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Coupling water and carbon cycle in the biosphere. / *Couplage du cycle de l'eau et du carbone dans la biosphère*

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Abstract

Coupling the carbon and water cycles in the biosphere is of first importance for understanding both the carbon cycle and the role of the biosphere in the climate system. In this paper we present such coupling between a land surface scheme SECHIBA and biogeochemical processes (e.g. photosynthesis). Two approaches are proposed : (1) coupling SECHIBA with an existing biogeochemical model FBM, and (2) make a new model based on SECHIBA. This second way appears to be more promising. Hence coupling between SECHIBA and FBM that have not been designed for this purpose introduce large problem of instability.

The SECHIBA was modified to include parameterization of photosynthesis and a new parameterization of stomatal conductance that takes into account the effect of atmospheric CO_2 on stomatal conductance. Validation with ground measurements gives satisfying results. Simulation with a doubled atmospheric CO_2 shows little effect on transpiration when CO_2 fertilization effect is important. But if this effect is limited for instance by nitrogen limitation, the decrease of transpiration becomes important.

Résumé

Couplage du cycle de l'eau et du carbone dans la biosphère

Le couplage entre cycle de carbone et cycle de l'eau dans la biosphère terrestre est très important pour comprendre son rôle dans le cycle du carbone et sur le système climatique. Cet article présente un tel couplage entre un schéma de surface (SECHIBA) et une paramétrisation de processus biogéochimiques (comme par exemple la photosynthèse). Deux approches sont proposées : (1) coupler SECHIBA avec un modèle existant (FBM) et (2) construire un nouveau modèle biogéochimique sur la base de SECHIBA. Cette deuxième approche semble plus prometteuse. En effet, le couplage entre deux modèles (SECHIBA et FBM) qui n'ont pas été conçus dans cette optique pose de gros problèmes d'instabilité.

SECHIBA a été modifié pour inclure une paramétrisation de la photosynthèse et de la conductance stomatique qui prenne en compte l'effet du CO_2 atmosphérique sur cette dernière. La comparaison à des mesures de terrain donne des résultats satisfaisants. Une simulation en doublement de CO_2 montre une influence faible sur le flux de transpiration lorsque l'effet de fertilisation est total. En revanche, la limitation de la transpiration devient nettement plus importante si l'on suppose que l'effet de fertilisation est limité par un manque d'azote par exemple.

COUPLING WATER AND CARBON CYCLE IN THE BIOSPHERE

Nicolas VIOVY¹ et Nathalie de NOBLET¹

ABSTRACT - Coupling the carbon and water cycles in the biosphere is of first importance for understanding both the carbon cycle and the role of the biosphere in the climate system. In this paper we present such coupling between a land surface scheme SECHIBA and biogeochemical processes (*e.g.* photosynthesis). Two approaches are proposed: (1) coupling SECHIBA with an existing biogeochemical model FBM, and (2) make a new model based on SECHIBA. This second way appears to be more promising. Hence coupling between SECHIBA and FBM that have not been designed for this purpose introduce large problem of instability.

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Carbon cycle, Hydrology, Terrestrial biosphere models

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Cycle du carbone, Hydrologie, Modèle de fonctionnement de la biosphère terrestre

INTRODUCTION

During the last decade, biosphere models have been developed in two different ways:

1. To study interactions between vegetation and atmosphere or to be used as boundary conditions for atmospheric general circulation models (AGCM), Soil Vegetation Atmosphere Transfer has been developed. Such models give a good description of physical processes such as the energetic or hydrological budget. However biological processes such as LAI development are prescribed or crudely modeled.

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2. On the other hand, biogeochemical models were developed to understand and describe the carbon cycle in the biosphere. With these models, biological processes are well represented but the water cycle is represented in a simplified way.

A new trend is to couple these two kind of models. Since water and carbon cycles are highly coupled.

In this paper we present a coupled SVAT model: SECHIBA used as land surface scheme of the LMD ACGM and biogeochemical process. To this end a two-step approach is proposed:

1. To evaluate the feasibility of a coupling between two existing models: SECHIBA, the land surface scheme developed by DUCOUDRE *et al.* (1993), and the Frankfurt Biosphere Model (FBM, JANACEK *et al.*, 1989). SECHIBA includes detailed parameterizations of the hydrological exchanges that occur at the biosphere / atmosphere interface, but has a rather crude representation of phenology. On the contrary, FBM has a complex description of the carbon cycle but a simplified calculation of hydrology. Our aim is to couple the two models, in collaboration with IPTC in Frankfurt, to improve both the simulation of water and carbon budgets.
2. To improve SECHIBA by including a mechanistically based parameterization of stomatal resistance that allows for exchanges of both carbon and water.

