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

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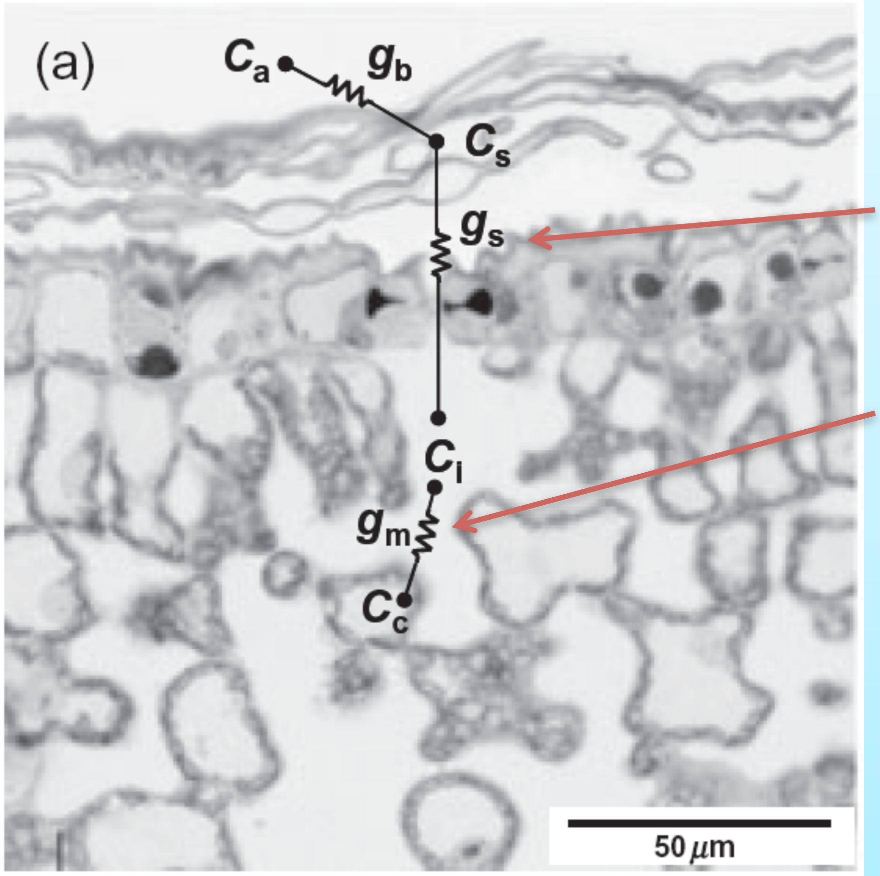
Based on: *Egea, G., Verhoef, A. and Vidale, P. L. (2011) Towards an improved and more flexible representation of water stress in coupled photosynthesis–stomatal conductance models.* ***Agricultural and Forest Meteorology, 151: 1370-1384.***

Jules meeting, 19-20 June 2013

EFFECT OF WATER STRESS ON PLANT FUNCTION

HOW DOES WATER STRESS LIMIT CO_2 ASSIMILATION AND THE TRANSPIRATION OF H_2O?



Water stress affects the CO_2 concentration at chloroplast level, $\mathbf{C_c}$ by:

a. Stomatal Conductance Limitation **(SCL)**, reducing stomatal conductance g_s (diffusion of CO_2 and H_2O)

b. Mesophyll Conductance Limitation **(MCL),** reducing mesophyll conductance to CO_2 diffusion (g_m)

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

a. Reducing V_{cmax} (carboxylation rate)

b. Reducing J_{max} (electron transport rate)

TRADITIONAL TREATMENT OF WATER STRESS

The **soil moisture stress** in each soil layer (*l*), β^l, is computed as:

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

where θ^l, θ_c^l and θ_w^l are volumetric soil water content, critical point (c) and wilting point (w), respectively (m^3/m^3). **β^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 β is the weighted sum of β^l (by root density in each soil layer *l*, r^l):

$$\beta = \sum_l r^l \beta^l$$

GENERALISED, NEW APPROACH

MODELS SUCH AS JULES NEGLECT DIFFUSIONAL LIMITATIONS (I.E. STOMATAL AND/OR MESOPHYLL CONDUCTANCE LIMITATIONS)

