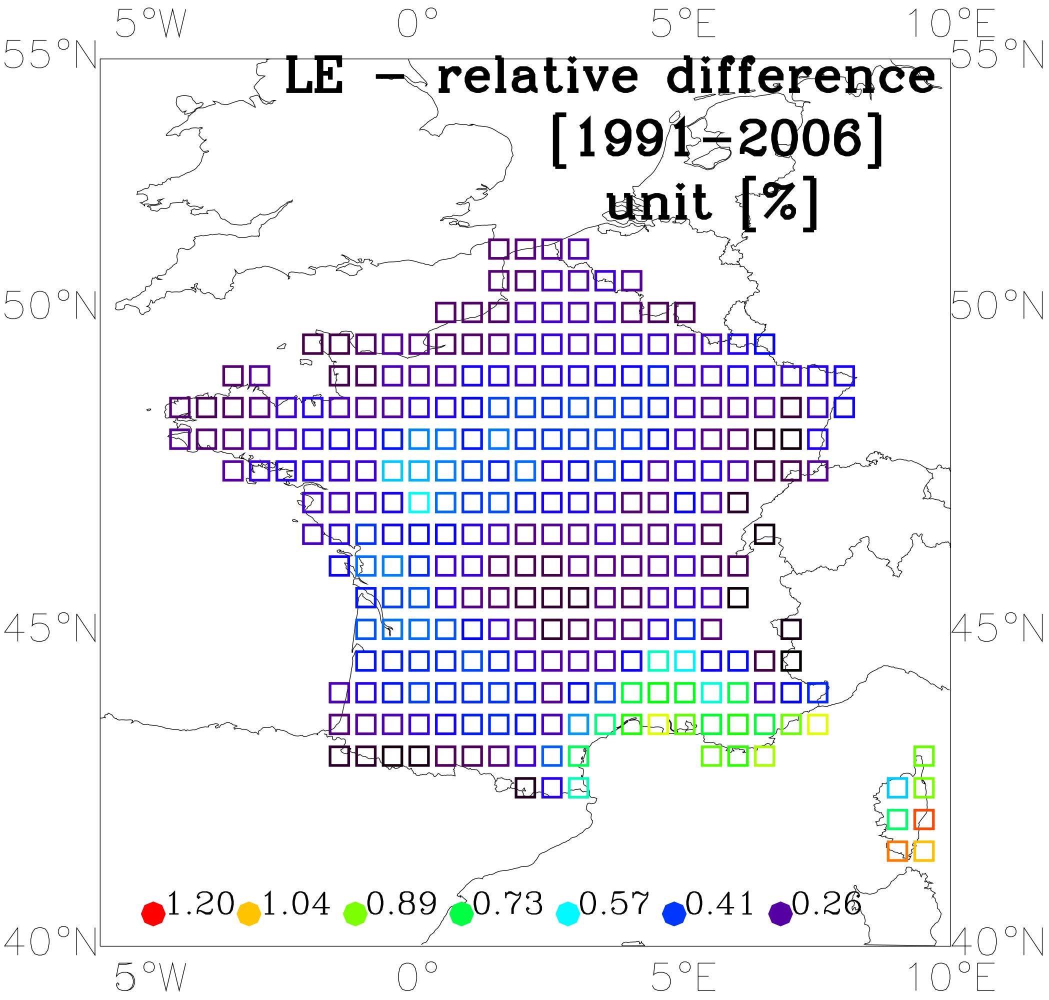

Figure 8: Relative difference in total evapotranspiration over France from 1991-2006 (present climate) using the proposed modification (Eq. 13). ISBA-Ags is used to compute the photosynthesis (the AST option is used: LAI is prescribed from ECOCLIMAP). Figure from D. Carrer.

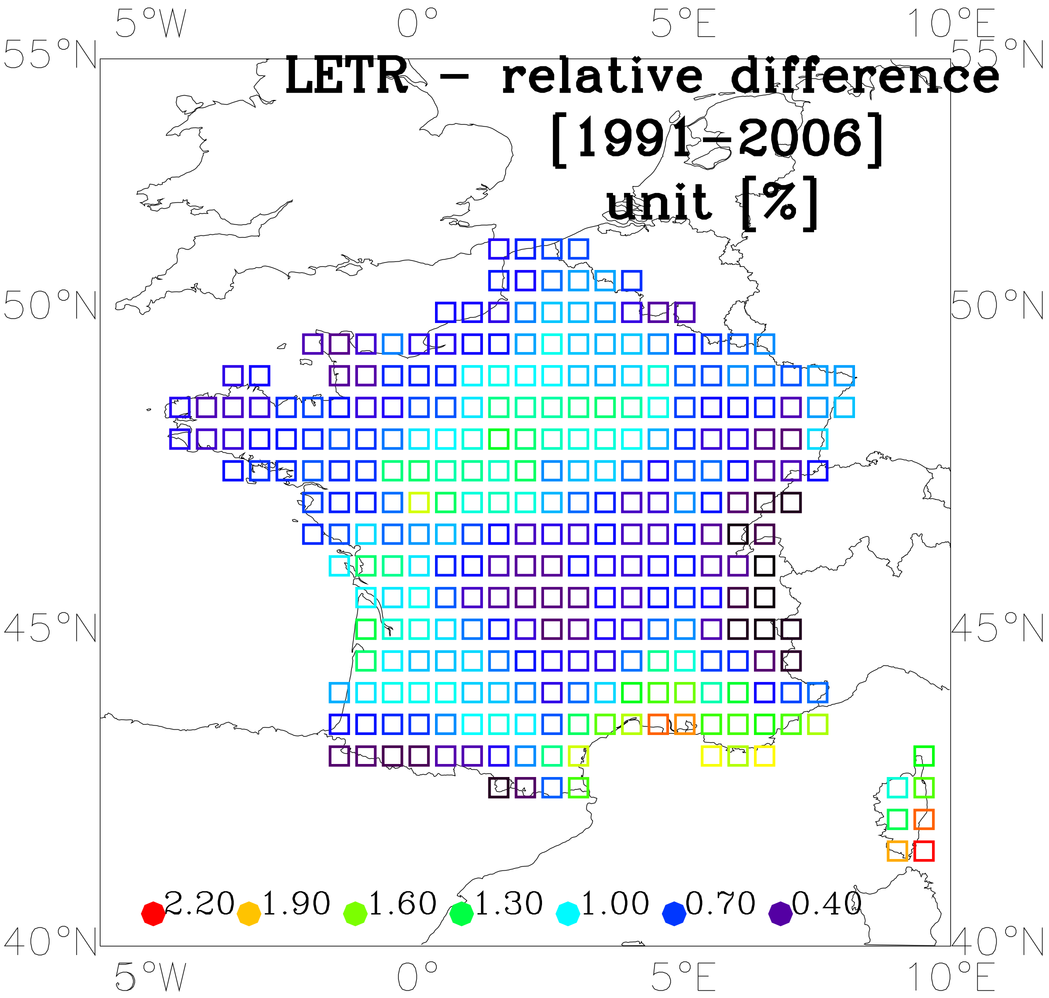

Figure 9: As in Fig. 8, except for the relative difference in transpiration (only) is shown.