The two approaches are parallel.

I - COUPLING SECHIBA TO FBM

1. Brief description of the models

SECHIBA is the French acronym for « Schématisation des Echanges Hydriques à l'Interface Biosphère-Atmosphère ». It is a land-surface model that was developed for use within AGCMs. It calculates the fluxes of water, momentum and heat exchanged within the soil-plant-atmosphere continuum, as well as the water status of both soil and canopy and the temperature of the land-surface. Six climatic variables are required to force the model: surface air temperature (T_a), water vapor concentration deficit of the ambient air, incident short-wave (R_g) and long-wave radiations (R_{lw}) reaching the land, surface wind speed ($\bar{W}$) and incident rainfall (Pr). The time-step of the model can vary, depending on the sampling of the forcing, from a few minutes to a few hours.

FBM is a global process oriented model that calculates the seasonal patterns of uptake and release of CO_2 by vegetation and soil, and the resultant biomass and carbon budgets in both media. It is forced by T_a , R_g , Pr and soil moisture (SM). Because there is no global climatology of SM, FBM calculates, off-line, an annual cycle of daily soil moisture using a simplified model of hydrology forced by the given incident rainfall. For each biome represented in FBM some parameters were calibrated against mean ecological estimates of biomass, Net Primary Production (NPP) and annual respiration. The model runs with an hourly time-step but produces daily outputs. For a given climate FBM is run until an equilibrium is reached between NPP and litter production, within a given error bar.

2. Description of the coupling

A bidirectional pipe was then developed to allow the exchange of two variables between the models:

1. The Leaf Area Index (LAI) is calculated in FBM and is passed to SECHIBA through the pipe. In the standard version of SECHIBA, LAI is calculated using an empirical function of temperature, limited by prescribed minimum and maximum values. This variable is used for the calculation of canopy resistance, evapo-transpiration and interception of rainfall by the foliage.

2. The soil water content is calculated in SECHIBA and the pipe transmits it to FBM. Soil moisture is used in FBM to modulate the rate of photosynthetic activity. This is a rather major change for this model since, in its standard version, soil moisture is calculated off-line and once for all, that is it remains the same no matter how many iterations are needed for the model to reach its equilibrium. SM now varies from one integration to the other and, as will be discussed in the next subsection, this has some implications on the convergence criteria.

Both models are run with an hourly time step but LAI and SM are only exchanged daily, their variations being relatively slow with respect to the hour. Figure 1 displays the principle of this coupling.

Fig. 1- Principle of the SECHIBA-FBM coupling. Principe du couplage SECHIBA-FBM.

3. Preliminary results and comments

As a first test of this coupled model, we have chosen to concentrate ourselves on a specific site located in Germany and covered with temperate deciduous forest. Figure 2 displays the LAI and the soil water content simulated respectively by SECHIBA, FBM and the coupled model. The forcing climate is derived from the Atlas of SHEA (1986), and the time evolution of both incident rainfall and ambient air temperature is displayed on figure 3.

If we focus on the uncoupled models their major difference resides in: (1) the extreme values of the simulated leaf area index, and (2) the timing of the shooting and shedding phases.

In SECHIBA, the winter LAI value is about 2.5, while it is 0 in FBM. The minimum LAI value is prescribed to 1 in the former model for this particular biome, but the 2.5 value simulated points out that the relationship that has been chosen to link phenology to soil temperature in the root zone is certainly not appropriate. At winter time, such a deciduous forest has no more leaves! It is interesting to note though that the amplitude of the seasonal cycle of LAI is similar in both models. Regarding the timing of both the growing and the decay season, again the results simulated by SECHIBA look less realistic than the ones obtained with FBM. Moreover SECHIBA seems to regrow a few leaves in December, feature that is certainly not right. The total soil moisture computed looks quite similar in both models but we may note an earlier and more pronounced summer drying in

SECHIBA than in FBM, as well as a more rapid refill of the soil in autumn in the former. But for the two models, soil moisture depletion in summer seems rather drastic and early in season.

