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A SIMPLE POTENTIAL VEGETATION MODEL FOR COUPLING WITH THE SIMPLE BIOSPHERE MODEL (SIB)

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RESUMO

Elaborou-se um modelo de vegetação potencial (i.e., um modelo que diagnostica o bioma em equilíbrio com um dado clima) capaz de reproduzir a distribuição global dos principais biomas e, em escala regional, o mapa de vegetação da América do Sul. A partir da climatologia mensal de precipitação e temperatura do ar à superfície, obtém-se um conjunto de variáveis ambientais: tempo térmico acumulado, temperatura média do mês mais frio e dois índices, um para diferenciar climas quentes de frios e outro para representar a sazonalidade do armazenamento de água do solo. Dado o conjunto de variáveis ambientais, o modelo gera como saída um bioma que pertence à classificação de vegetação utilizada pelo modelo de superfície SiB (ou SSiB). Para calcular os índices, elaborou-se um modelo de balanço hídrico simples, que considera o congelamento do solo e calcula a evapotranspiração real através da formulação de Penman-Monteith. O modelo de balanço hídrico consegue reproduzir a distribuição global de água do solo. Por comparação visual, nota-se que o modelo de vegetação potencial, chamado de CPTEC PVM, conseguiu reproduzir o padrão global dos principais biomas. Na América do Sul, o modelo foi capaz de reproduzir a vegetação dos Pampas e evita a substituição de caatinga por savanas. Uma análise objetiva mostrou que o desempenho do modelo, em escala global, é muito bom para floresta tropical e deserto; bom para floresta de coníferas, savana, semi-deserto e tundra; regular para floresta temperada, campos e caatinga; e ruim para floresta mista. Em geral, o desempenho do CPTEC PVM é comparável ao apresentado por outros modelos atualmente utilizados em estudos climáticos. Esse bom desempenho motiva o acoplamento do CPTEC PVM a modelos atmosféricos que utilizem o SiB (ou SSiB) como seu esquema de superfície.
Palavras-chave: bioma, modelo de vegetação potencial, modelo de vegetação dinâmica, SiB.

ABSTRACT: A SIMPLE POTENTIAL VEGETATION MODEL FOR COUPLING WITH THE SIMPLE BIOSPHERE MODEL (SIB)
A simple potential vegetation model (i.e., a model which diagnoses the biome in equilibrium with a given climate) was developed. Given a set of environmental variables derived from climatologies of monthly mean surface temperature and precipitation - namely, growing degree-days, temperature of the coldest month and two moisture indices (one to distinguish between wet and dry climates and the other to represent soil moisture seasonality) - the model outputs a biome of the vegetation classification used in SiB (or SSiB) land surface scheme. A water balance model - which includes the possibility of soil water freezing and evaluates the actual evapotranspiration using the Penman-Monteith formulation - was developed to calculate the two moisture indices. The water balance model produces a consistent global distribution of soil moisture. The potential vegetation model, named CPTEC PVM, was able to represent the global biome patterns. On a regional level in South America, the model was able to reproduce the Pampas grasslands and avoid the replacement of caatinga by savannas in Northeast Brazil. Objective analysis for each biome revealed a very good agreement for tropical forests and deserts; good agreement for conifer forests, savannas, semi-deserts and tundra; regular agreement for temperate forest, grasslands and caatinga vegetation; and poor agreement for mixed forest. In general, the model skill is comparable to other potential vegetation models currently in use for climate studies. The good skill showed by CPTEC PVM motivates its coupling to AGCM's that use SiB (or SSiB) as its land surface model to create a dynamic vegetation model.
Key words: biome, potential vegetation model, dynamic vegetation model, SiB.

1. INTRODUCTION

The relatively well-known relationship between the global distribution of vegetation types - the biomes - and the climate can be expressed in a quantitative manner by potential vegetation models (PVM's). A PVM diagnoses the biome in equilibrium with a given climate. Since climate is not the only factor that determines the vegetation type (other factors, such as topography, soil type, nutrient shortage, fire occurrence and various disturbances, CO_2 concentration, etc. also influence the vegetation distribution), there are differences between the spatial distribution of potential (i.e., output of PVM's) and natural vegetation (or native vegetation, i.e., without anthropogenic land cover changes). However, there is a reasonable correspondence between the global distribution of potential and natural biomes for large spatial scales. This is the reason why PVM's are used in climate studies. Numerous PVM's are found in the literature (e.g., BIOME of Prentice et al., 1992; BIOME3 of Haxeltine and Prentice, 1996; MAPSS of Neilson, 1995; Brovkin et al., 1997, etc.).

The simplest way to allow for bidirectional dynamic vegetation interactions in climate models consists of asynchronous coupling of a PVM to an Atmospheric General Circulation Model (AGCM). For a given global vegetation distribution, the AGCM is run for a few years without changing the vegetation distribution; then, using the climatology generated by the AGCM integration as input for the PVM, the vegetation distribution is updated. Keeping this updated vegetation distribution fixed, the AGCM is rerun, and so on. This procedure, albeit simple, has been used in several climate studies (i.e., paleoclimate studies, global change assessments, etc.) over the last decade (Foley et al., 2000).

The vegetation classification used by AGCM land surface models and PVM's may be different. For instance, the Simple Biosphere Model (SiB, Sellers et al., 1986) or the Simplified SiB (SSiB, Xue et al., 1991) uses the vegetation classification proposed by Dorman and Sellers (1989, hereafter referred to as DS89). Even though SiB (or SSiB) has been implemented in several AGCM's (e.g., COLA, CPTEC; see Sato et al., 1989), none of the existing PVM's uses the DS89 vegetation classification. To overcome this problem, one strategy is to develop a procedure that relates the biomes of an already existent PVM to the DS89 biomes. However, since the conversion procedure acts as an additional source of errors, a different strategy must be sought. To attain the best possible results, we developed a new PVM that relates climate variables to the biomes belonging to DS89 vegetation classification. This new PVM can be directly coupled to SiB (or SSiB). This strategy takes into consideration that ultimately we want to couple a PVM to CPTEC/COLA AGCM (Cavalcanti et al., 2002) to create a dynamic vegetation AGCM, with a particular goal to study past, present and future biome-climate interactions focusing on South America.