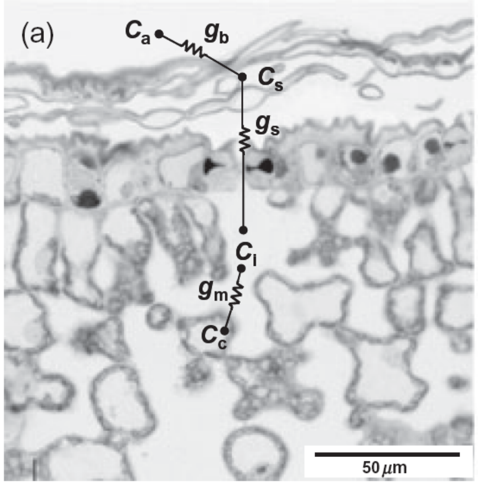
Egea et al. (2011) introduced an **exponential dependence**, which allows for non-linear $\beta = \beta(\theta)$ functional dependencies through the exponent q_i:

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

Furthermore, the indices (i=S,B,M) **enable three pathways** (**S**tomatal, **B**iochemical, **M**esophyll) for soil water stress β 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: $g_s = g_0 + a_1 \frac{1.6A}{(C_s - \Gamma)\left(1 + \frac{DS}{D_*}\right)}$

where $a_1 = 1/(1 - f_0)$ and $D_* = D_{max}/(a_1 - 1)$

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

Equation 2: $\boldsymbol{A = min(A_c, A_j) - R_d}$

where A_c and A_j are C_c-dependent (C_c is the CO_2 concentration at the chloroplasts).

Equation 3: $\boldsymbol{C_c = C_i - \frac{A}{g_m}}$

with g_m the mesophyll conductance, which is temperature-dependent

Equation 4: $\boldsymbol{C_i = C_s - \frac{A}{g_s}}$

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: $$g_s = g_0 + \boxed{\beta_s} a_1 \frac{1.6A}{(C_s - \Gamma)\left(1 + \frac{D_s}{D_*}\right)}$$

For BL: $$V_{cmax} = \boxed{\beta_B} V_{cmax,0} \quad \text{and} \quad J_{cmax} = \boxed{\beta_B} J_{cmax,0}$$

For MCL: $$g_m = \boxed{\beta_M} g_{m,0}$$

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.

METHODOLOGY

- 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.

β Treatment	SCL	BL	MCL	COMB
Biochemical exponent q_B	0	1	0	0.25
Mesophyll exponent q_M	0	0	1	0.5
Stomatal exponent q_S	1	0	0	0.25