Soil moisture simulated by the coupled model does not vary much from the one calculated in SECHIBA, except that summer drying occurs a few days earlier. We would need some data to see whether this change is or not an improvement. On the other hand changes in the seasonal evolution of LAI are quite large. The maximum value of LAI decreases from 4 in FBM to 3 in the coupled model and we note a 20-day shift of the whole cycle (shooting and shedding phases). We are embarrassed at this point to say whether all these changes have improved the simulation or not, due to the lack of surface data. We will continue running the coupled model over some other locations, with different land-surface cover.

Fig. 2- LAI and soil water content simulated by SECHIBA, FBM and by the coupled SECHIBA/FBM model on a deciduous forest. LAI et contenu en eau du sol simulés par SECHIBA, le FBM et par le modèle couplé dans la cas d'une forêt caducifoliée.

Fig. 3- Air temperature and rainfall from climatology for the deciduous forest site. Température de l'air et pluviométrie sur le site de forêt.

To achieve the convergence of the coupled model though, we had to strongly enhance the critical value of the difference between annual NPP and litter production (*i.e.* the convergence criteria). As a matter of fact, when the initial value of $0.006 \text{ (kg C m}^{-2}\text{)}$ is kept, the only solution the model can find is to put vegetation to death. We had to give a value of 0.08 to this threshold (*i.e.* more than 13 times the value needed in FBM) for the model to

converge to the solution discussed above. These preliminary results have proved the feasibility of such coupling. Moreover it seems relatively difficult to extend this approach. Hence first there is not a direct coupling of cycles at stomata level which is the main process where coupling takes place, second because models are not designed to be coupled each others, The soil water calculated by SECHIBA introduce large instability in the FBM.

II - SECHIBA-BGC: A COUPLED SVAT-BGC MODEL

Up to now most land-surface models that have been implemented within atmospheric general circulation models (AGCMs) did not account for the exchanges of CO₂ between the biosphere and the atmosphere. Yet this problem is of importance because a change in atmospheric CO₂ can induce changes in vegetation functioning with direct effect on hydrology and Albedo, and consequently on climate. *Vice versa*, changes in soil water status can strongly influence vegetation production (WAELEBROECK, 1993). The international community has now realized the importance of coupling the hydrological and the carbon cycles and gave rise to the Regional Interactions of Climate and Ecosystems (RICE) IGBP/GAIM project.

Following this trend, we have decided to improve SECHIBA. Because stomata is the place where exchanges of both CO₂ and water vapor take place, we have chosen to replace the original parameterization of stomatal resistance, that is a function of incident solar radiation, water vapor concentration deficit of the ambient air and leaf area index (LAI), by a more sophisticated function based on the models developed by FARQUHAR *et al.* (1980) and BALL *et al.* (1987) (hereafter respectively FCS and BWB). FCS is a mechanistic model of photosynthesis for C₃ plants based on enzymes kinetics and electron transport properties. BWB is a semi-empirical model of stomatal conductance in response to humidity, CO₂ concentration and assimilation. Such models based on biochemical processes are very interesting because they allow for the study of the complex interactions between assimilation and transpiration. Recently SELLERS *et al.* (1992a) have used this approach to improve the SiB model.

1. The original parameterization of stomatal resistance

In the standard version of SECHIBA, canopy resistance is calculated using an empirical formulation derived by LOHAMMAR *et al.* (1980) from JARVIS (1976):

$$r_c = \frac{1}{LAI} \frac{I_0 + I_{hs}}{I_0} \frac{a + \lambda \delta_c}{k_0} \quad (1)$$

δ_c = water vapor concentration deficit of the ambient air (kg m⁻³)

I_0 = incoming solar radiation

I_{hs} = half light saturation factor (125 W m⁻²)

a, k_0, λ = constants that link δ_c to r_c

Even though the stomata aperture is not modulated by soil water, this variable influences canopy transpiration through the use of the so-called « surface relative humidity h_g » entering the calculation of the gradient of specific humidity between the land-surface and the overlying air (Δq_m).

An architectural resistance r_0 is added to r_c to account for (1) the attenuation of light and wind within the foliage, and (2) the gradient of specific humidity between the lower and the upper leaves. This additional resistance is an improvement to the « Big Leaf » approximation that is made in SECHIBA.

But this approach suffers from a number of shortcomings:

1. Stomatal conductance does not depend on CO₂, nor on temperature or nutrients availability, yet we know that those variables are not negligible.

2. As a consequence of the « Big Leaf » approximation, vegetation has no vertical dimension and the correction factor (r_0) is unable to reproduce with enough accuracy the effect of light attenuation within the canopy and of plant's resources optimization (e.g. nitrogen).