PVM skill may refer to two different scales. On a global scale, skillful prediction means that the global biome patterns are reproduced. Skillful prediction has been attained by current PVM's (e.g., BIOME). On a regional scale, however, these PVM's show some deficiencies. For instance, for South America, the BIOME PVM, which has been widely used in climate studies (e.g., Claussen, 1997), does not reproduce the grasslands in the Pampas (southern Brazil, eastern Argentina and Uruguay) and underestimates the caatinga (xerophytic woods/shrub in BIOME, broadleaf shrubs with perennial groundcover in DS89) area in Northeast Brazil (NEB). The same problems are found in BIOME3, which is an upgrade of BIOME (BIOME3 includes carbon cycling; however, in spite of this improvement, BIOME3 skill for savannas is poorer than its predecessor, BIOME). In the Pampas, due to its humid climate, grasslands are replaced by forests. In NEB, except in the driest region, caatinga is replaced by savannas. The behavior in NEB is particularly sensitive on how the transition between savannas and caatinga is defined. These two problems may happen in any PVM, and are addressed in this work, given the intended goal of developing a PVM that, albeit global in extent, puts special emphasis in reproducing the biomes of South America.

Summing up, the objectives of this work are twofold: firstly, to develop a new PVM that uses the DS89 vegetation classification, thus allowing dynamic vegetation for AGCM's that use SiB (or SSiB) as land surface model; secondly, while attaining a skillful representation of biomes on a global scale, to overcome two PVM deficiencies in South America, namely, in the Pampas, the replacement of grasslands by forests; and, in NEB, the replacement of caatinga by savannas. We will attempt to develop a simple PVM, that is, a model that can be forced by readily available monthly mean climate data and that uses as few climate parameters as possible.

2. CLIMATE DATA AND SIMPLE WATER BALANCE MODEL

2.1. Natural vegetation map

The DS89 vegetation classification - which is based on Kuchler's vegetation categories (e.g., Kuchler, 1988) - is shown in Table 1. For each biome, there is a set of physical, morphological and physiological parameters that are used by SiB (or SSiB). Biome 12 refers to agriculture land use (winter wheat) and is not used in this work. The third column contains shorthand names that are used throughout this work.

The natural vegetation map, i.e., vegetation without anthropogenic land cover changes, builds on DS89. The DS89 map has been used for CPTEC/COLA AGCM climate simulations. To correct some deficiencies found in DS89 - e.g., lack of Atlantic tropical forest (tropical forests that cover the coast and southern part of Brazil), the Pampas grassland in Brazil, the Patagonia semi-desert in Argentina, excess of semi-deserts in Sahara, etc. - other maps (Eyre, 1968; Matthews, 1983; Defries and Townshend, 1994; IBGE, 1993) are used. The correspondence between Matthews and DS89 vegetation classification follows Sellers et al. (1994). The final natural

vegetation map is shown in Fig. 7a.

2.2. Climate data

The precipitation and surface air temperature monthly climatology are obtained from Willmott and Matsuura (1998). The data, originally on a 0.5° resolution, are degraded to the vegetation maps (both natural and potential) resolution, which is about 2°.

2.3. Water balance model

The water balance model is based on Willmott et al. (1985, hereafter referred to as W85). The main differences between the present model and W85 are:

- possibility of soil freezing;
- actual evapotranspiration calculated by Penman-Monteith equation (instead of Thornthwaite's).

The water balance model is used to calculate water-related input quantities for the PVM.

2.3.1. Formulation

The water balance is evaluated over an homogeneous soil layer covered by a single type of vegetation (short grass). Different soil and vegetation types are not considered. Even though this assumption seems unrealistic, it is usually assumed by water balance models for the sake of simplicity. The soil water availability (S_{max}) is 500 mm. This value is much larger than the values found in the literature; for instance, Mintz and Serafini (1992) adopt 150 mm, which is rather low for tropical forests. For central Amazonia, Hodnett et al. (1996) show that, during the dry season, vegetation extracts soil water from depths larger than 2 m. A soil water availability of 500 mm is adopted in order to attain a better (albeit not ideal) representation for biomes (like tropical forests) which extract soil water from deeper layers. However, this choice overestimates the soil water availability for biomes with shallow root zone.

The model evaluates the soil water and snow budgets separately. The budget equations are:

$$\frac{dS}{dt} = P_r - E - R + M \tag{1}$$

$$\frac{dN}{dt} = P_s - M \tag{2}$$

where S is soil water storage; P_r, rainfall; E, actual evapotranspiration; R, runoff; M, snowmelt; N, overland snow storage; and P_s, snowfall. Eqs 1-2 are coupled by snowmelt (M).

Precipitation is in the form of rain (P_r) or snow (P_s) according to the monthly temperature (T):

$$P = \begin{cases} P_r, & T \geq -1^\circ\mathrm{C} \\ P_s, & T < -1^\circ\mathrm{C} \end{cases} \tag{3}$$

and snowmelt (M, mm day^{-1}) is parameterised as function of monthly temperature (T, °C) and rainfall (P_r, mm day^{-1}):

$$M = 2.63 + 2.55\ T + 0.0912\ T P_r \tag{4}$$

Eqs 1-4 follow W85.