REGIONAL STUDY DOMAINS

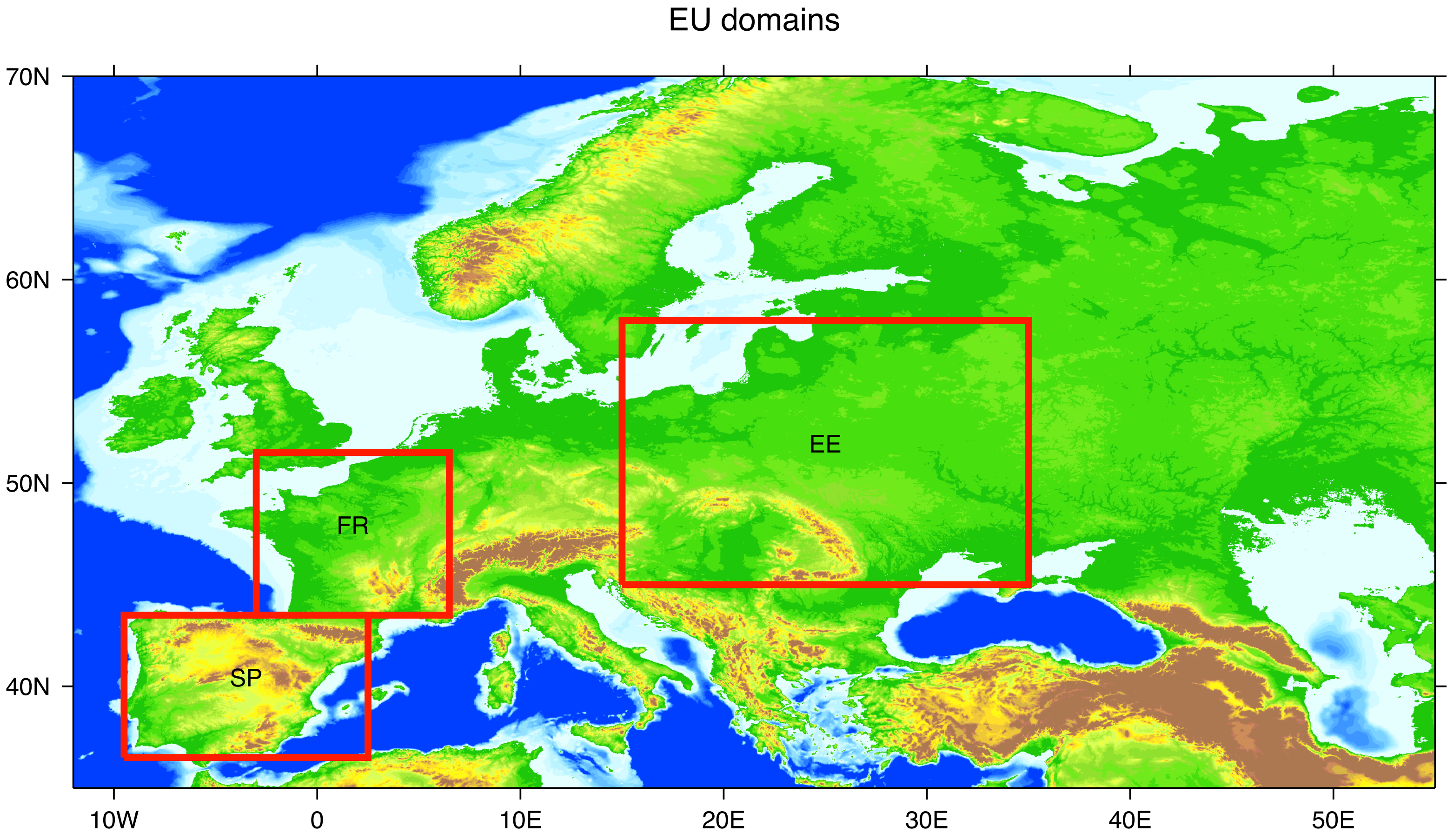
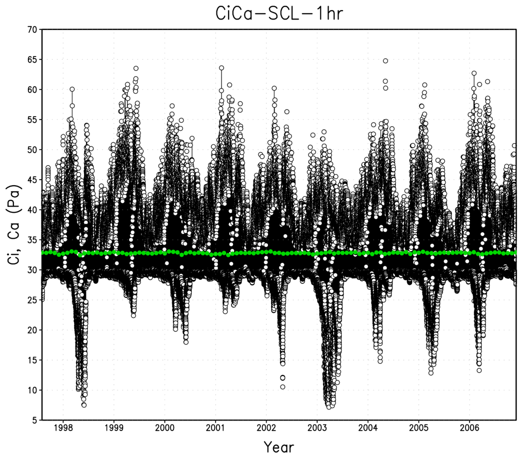


Fig. 1: The study region and **three of the domains** used to present results (as domain averages) in this study. EE: Eastern Europe; FR: France; SP: Spain.

EFFECT ON CI



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 β on stomatal control.

