On the treatment of soil water stress in LSM simulations of vegetation function;

Europe-wide JULES simulation runs with Egea et al. (2011) parameterisation embedded

Pier Luigi Vidale, Gregorio Egea, Anne Verhoef

HOW DOES WATER STRESS LIMIT CO₂ ASSIMILATION AND THE TRANSPIRATION OF H₂O?

**Water stress** affects the CO₂ concentration at chloroplast level, $C_c$, by:

a. Stomatal Conductance Limitation *(SCL)*, reducing stomatal conductance $g_s$ (diffusion of CO₂ and H₂O)
b. Mesophyll Conductance Limitation *(MCL)*, reducing mesophyll conductance to CO₂ diffusion ($g_m$)

Water stress affects the biochemical capacity *(BL)* by:

a. Reducing $V_{cmax}$ (carboxylation rate)
b. Reducing $J_{max}$
   (electron transport rate)
The soil moisture stress in each soil layer \( l \), \( \beta^l \), is computed as:

\[
\beta^l = \begin{cases} 
1 & \theta^l \geq \theta_c^l \\
\frac{\theta^l - \theta_w^l}{\theta_c^l - \theta_w^l} & \theta_c^l > \theta^l > \theta_w^l \\
0 & \theta^l \leq \theta_w^l
\end{cases}
\]

where \( \theta^l, \theta_c^l \) and \( \theta_w^l \) are volumetric soil water content, critical point (c) and wilting point (w), respectively \( (m^3/m^3) \). \( \beta^l \) provides the factor that limits photosynthesis in JULES as a function of soil moisture availability in each soil layer, following:

\[
A = A_p \beta
\]

where \( A_p \) is the unstressed photosynthesis and \( \beta \) is the weighted sum of \( \beta^l \) (by root density in each soil layer \( l \), \( r^l \)):

\[
\beta = \sum_l r^l \beta^l
\]
Egea et al. (2011) introduced an exponential dependence, which allows for non-linear $\beta = \beta(\theta)$ functional dependencies through the exponent $q_i$:

$$
\beta_i^l = \begin{cases} 
1 & \theta^l \geq \theta_c^l \\
\left[\frac{\theta^l - \theta_w^l}{\theta_c^l - \theta_w^l}\right]^{q_i} & \theta_c^l > \theta^l > \theta_w^l \\
0 & \theta^l \leq \theta_w^l
\end{cases}
$$

Furthermore, the indices (i=S,B,M) enable three pathways (Stomatal, Biochemical, Mesophyll) for soil water stress $\beta$ to affect plant function individually, or in any combination.
IMPLICATIONS OF INCLUDING DIFFUSIONAL LIMITATIONS OF PHOTOSYNTHESIS UNDER WATER STRESS

We have implemented in JULES an analytical solution to solve this set of equations:

**Equation 1:** \( g_s = g_0 + a_1 \frac{1.6A}{(C_s - \Gamma)(1 + \frac{D_s}{D_*})} \)

where \( a_1 = \frac{1}{(1 - f_0)} \) and \( D_* = D_{\text{max}}/(a_1 - 1) \)

\( f_0 \) and \( D_{\text{max}} \) parameters proposed by Jacobs et al. (1994).

**Equation 2:** \( A = \min(A_c, A_j) - R_d \)

where \( A_c \) and \( A_j \) are \( C_c \)-dependent (\( C_c \) is the CO\(_2\) concentration at the chloroplasts).

**Equation 3:** \( C_c = C_i - \frac{A}{g_m} \)

with \( g_m \) the mesophyll conductance, which is temperature-dependent

**Equation 4:** \( C_i = C_s - \frac{A}{g_s} \)
IMPLICATIONS OF INCLUDING DIFFUSIONAL LIMITATIONS OF PHOTOSYNTHESIS UNDER WATER STRESS

Water stress can be included using the following three pathways or a combination thereof:

For SCL:  \[ g_s = g_0 + \beta_s a_1 \frac{1.6A}{(C_s - \Gamma)(1 + \frac{D_s}{D_*})} \]