The monthly soil temperature (T_s) is calculated

biome	description	shorthand name
1	broadleaf-evergreen trees	tropical forest
2	broadleaf-deciduous trees	temperate forest*
3	broadleaf and needleleaf trees	mixed forest
4	needleleaf-evergreen trees	boreal forest
5	needleleaf-deciduous trees	larch
6	broadleaf trees with groundcover	savanna
7	groundcover only (prairie, steppes)	grasslands
8	broadleaf shrubs with perennial groundcover	caatinga
9	broadleaf shrubs with bare soil	semi-desert
10	dwarf trees and shrubs with groundcover	tundra
11	bare soil	desert
13	ice	ice

*Includes not only the extratropical temperate forests, but also the tropical deciduous and semi-evergreen forests.

Table 1: Dorman and Sellers (1989) vegetation classification.

from:

$$\frac{dT_s}{dt} = -\frac{T_s - T}{\tau} \tag{5}$$

where τ is the system equilibrium timescale. We assume a constant value of 15 days for τ. This value is obtained using a constant global average of 4×10^{-7} m^2 s^{-1} for soil thermal diffusivity (Garrat, 1992) and a damping depth of 1 m.

When soil freezes, infiltration ceases and soil water becomes unavailable. An observed fact is that soil freezing occurs at temperatures well below 0ºC. Simple soil freezing parameterizations, for instance, Viterbo et al. (1999) and Slatter et al. (1998), consider a gradual freezing between 0 or 1ºC (no freezing), and -3 or -4ºC (total freezing). We follow an even simpler criterion: if the monthly soil temperature is below -2.5ºC, then the soil is totally frozen; otherwise, there is no freezing. For permafrost regions, the water balance model estimates that the number of months with frozen soil is greater than 6 (not shown). This result agrees with observations.

The actual evapotranspiration (E) is evaluated by the Penman-Monteith equation:

$$\lambda E = \frac{\Delta}{\Delta + \bar{\gamma}} AE + \frac{\rho c_p}{r_a} \frac{e_{s,T}(1-h)}{\Delta + \bar{\gamma}} \tag{6}$$

$$\Delta = \frac{de_{s,T}}{dT}; \quad \bar{\gamma} = \gamma \frac{r_a + r_c}{r_a}; \quad \gamma = \frac{pc_p}{L\varepsilon} \tag{7}$$

where L is the latent heat of vaporization; AE, available energy (net radiation minus soil heat flux); ρ, air density; $e_{s,T}$, saturation partial pressure of water vapour at temperature T; h, relative humidity; r_a and r_c, aerodynamic and canopy resistances, respectively; p, surface pressure; c_p, specific heat of air at constant pressure; and ε is a constant (= 0.622).

The available energy (AE, W m^{-2}) is calculated as a linear function of the monthly surface air temperature (T, ºC):

$$AE = 2.265\ T + 67.588 \tag{8}$$

and the coefficients are adjusted using the net radiation (it is used since, on monthly timescale, the soil heat flux can, in general, be neglected - exceptions for this assumption are restricted to regions where colder biomes, such as boreal forest, larch and tundra, take place) and surface air temperature monthly data of the CPTEC/COLA AGCM climatic run (Cavalcanti et al., 2002). The coefficient of determination (r^2) of Eq. 8 is about 85%.

The surface relative humidity is assumed as constant, equal to 60%. This value may be regarded as the observed annual average of relative humidity over land surfaces (Peixoto and Oort, 1992). The canopy resistance (r_c) is given by:

$$r_c = \frac{r_{c,\min}}{f_\delta f_w}; \quad f_\delta = 1 - C_1 \delta e; \quad f_w = \frac{1 - e^{-C_2 w}}{1 - e^{-C_2}}; \quad w = \frac{S}{S_{\max}} \tag{9}$$

where $r_{c,min}$ is the minimum canopy resistance; f_δ and f_w, stress factors due to water vapour deficit (δe) and soil water degree of saturation (w, ratio between soil water storage, S, and soil water availability, S_{max}), respectively; and C_1 and C_2, constants. The expression for f_δ follows Sellers et al. (1986). The value of C_1 (= 0.0275 hPa^{-1}) is an average of all values (for different biomes) proposed by DS89. The expression for f_w and the value of C_2 (= 1.7) follows Cox et al. (1998). The aerodynamic resistance (r_a) is assumed as constant (= 100 s m^{-1}), and the minimum canopy resistance ($r_{c,min}$) is assumed as equal to the aerodynamic resistance.

We shall define actual evapotranspiration (E) when both stress factors, f_δ and f_w, are taken into account; potential evapotranspiration (EP) when only f_δ is considered (i.e., $f_w = 1$); and maximum evapotranspiration (E_{max}) when both stress factors are not considered (i.e., $f_\delta = f_w = 1$). Comparing the present formulation of EP with Thornthwaite's formulation (Fig. 1), which is widely used in water balance models, one can notice that two problems inherent to Thornthwaite's formulation - namely, the high sensitivity of EP with respect to temperature between 20 and 30ºC, and the supression of EP below 0ºC - are remedied. Besides, E_{max} of the present formulation follows the same behaviour of the relationship between the highest values of annual precipitation (P_{max}) and average temperature (the relationship, obtained from the climate data described earlier, is $P_{max} \sim 1.5\, e^{T/20}$, P_{max} in mm day^{-1} and T in ºC). In both formulations, for temperatures greater than 35ºC, EP decreases due to f_δ.

The large sensitivity of EP with respect to temperature between 20 and 30ºC, which is found in Thornthwaite's formulation, is undesirable. In the tropical belt, there is little seasonality of surface air temperature. For illustration purposes, consider two regions in which the annual average temperature ranges between 25 and 30ºC. For the sake of simplicity, further suppose that the surface air temperature in both regions does not change throughout the year (no seasonality). Small temperature differences between these two regions, for the same annual precipitation, would lead to completely different values of soil water storage if EP is very sensititive to temperature. Therefore, from the PVM viewpoint, an artificial biome change would take place between these two regions due to this extreme sensitivity.