2. The new formulation of stomatal conductance

a) At the leaf level

BALL *et al.* (1987) have derived an empirical expression for stomatal conductance g_s ($\text{mol.m}^{-2}.\text{s}^{-1}$) as a function of assimilation A ($\mu\text{mol.m}^{-2}.\text{s}^{-1}$), atmospheric CO_2 concentration C_a (ppm) and relative humidity h_r (%) of the ambient air:

$$g_s = mA \frac{h_r}{C_a} + b \quad (2)$$

m and b are derived from laboratory measurements using C_3 species.

Photosynthesis is calculated from FARQUHAR *et al.* (1980):

$$A = V_c(1 - \Gamma^*/C_i) - R_d \quad (3)$$

V_c ($\mu\text{mol.m}^{-2}.\text{s}^{-1}$) is the rate of carboxylation, Γ^* (ppm) the CO_2 compensation point in absence of non-photo-respiratory respiration, R_d ($\mu\text{mol.m}^{-2}.\text{s}^{-1}$) the rate of non-photorespiratory respiration and C_i the CO_2 concentration at the carboxylation site.

The rate of carboxylation is expressed as the more limiting factor of Rubisco activity, W_c , and RuBP regeneration, W_j ($\mu\text{mol.m}^{-2}.\text{s}^{-1}$):

$$V_c = \min(W_c, W_j) \quad (4)$$

The Rubisco-limited rate is given by:

$$W_c = \frac{V_{cmax} C_i}{C_i + K_c(1 + O_i / K_o)} \quad (5)$$

V_{cmax} ($\mu\text{mol.m}^{-2}.\text{s}^{-1}$) is the maximum rate of RuBP carboxylation, K_c and K_o are the Michaelis-Menten constants for enzyme catalytic activity for CO_2 and O_2 respectively, and O_i is the intercellular concentration of oxygen.

The RuBP-regeneration-limited rate is defined by:

$$W_j = \frac{V_j}{1 + 2\Gamma^*/C_i} \quad (6)$$

V_j is the potential rate of RuBP regeneration. It depends on the incident photon flux Q . V_j can be empirically described using a non-rectangular hyperbola:

$$V_j = \frac{1}{2\Theta} \left[\alpha_j Q + V_{jmax} - \sqrt{(\alpha_j Q + V_{jmax})^2 - 4\Theta \alpha_j Q V_{jmax}} \right] \quad (7)$$

α_j is the quantum yield of RuBP regeneration, V_{jmax} the maximum potential rate of RuBP regeneration at quantum-saturation and Θ the curvature of the quantum response. Equation (2) gives the stomatal conductance g_s as a function of assimilation A . Equation (3) gives A as a function of C_i . A third equation can be expressed that relates assimilation and stomatal conductance to the gradient of CO_2 between the atmosphere and the carboxylation site:

$$A = g_s(C_a - C_i) / 1.6 \quad (8)$$

The value of 1.6 represents the ratio of water vapor diffusivity to the diffusivity of CO_2 .

The system formed by equations 2, 3, 8 is solved using a simple iterative method that converges very rapidly in most cases.

The effect water stress

There have been so far very few studies of the effect of water stress on stomatal aperture. But it is well known that if soil moisture decreases, stomatal resistance will increase because of the subsequent decrease of leaf water potential or of chemical mediators such as abscisic acid (WILLMER, 1988; ZHANG and DAVIES, 1989). When the water stress becomes important it can also affect directly photosynthesis (FARQUHAR and SHARKEY, 1982). In the model, we will not consider the problem of chemical mediators. A moisture stress factor γ_w (comprised between 0 and 1) is introduced in equation (2):

$$g_s = mA\gamma_w \frac{h_s}{C_a} + b \quad (9)$$

γ_w is defined after McMURTRIE *et al.* (1960):

$$\gamma_w = \begin{cases} 1 & \text{if } f_w > f_{w1} \\ 1 - \frac{f_w - f_{w0}}{f_{w1} - f_{w0}} & \text{if } f_{w0} < f_w < f_{w1} \\ 0 & \text{if } f_w < f_{w0} \end{cases} \quad (10)$$

f_w is the water fraction available for the plant in the root zone; $f_{w0} = 0.028$ and $f_{w1} = 0.5$ are the soil water fractions inducing respectively closure and maximum opening of the stomata.

b) At the canopy level

Calculation of the equivalent stomatal conductance at the canopy level, g_c ($g_c = 1/r_c$), requires the integration of g_s over the depth of the canopy, that is over the leaf area index (LAI):

$$g_c = \int_0^{LAI} g_s(l) dl \quad (11)$$

Similarly we can integrate the assimilation rate ($A_c = \int_0^{LAI} A(l) dl$).