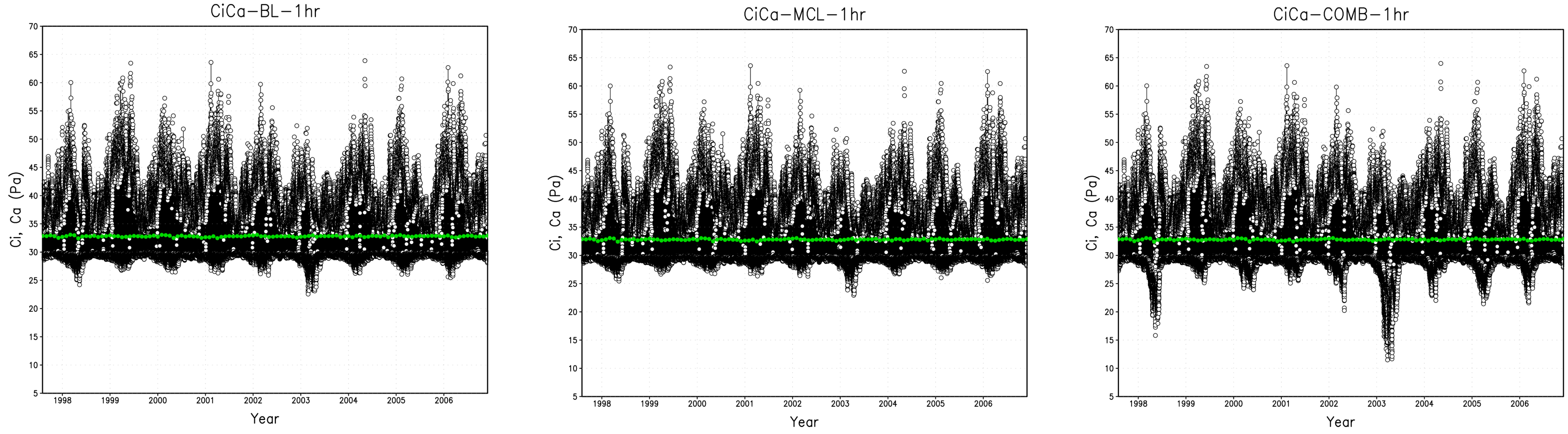
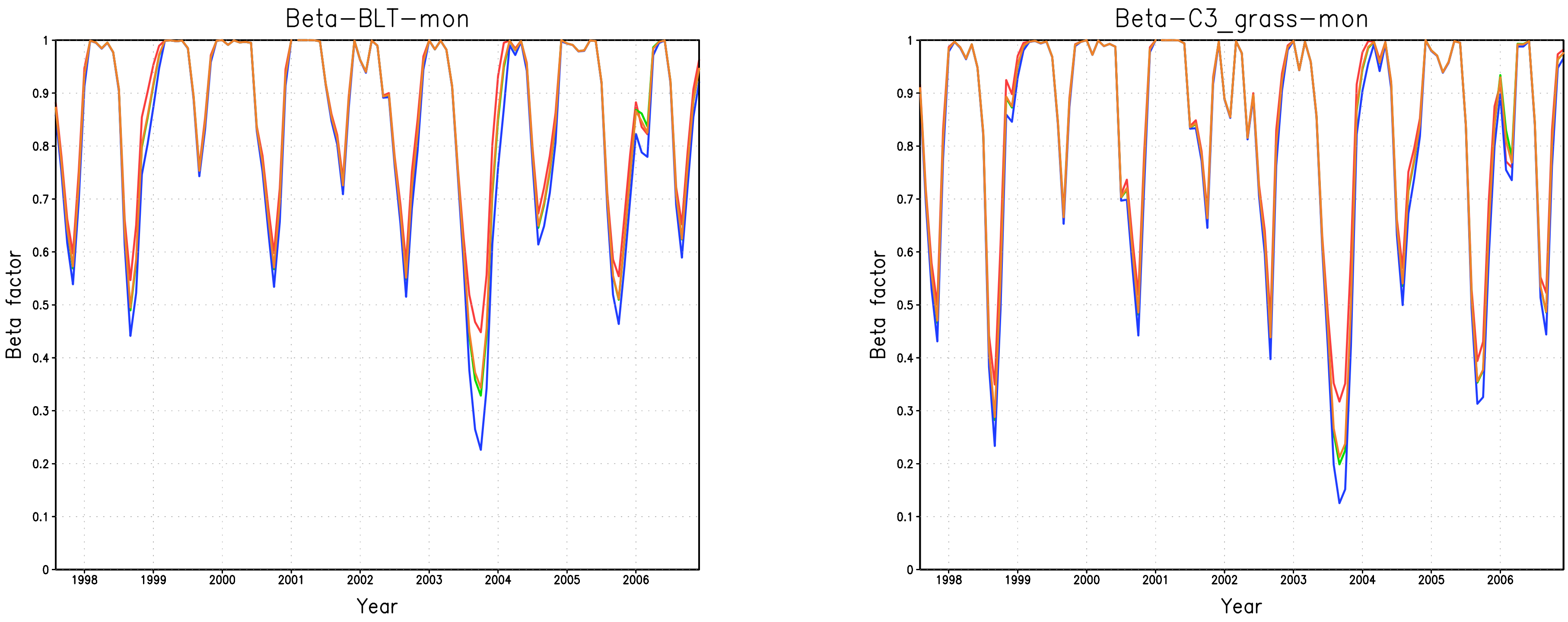