For temperate climates, the existence of a non-null EP even for temperatures below 0ºC is fairly important. It is clear that for temperatures well below 0ºC there is no EP since soil is frozen - f_w is zero, which suppresses evapotranspiration. In temperate regions, where seasonality is high, winter temperatures well below 0ºC are found. Therefore, a more precise formulation of EP for temperatures around 0ºC allows the calculation of a more realistic soil water balance in the transition seasons between summer and winter (and vice

rsa).

Runoff (R, mm day^{-1}) is evaluated following Candido al. (2001):

$$= aw^b ; \; a = 38 ; \; b = 11 \qquad (10)$$

The high value of b indicates that runoff takes place ly for high values of w (i.e., close to saturation). Besides, prevents soil water from attaining supersaturation (which is ysically unrealistic).

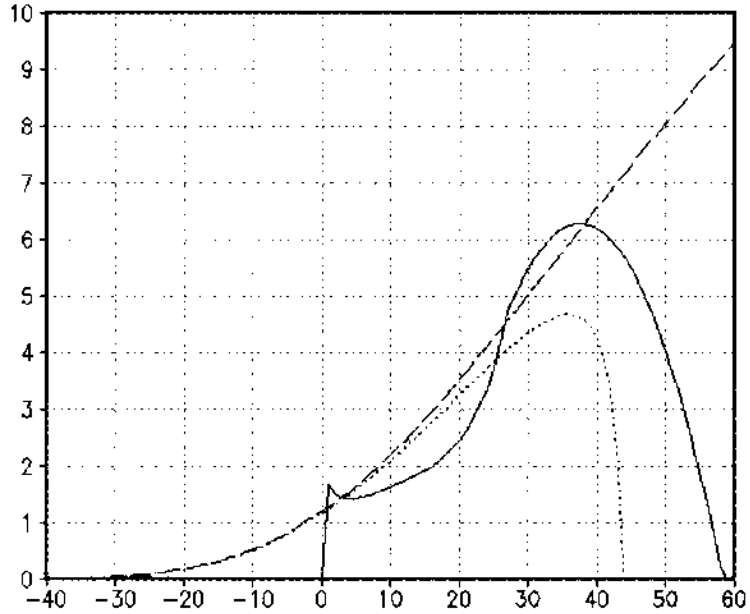
The model is run with a timestep of 1 day. The nthly precipitation is uniformly distributed over all days the month, even though this procedure decreases runoff and creases evapotranspiration. For a given month, firstly, the soil mperature is calculated; then, the water balance is calculated plicitly on a daily basis. When forced by climatological lues, the model is run until the seasonal cycle difference tween successive years is close to zero.

3.2. Comparison with W85

Forced by the monthly climatological values of ecipitation and surface air temperature, the water balance odel is run for several years (until equilibrium is reached). e model skill is evaluated by comparison of the simulated il moisture with W85. On a global level, we regard the soil oisture distribution simulated by W85 as representative of e actual values. Our water balance model, which is based W85, aims at improving specific features of W85 (for stance, correcting the large sensitivity of EP with respect to mperature between 20 and 30°C).

In ice-covered regions, soil is saturated in W85 and dry (since soil is frozen) in the present model. Since this difference may affect the evaluation of the model skill, the latitude range is restricted to avoid including permanently ice-covered regions. Only land areas within 60°S and 70°N are taken into account for the analysis.

In general, there is good agreement between the annual average degree of saturation (ratio between actual and saturation volumetric soil moisture content) calculated by the model and W85 (Fig. 2). The model is able to reproduce the large scale wet and dry regions shown in W85. In terms of magnitude, the greatest differences (Figs 2c and 3) take place in wet regions, where the model produces lower soil moisture content than W85. This may be related to the model's runoff parameterization, which avoids high values of soil moisture. For most parts of the world, the magnitude of the annual average differences is less than 0.1 (i.e., 10% degree of saturation). Throughout the year, the linear correlation between the model's monthly degree of saturation and W85 is about 0.80 (Fig. 4), and this value shows a small seasonal variation. Thus, model skill is not affected by seasonality. On a regional level, for Amazonia (70°W-50°W, 10°S-Equator, wet climate) and Northeast Brazil (45°W-40°W, 15°S-5°S, dry climate), even though the model underestimates the magnitude, the phase of the seasonal behaviour shows a good agreement with W85 (Figs 5a and 5b, respectively). The less pronounced seasonal change - of about 150 to 200 mm - seems to be more realistic for Amazonia. For Manaus (central Amazonia), Hodnett et al. (1996) recorded a maximum seasonal change of 154 mm in the upper 2 m soil. A more comprehensive validation procedure will be addressed in future work.



gure 1: Potencial (EP) and maximum (E_{max}) evapotranspiration as function of the temperature for Penman-Monteith (EP and $_{ax}$) and Thornthwaite (EP) formulations. Solid line: Thornthwaite, EP; dashed line: Penman-Monteith, E_{max}; dotted line: Penman-onteith, EP.