And, for the sake of simplification, we assume there is no gradient of humidity nor of CO_2 within the canopy. $A(l)$ is expressed, through V_{cmax} and V_{jmax} following the Beer's law of attenuation, as for light within the canopy (MONSI and SAEKI, 1953; FIELD, 1983; FIELD and MOONEY, 1986; FARQUHAR, 1989; SELLERS *et al.*, 1992a).

$$V_{cmax}(l) = V_{cmax}^0 e^{-kl}, \quad V_{jmax}(l) = V_{jmax}^0 e^{-kl} \quad (12)$$

l is the cumulated LAI and k the attenuation coefficient.

3. Validation for a tropical forest site (ARME site) and a C_4 grassland (FIFE)

To validate SECHIBA-BGC we have used two sets of data obtained from two regional experiments: ARME (SHUTTLEWORTH, 1988; SHUTTLEWORTH *et al.*, 1984a) in 1984 on a tropical evergreen forest and FIFE (SELLERS *et al.*, 1988; SELLERS *et al.*, 1992b; SELLERS and HALL, 1992) in 1987-1989 on a C_4 grassland. These two sites represent very different ecosystems, which is very interesting for several reasons:

- It will validate both the parameterization of C_3 and C_4 models of photosynthesis.
- Tropical forest has a high LAI. It will then be a good way to test the parameterization of light and photosynthetic rate decrease into the canopy.

•The C_4 grassland on the other hand has a great limitation of water which will allow testing of water stress parameterization.

a) Validation on the tropical forest site

Fig. 4- Simulated and observed daily stomatal conductance course at the top of the canopy at Ducke. Cycle diurne de la conductance stomatique au sommet de la canopée sur le site de Ducke.

Fig. 5- Simulated daily stomatal resistance with the old and new parameterization at Ducke. Conductance stomatique journalière simulée avec l'ancienne et la nouvelle paramétrisation à Ducke.

The canopy (or equivalent stomatal) resistance simulated by SECHIBA-BGC (hereafter S350) agrees well with the field measurements of SHUTTLEWORTH *et al.* (1984b) and DOLMAN *et al.* (1991). In particular we simulate correctly the decrease of conductance into the canopy. The daily mean stomatal resistance simulated by both SECHIBA (hereafter sold) and SECHIBA-BGC are very similar but the daily course is very different. In S350 there is an important diurnal variation as it was observed by ROBERTS *et al.* (1990) (fig. 4), while in sold there is very little variation of r_c throughout the day (fig. 5).

For the grassland site simulation of SECHIBA-BGC both latent heat flux and assimilation agree well with measurements (fig. 6, 7).

Fig. 6- Simulated vs observed hourly evapotranspiration for FIFE. Comparaison modèle/mesure de l'évapotranspiration pour FIFE.

b) Doubled CO_2 experiments

Since this new version of SECHIBA was developed to allow for some scenarios of climate change, we have carried out a doubled CO_2 experiment. In the first one (hereafter S700) we assume there is no limitation to the CO_2 fertilization effect. In the second one (hereafter S700Nlim) we introduce an indirect limitation by halving the ratio of carboxylation to regeneration. This simulates the limitation that can be caused by a deficit in soil nitrogen (MCMURTRIE *et al.*, 1990).

The table displays some annual results obtained for two different types of land-surface: the tropical evergreen forest site already presented in the previous subsection, and a grassland site located in the Netherlands for which the climatic data were provided within the framework of PILPS (Project of Intercomparison of Land-surface Parameterization Schemes).