Figure 2: **Leaf internal CO_2 pressure** (C_i, black) and reference atmospheric partial pressure of CO_2 (C_a, green) for the four treatments in Table 1. All plots show data from the **French sub-domain**, same as in Fig. 3.

RESULTING β EVOLUTION

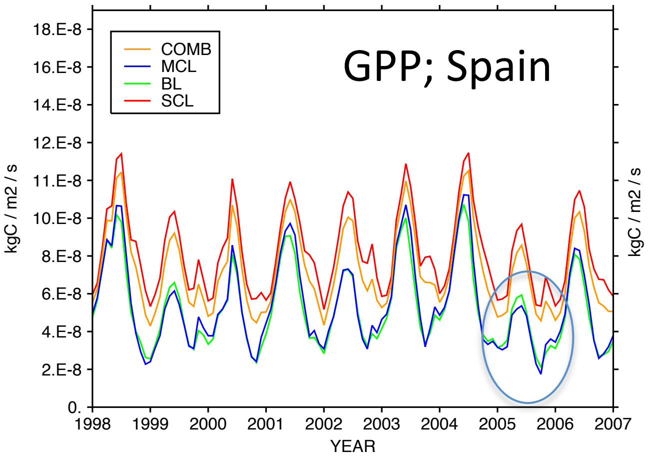


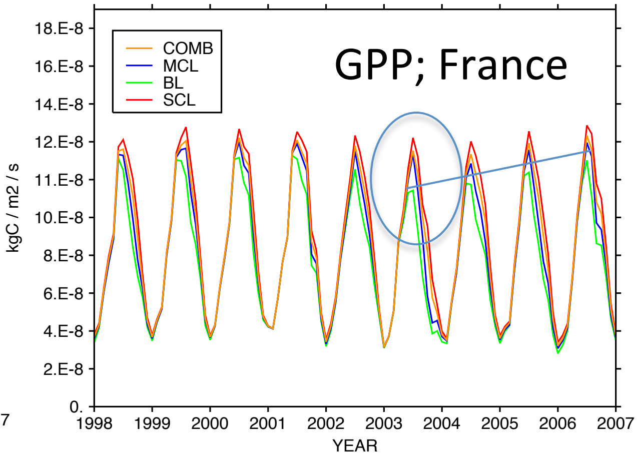
Broadleaf Trees

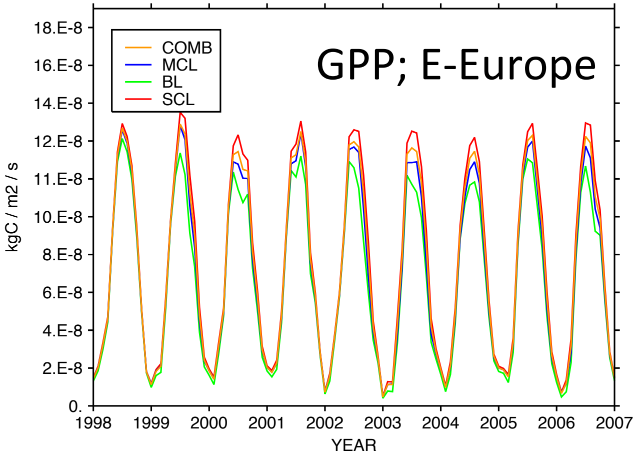
C3 grasses

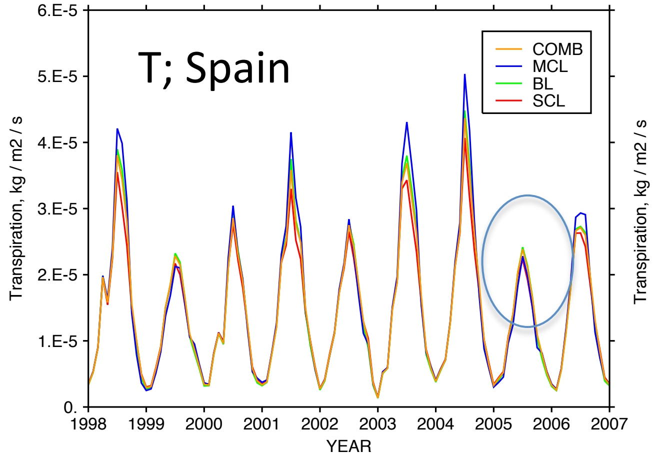
Fig. 3: β in the **French sub-domain** for BroadLeaf Trees (BLT, left) and C3 grass (C3, right).
SCL=red; BL=green; MCL=blue; COMB=orange