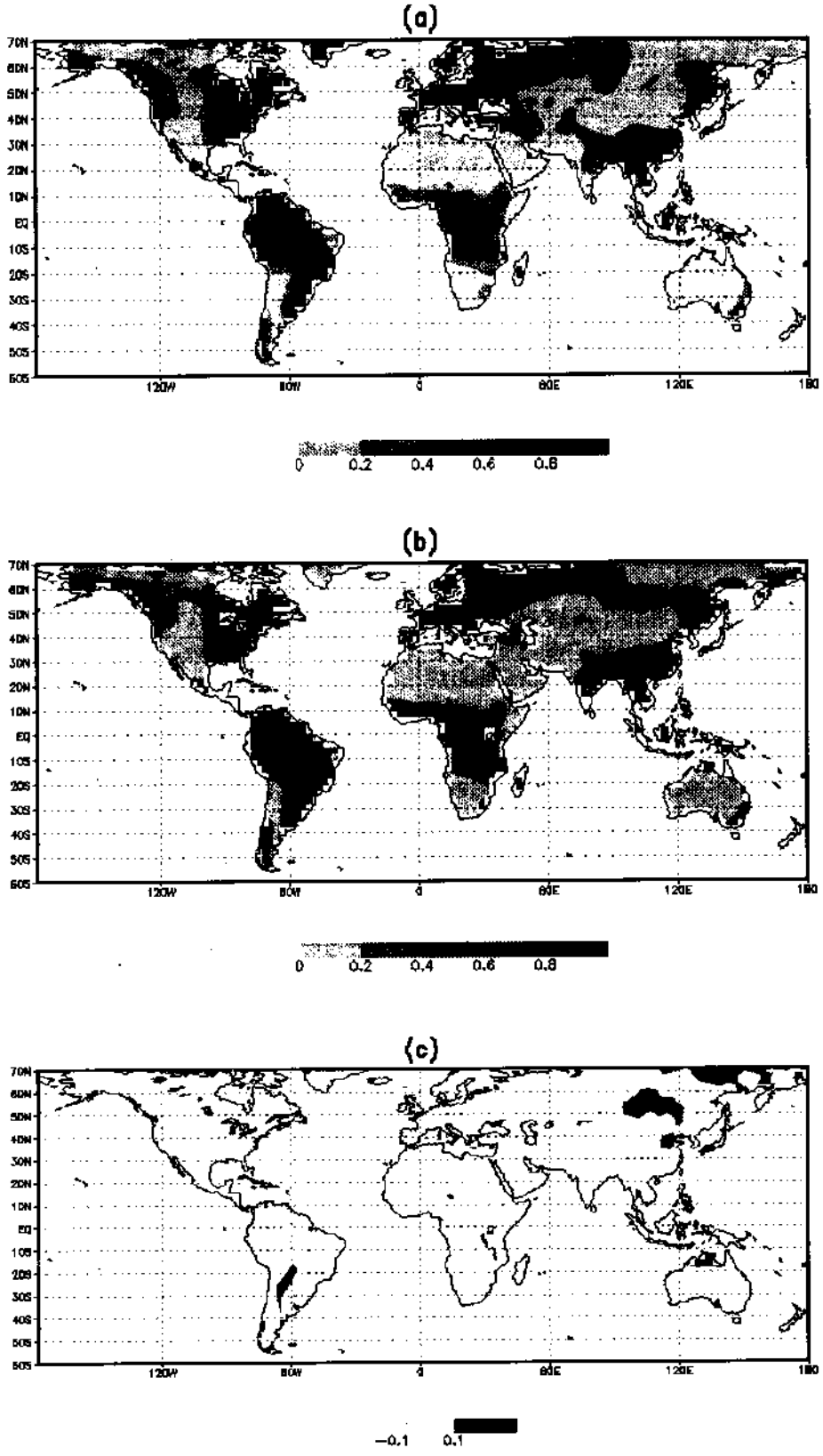


Figure 2: Annual average soil water degree of saturation (ratio between soil water storage and soil water availability). a) Willmott et al. (1985); b) the present water balance model; and c) difference between a) and b).

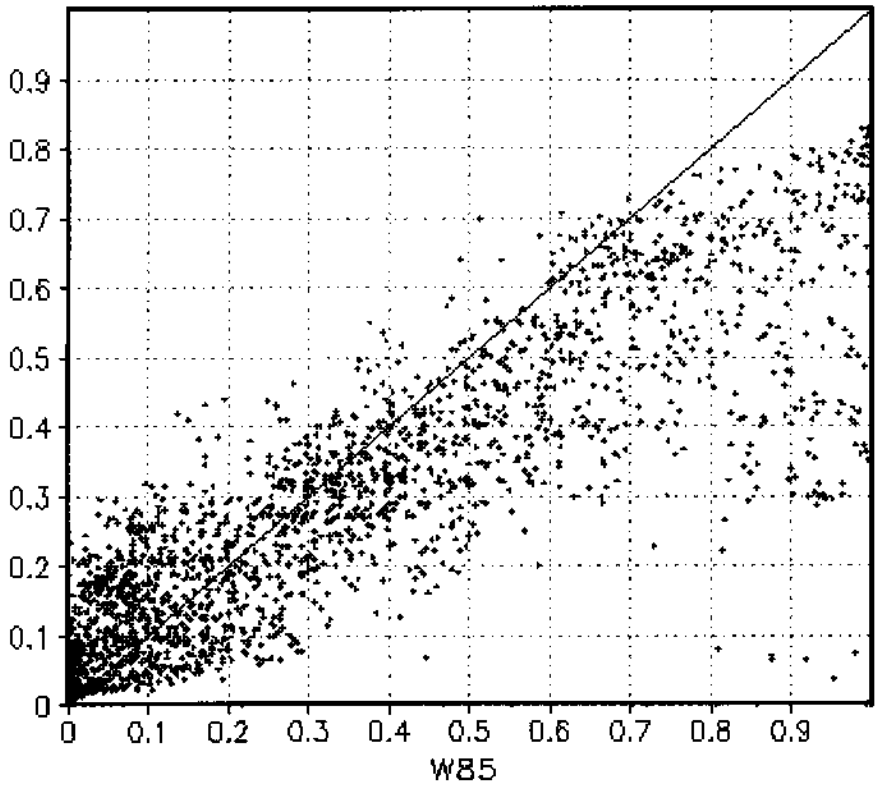


Figure 3: Annual average soil water degree of saturation according to Willmott et al. (1985, horizontal axis) and the present model (vertical axis).