For BL:  \[ V_{c_{max}} = \beta_B V_{c_{max},0} \quad \text{and} \quad I_{c_{max}} = \beta_B I_{c_{max},0} \]

For MCL:  \[ g_m = \beta_M g_{m,0} \]

Original JULES is not fully coupled (in terms of \( A \) and \( g_s \)) because to decrease \( g_s \) you have to decrease \( A \) first. Now we can impose three types of drought limitations with different effects to those obtained with original JULES where water stress was only implemented through \( A \) depletion.
Following Egea et al. (2011), we implemented higher levels of biophysical complexity in the A-gs model embedded in JULES. Our scheme allows root zone soil moisture to limit plant function via three individual routes: biochemical (BL), stomatal conductance (SCL), and mesophyll conductance (MCL), as well as combinations thereof.

- We start with a simple experimental setup: a LSM, removed from its parent GCM, and driven by observed atmospheric forcing, in order to isolate the soil-vegetation feedbacks in controlled conditions.

- We performed simulations of land surface climate interactions over a large European domain for the period 1980 to 2009. All integrations were iteratively spun up, with data from 1970 to 1980 until soil conditions (temperature, moisture) converged.

<table>
<thead>
<tr>
<th>$\beta$ Treatment</th>
<th>SCL</th>
<th>BL</th>
<th>MCL</th>
<th>COMB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biochemical exponent $q_B$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.25</td>
</tr>
<tr>
<td>Mesophyll exponent $q_M$</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Stomatal exponent $q_S$</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Fig. 1: The study region and three of the domains used to present results (as domain averages) in this study. EE: Eastern Europe; FR: France; SP: Spain.
$C_i$ varies strongly between day/night and summer/winter, but also shows strong interannual signatures. Years like 1998 (El Niño) and 2003 (European heatwave) very strongly reveal the response of photosynthesis to atmospheric forcing. This response is accentuated in treatments that include the direct influence of $\beta$ on stomatal control.

Figure 2: Leaf internal CO$_2$ pressure ($C_i$, black) and reference atmospheric partial pressure of CO$_2$ ($C_a$, green) for the four treatments in Table 1. All plots show data from the French sub-domain, same as in Fig. 3.
Fig. 3: $\beta$ in the **French sub-domain** for BroadLeaf Trees (BLT, left) and C3 grass (C3, right). **SCL**=red; **BL**=green; **MCL**=blue; **COMB**=orange
SENSITIVITY OF CARBON & TRANSPIRATION FLUXES

GPP; Spain

Transpiration, BLT, for subdomain SP

GPP; France

Transpiration, BLT, for subdomain FR

GPP; E-Europe

Transpiration, BLT, for subdomain EE

Broad Leaf Trees

Jules meeting, 19-20 June 2013
SOIL MOISTURE FINGERPRINTS & WUE

Broad Leaf Trees

Available SMC
In 3 m soil column;
Spain

SCL=red; BL=green;
MCL=blue;
COMB=orange

Available SMC
In 3 m soil column;
France

Available SMC
In 3 m soil column;
Eastern Europe

GPP/T ratio; Spain

GPP/T ratio; France

GPP/T ratio; Eastern Europe
8. Soil-Vegetation-(atmospheric) feedbacks
Vegetation models retaining **stomatal and mesophyll** mechanisms in the imposition of soil water stress on plants strongly discriminate their responses to water-limited conditions, especially in **radiation-limited** regions. The response to extreme years (e.g. the El Niño year of 1998, the heatwaves of 2003 in France or 2005 in Spain) reveal the strongest feedbacks, so that:

1. **ML**, the mesophyll conductance route to the imposition of soil water stress causes the **largest soil moisture anomaly and loss of GPP** (the **BL** model follows closely);
2. **Lower transpiration** rates (but **higher GPP**) are produced with **SCL**, because the stronger stomatal regulation conserves water in the soil and produces a less frequent occurrence of critical $\beta$ factors;
3. **Higher WUE** (up to ~20% larger in some months) in **SCL** produces significant soil moisture fingerprints, particularly evident for domains that are **not radiation-limited**.