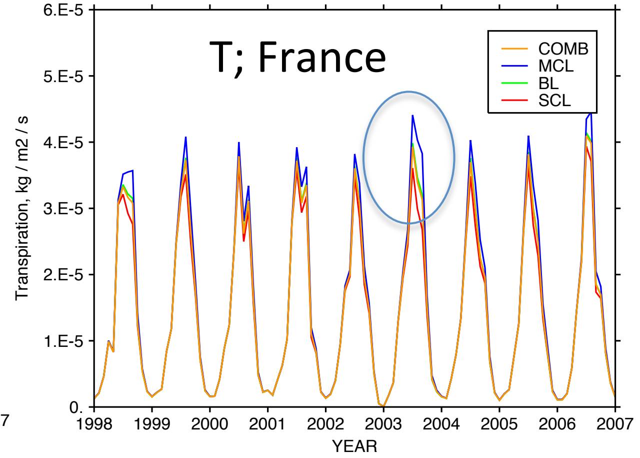
SENSITIVITY OF CARBON & TRANSPIRATION FLUXES

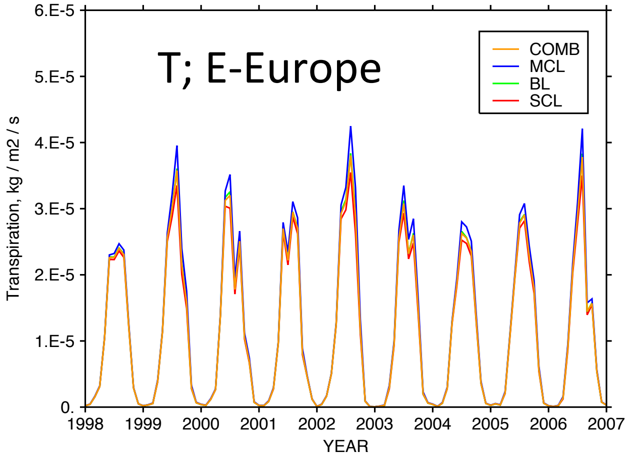

GPP, BLT, for subdomain SP


GPP, BLT, for subdomain FR


GPP, BLT, for subdomain EE


Transpiration, BLT, for subdomain SP


Transpiration, BLT, for subdomain FR


Transpiration, BLT, for subdomain EE

Broad Leaf Trees

University of Reading

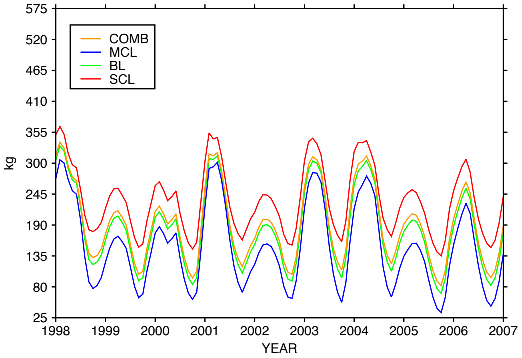
SOIL MOISTURE FINGERPRINTS & WUE

Broad Leaf Trees

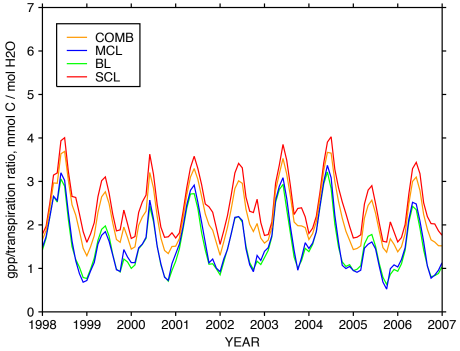
Available **SMC**
In 3 m soil column;
Spain