Fig. 7- *Simulated vs observed net CO₂ fluxes. Comparaison modèle/mesure du flux net de CO₂.*

Table - *Annual changes in the simulated GPP and ETR when doubling CO₂ with and without fertilization effect. Changement de la production primaire brute et de l'évapotranspiration en cas de doublement de CO₂ avec ou sans limitation de l'effet de fertilisation.*

Simulations	Tropical forest	Grassland
<i>1. Increase of GPP</i>		
S700 - S350	+61 %	+44 %
S700Nlim - S350	+9 %	+8 %
S700Nlim - S700	+49 %	+19 %
<i>2. Decrease of ETR</i>		
S700 - S350	-6 %	-7 %
S700Nlim - S350	-22 %	-7 %
S700Nlim - S700	-17 %	-2 %

Tropical forest

Doubling CO₂ with no limitation of its fertilization effect results in an increased annual photosynthetic activity of about 61%, and a consequent decrease of stomatal conductance (22.5%). The resulting transpiration rate is also lower in S700 than in S350 (-11%). When a limitation effect due to nitrogen is introduced, stomatal resistance increases much more (+61% in S700Nlim when compared to S350), inducing a larger decrease in the rate of transpiration (-38%) but an almost unchanged gross primary production (+9%). CO₂ fertilization effect can therefore be very strongly cut off by the impoverishment of soils.

In both runs total evapotranspiration, calculated as the sum of transpiration, interception loss and evaporation of soil water, decreases less than transpiration alone. This is because, as plants extract less water from the soil, the soil resistance to evaporation decreases, surface relative humidity increases and so does the evaporation of

soil water. The partitioning of evapotranspiration between canopy and soil therefore changes: in S350 transpiration represents 75% of the total water flux whereas in S700Nlim it accounts for only 50%.

Grassland

The total annual evapotranspiration (ETR) does not change much for this grassland site, contrary to what we obtained for tropical evergreen forest. However the seasonal evolution of ETR is very different (fig. 8) from one simulation to the other. In S700 and S700Nlim, ETR is reduced in Spring and Autumn, enlarged in summer when compared to S350. The seasonal contrast is then reduced when CO_2 is doubled.

Fig. 8- Monthly mean of ETR and assimilation over grassland for S350, S700 and S700Nlim. Moyennes mensuelles de l'ETR et de l'assimilation sur la prairie pour S350 S700 et S700Nlim.

SUMMARY AND CONCLUSION

The coupling between SECHIBA and FBM seems to be difficult to achieve since models have been designed separately and great problems of stability of the two models occurred.

The second approach which consists in developing the biogeochemical model directly from SECHIBA appears to be more promising. In SECHIBA-BGC:

- We now consider both exchanges of water vapor and CO_2 . Furthermore the stomatal conductance depends directly on assimilation and thus it varies not only with light but also with all factors influencing photosynthesis (e.g. nutrients, temperature, water stress).

- Stomatal conductance is explicitly integrated over the depth of the canopy and we can avoid the use of artificial parameters such as the architectural resistance that is used in the standard version of SECHIBA.

- Two more variables are now simulated and can be compared to available measurements: the gross primary production and the intercellular CO_2 concentration.

The improvements brought by this new parameterization of stomatal conductance (g_c) appear clearly in the simulation carried on for the tropical evergreen forest and grassland site. Both the seasonal and the diurnal cycles of g_c agree with the measurements. It should be noted that the parameters of BALL and FARQUHAR have been calibrated independently.

When CO_2 is doubled, and there is no limitation of its fertilization effect, changes in evapotranspiration are small because the photosynthetic activity has not yet reached its saturation value, and the stomata stay quite opened. When we prescribe a limitation of the CO_2 fertilization effect by some nutrients such as nitrogen, the stomatal closure becomes important. In this case, we get a sensible decrease in plant transpiration. Changes in the hydrological cycle are quite different from one vegetation type to the other. For the tropical evergreen forest we get a relatively constant decrease of ETR throughout the year, while for grassland the seasonal variation of ETR is modified but not so much its annual value.

We must note that there is no feedback to the atmosphere, that is the changes we simulate do not affect the climate variables that are prescribed to their present-day values in all simulations.

We expect that, if this model was implemented in a climate model, the decreased ETR in case of a doubling CO_2 will reduce the relative humidity of the ambient air, and therefore induce a further closure of the stomata. We therefore imagine a positive feedback. Moreover we must say that some inconsistencies remain in the model regarding the time evolution of leaf area index: LAI is still calculated as in the standard version of SECHIBA, and there is therefore no link between assimilation and phenology which, obviously, has to be corrected.

Such study though demonstrates the impact of coupling both cycles of water vapor and carbon on the simulated surface hydrological cycle and points out to the necessity of improving the land surface schemes used within AGCMs. It also demonstrates that because of the complex interactions between the hydrologic and carbon cycle, the change in stomatal conductance with increasing atmospheric CO_2 cannot be prescribed (for instance with a doubled stomatal resistance) and is strongly dependent of the ecosystem.

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