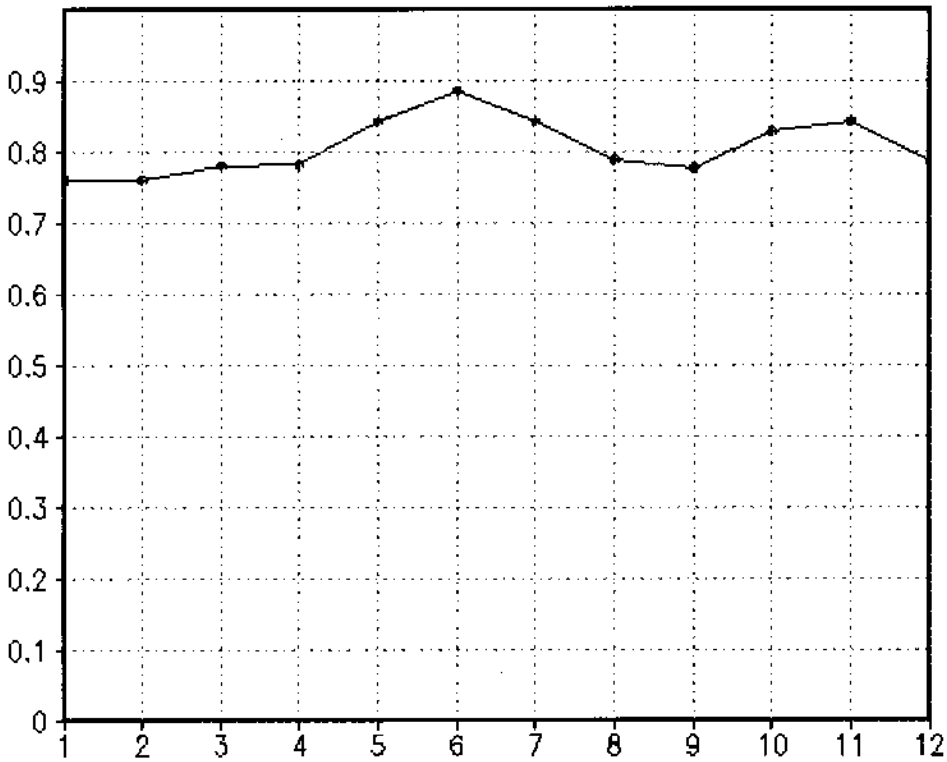


Figure 4: Linear correlation coefficient of the monthly average soil water degree of saturation between Willmott et al. (1985) and the present model results (for all land surface between 60°S and 70°N).

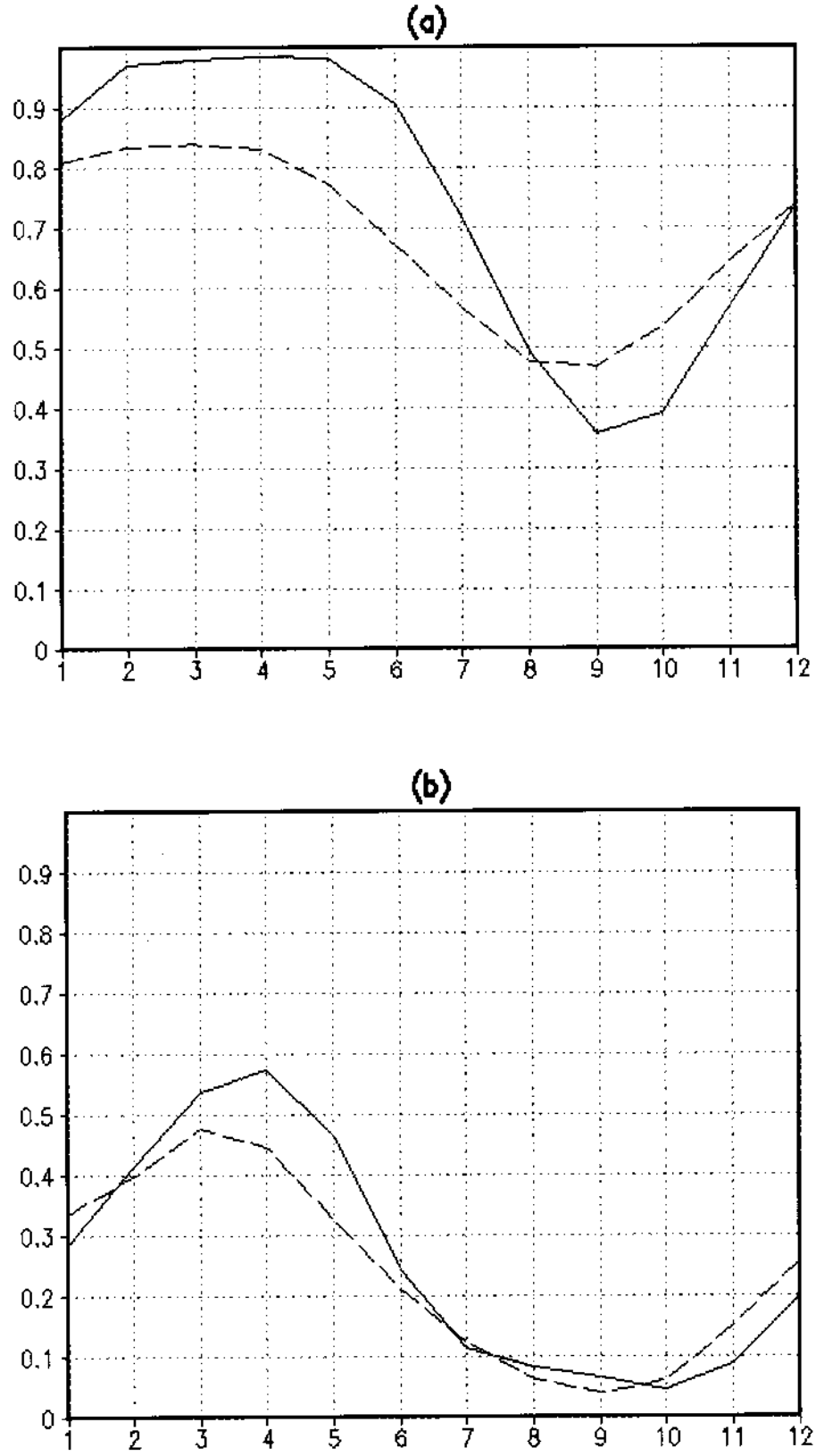


Figure 5: Soil water degree of saturation according to Willmott et al. (1985; solid lines) and the present model (dashed lines) for: a) Amazonia (70°W-50°W; 10°S-Equator); and b) Northeast Brazil (45°W-40°W; 15°S-5°S).