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

Available soil moisture content in 3m soil column, domain: SP



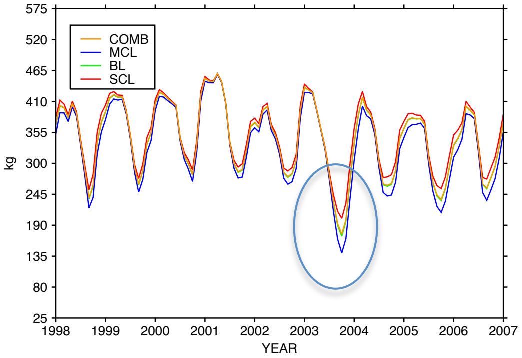
Transpiration efficiency for BLT, subdomain SP



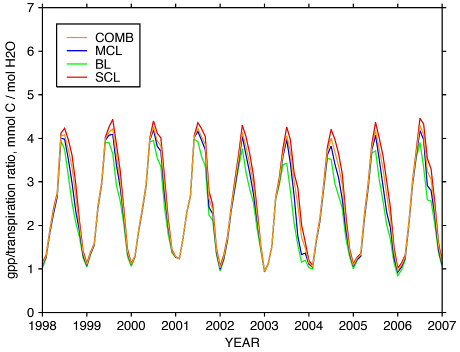
GPP/T ratio;
Spain

Available **SMC**
In 3 m soil column;
France

Available soil moisture content in 3m soil column, domain: FR



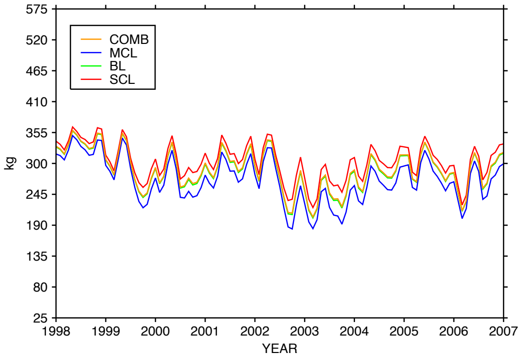
Transpiration efficiency for BLT, subdomain FR



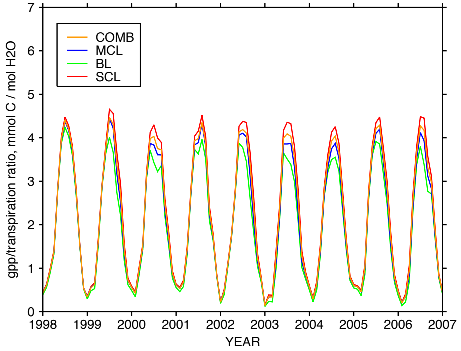
GPP/T ratio;
France

Available **SMC**
In 3 m soil column;
Eastern Europe

Available soil moisture content in 3m soil column, domain: EE



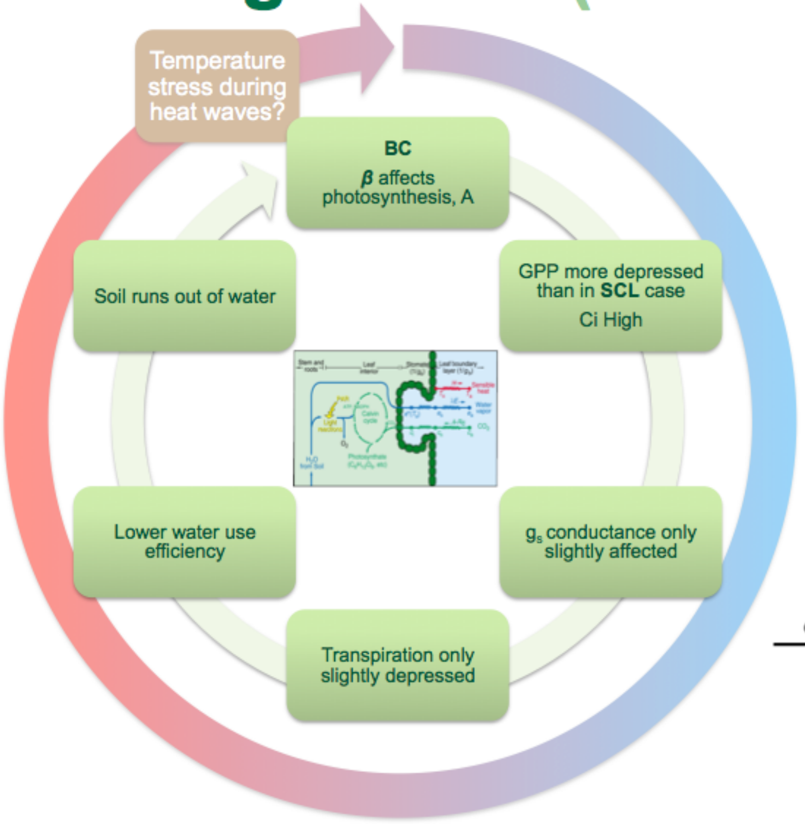
Transpiration efficiency for BLT, subdomain EE



GPP/T ratio;
Eastern Europe

SOIL-VEGETATION-ATMOSPHERIC FEEDBACKS

8. Soil-Vegetation-(atmospheric) feedbacks



Temperature stress during heat waves?

BC
β affects photosynthesis, A

GPP more depressed than in **SCL** case
Ci High

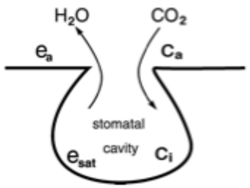
g_s conductance only slightly affected

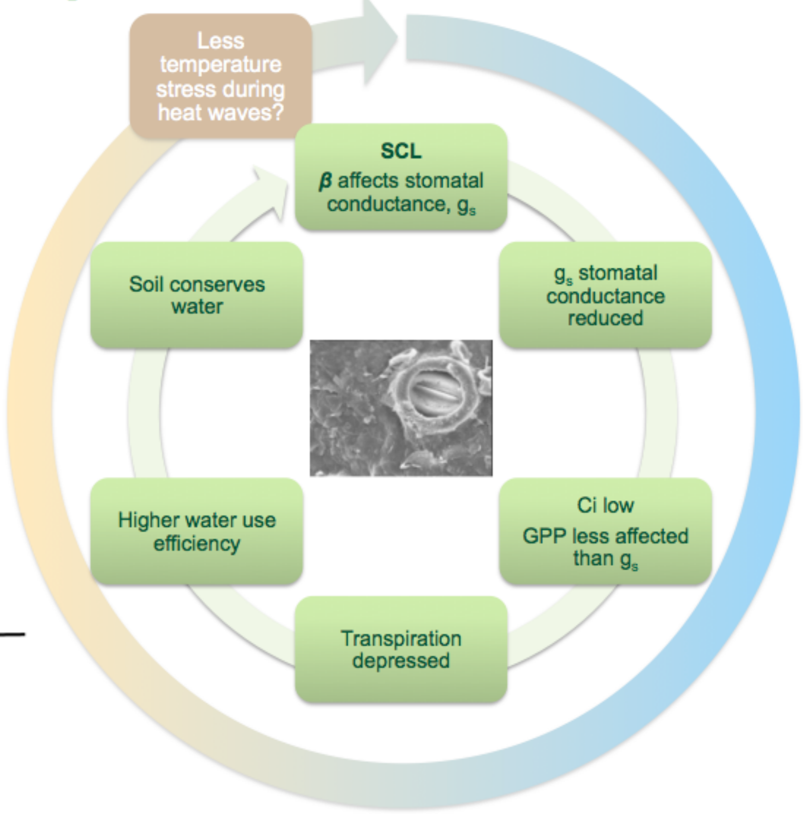
Transpiration only slightly depressed

Lower water use efficiency

Soil runs out of water

BL





Less temperature stress during heat waves?

SCL
β affects stomatal conductance, g_s

g_s stomatal conductance reduced

Ci low
GPP less affected than g_s

Transpiration depressed

Higher water use efficiency

Soil conserves water

SCL

CONCLUSIONS

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 β 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**.