3. THE CPTEC POTENTIAL VEGETATION MODEL (CPTEC PVM)

The input variables for the CPTEC PVM are defined as follows:

$$T_c = \min\{T_i\},\ i = 1...12 \tag{11}$$

$$G_0 = \sum_{i=1}^{12} n_i F[T_i - 0] \tag{12}$$

$$G_5 = \sum_{i=1}^{12} n_i F[T_i - 5] \tag{13}$$

$$H = \frac{\sum_{i=1}^{12} g_i E_i}{\sum_{i=1}^{12} g_i E_{\max,i}} \tag{14}$$

$$D = 1 - \frac{\sum_{i=1}^{12} F[0.5 - w_i]}{6} \tag{15}$$

$$F[x] = \begin{cases} x, & x \geq 0 \\ 0, & x < 0 \end{cases};\ g = \begin{cases} 1, & \text{unfrozen} \\ 0, & \text{frozen} \end{cases} \tag{16}$$

where G is the growing degree-days (°C day month^{-1}; G_0: on 0°C base; G_5: on 5°C base); T_c, the mean temperature of the coldest month (°C); H, a wetness index (adimensional); D, a seasonality index (adimensional); T, the monthly mean temperature (°C); n, number of days; E, actual evapotranspiration; E_{max}, maximum evapotranspiration; and the index i refers to the ith month. The choice of G_0, G_5, T_c and H is based on Prentice et al. (1992). CPTEC PVM does not represent ecological competition among plant functional types, such as in BIOME. Instead, it introduces a new climate parameter, the seasonality index, D. It represents explicitly the soil moisture seasonality. It is included in the set of input variables since dry season length is an important factor in shaping the forest-savanna boundary in tropical regions (Sternberg, 2001). A low value of growing degree-days (Eqs 12 and 13) means a deficient growing period for plants, frozen soil during long periods and possible damage to plant tissue (due to very low temperatures). In Eq. 14, the summation is done only for non-frozen soils; H ranges from 0 (driest climate) to 1 (wettest climate). In Eq. 15, seasonality is stressed by not given weight in summation to relatively dry months ($w < 0.5$); the bigger the soil moisture seasonality, the lower the value of D.

For each grid point, after the water balance model is run, the input variables (G_0, G_5, T_c, H and D) for the CPTEC PVM - hereafter referred to as environmental variables - are calculated. For a given set of environmental variables, the CPTEC PVM diagnoses the biome in equilibrium with a given climate, following the algorithm shown in Fig. 6. Let us briefly describe the CPTEC PVM algorithm. In general, under severe environmental conditions, i.e., low values of growing degree-days or wetness index, there is absence of vegetation: ice or bare soil (desert). If the environmental conditions become less severe, even though the values of growing degree-days and wetness index are small, or the mean temperature of the coldest month is very low, resistant or extreme biomes are found: tundra, semi-deserts or larch. Under milder conditions, tropical or extratropical biomes with larger biomass are found. Extratropical biomes cover regions where the coldest month has low temperatures. If the wetness index is sufficiently high, forests - temperate, mixed, boreal - are found. On the other hand, if the wetness index is low, grasslands are found. Tropical biomes cover regions where the coldest month has higher temperatures. If the wetness and seasonality indices are high, tropical forests are found. If they are low, in decreasing order, savannas and caatingas (dry shrublands) are found.

The model parameter (threshold) values are either taken from the literature or calibrated. Calibration is carried out in two steps. The first step is an optimization procedure.

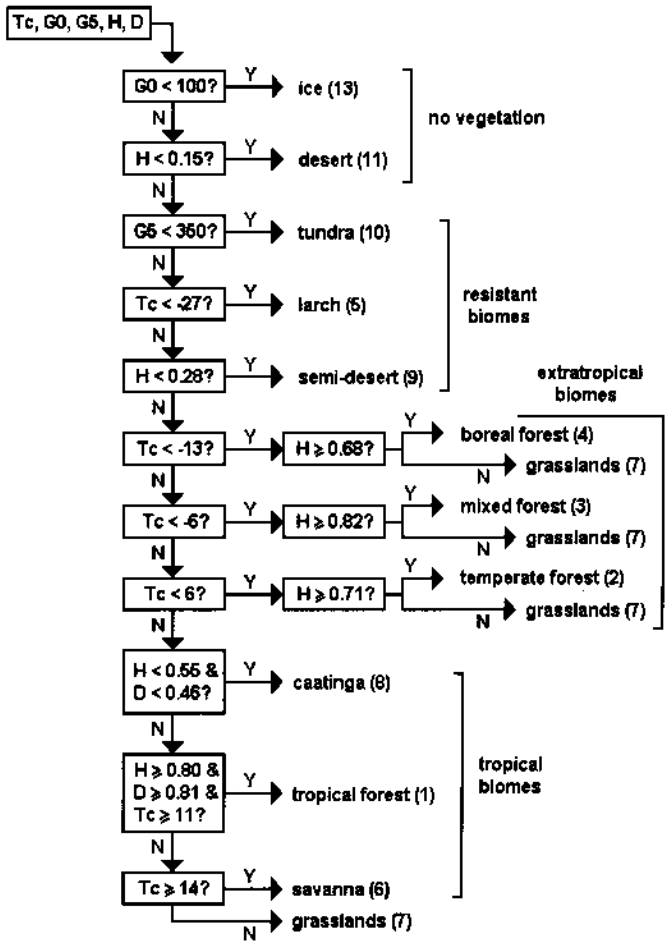


Figure 6: Algorithm used to obtain the potential biome from the environmental variables. Temperatures are given in °C; growing degree-days (G_0, G_5), in °C day month^{-1}.

For example, what is the threshold of H which separates deserts from other biomes? This threshold is an upper bound for deserts, and a lower bound for other biomes. The procedure consists of choosing a value which minimizes the number of grid points of biome 11 (desert) above this threshold and the number of grid points of other biomes below this threshold. Among the other biomes, the most sensitive to the threshold choice is biome 9 (semi-desert). Therefore, biomes 11 (desert) and 9 (semi-desert) are chosen for the optimization procedure (recall that, in this example, the problem is to find out an upper bound of H for biome 11). For a given value of H, let n_{11} be the number of biome 11 (desert) grid points above this value, and n_9 the number of biome 9 (semi-desert) grid points below this value. Define $f_{11} = n_{11}/N_{11}$ and $f_9 = n_9/N_9$, where N_{11} and N_9 are the total number of grid points covered by biome 11 (desert) and 9 (semi-desert), respectively. If the given value of H is chosen as threshold, f_{11} represents the fraction of biome 11 (desert) grid points that will be replaced by other biomes; the same interpretation is possible for f_9. Thus, error is defined as the maximum value between f_{11} and f_9. The threshold is chosen as the value of H which minimizes the error, i.e., the calibrated (adjusted) threshold of H minimizes the error between biomes 11 (desert) and 9 (semi-desert). Using the calibrated value as a first guess, the second step is a subjective adjustment. It aims at improving skill on a global or regional scale. However, it is not always necessary. For some thresholds, the first step is enough to produce a sufficiently good adjustment to the observed biome distribution.

A detailed account of the parameter (threshold) values choice is given as follows.

- Threshold (upper bound) of G_0 for ice (= 100°C day month^{-1}) and (lower bound) of G_5 for tundra (= 350°C day month^{-1}) follow Prentice et al. (1992).
- Threshold (upper bound) of H for deserts (= 0.15) minimizes the error, as shown previously, between biomes 11 (desert) and 9 (semi-desert).
- Threshold (upper bound) of H for semi-deserts (= 0.28) minimizes the error between biomes 9 (semi-desert) and 8 (caatinga).
- Threshold (upper bound) of T_c for larch (= - 27°C) minimizes the error between biomes 5 (larch) and 4 (boreal forest).
- Threshold (upper bound) of T_c for boreal forest (= -13°C) minimizes the error between biomes 4 (boreal forest) and 3 (mixed forest).
- The threshold of T_c for biomes 2 (temperate forest) and 3 (mixed forest) - upper bound for 3, lower bound for 2 - is chosen not only based on the optimization procedure. For biome 2 (temperate forest), it is necessary to define an upper limit of T_c. This prevents temperate forests from replacing the Pampas grasslands (the very humid environment of the Pampas favours the development of forests). The upper limit of 6°C is chosen. The lower this value, the greater the number of biome 2 (temperate forest) grid points replaced by other biomes. The higher this value, the greater the replacement of grasslands by temperate forests in the Pampas. The value chosen eliminates about 30% of biome 2 grid points (i.e., about 30% of biome 2 grid points lie in regions where T_c is greater than 6°C). Considering that, for the remainder biome 2 grid points (70%), a fraction has similar climate features of some biome 7 (grasslands) grid points, then we have to choose a T_c threshold between biomes 2 (temperate forest) and 3 (mixed forest) that allows a good representation for biome 2. We impose that the choice of this threshold eliminates a maximum of 10% of biome 2 grid points (i.e., only 10% of biome 2 grid points lie in regions where T_c is lower than this threshold). This leads to the threshold of -6°C. In summary, biome 2 (temperate forest) lies in regions where T_c ranges from -6°C to 6°C (this is a necessary condition).
- Thresholds (upper bound) of H for grasslands (0.68, 0.82 and 0.71) minimize the error between biome 7 (grasslands) and biomes 2 (temperate forest), 3 (mixed forest) and 4 (boreal forest), respectively.
- Threshold (lower bound) of H for tropical forest (0.80) is chosen not only to minimize the error between biomes 1 (tropical forest) and 6 (savanna; the optimized value is 0.78). The chosen value prevents the savanna area of Brazil from being replaced by tropical forests. Threshold (lower bound) of D for tropical forest (0.81) is chosen not only to minimize the error between biomes 1 (tropical forest) and 6 (savanna), even though it is close to the optimized value (0.80). The chosen value improves the representation of biome 6.
- Threshold (upper bound) of H for caatinga (0.55) is chosen not only to minimize the error between biomes 6 (savanna) and 8 (caatinga), even though it is close to the optimized value (0.54). The chosen values improve the representation of biome 8. Threshold (upper bound) of D for caatinga (0.46) minimizes the error between biomes 8 (caatinga) and 6 (savanna).
- Threshold (lower bound) of T_c for savanna (14°C) is chosen not only to minimize the error between biomes 6 (savanna) and 7 (grasslands; the optimized value is 17°C). The chosen value avoids the occurrence of spurious grasslands in the African savanna.

Upper bound thresholds of T_c seem artificial, but they are necessary since the PVM does not have an explicit dominance hierarchy (as in BIOME). For example, the upper bound of T_c for larch is -27°C. This threshold seems to be meaningless from a physiological point of view, since plant growth is limited by lower temperature thresholds. However, the -27°C threshold should not be interpreted as an upper bound of T_c, but as a lower bound for boreal forest, grasslands and semi-deserts. For T_c above -27°C, larch would be possible, but the PVM chooses other biomes (boreal forest, grasslands or semi-deserts) since the sequential decision process of the algorithm implicitly creates a dominance hierarchy. Another example is the upper bound of T_c for temperate forests (= 6°C).

An adequate interpretation is that for T_c greater than 6°C (other variables such as mean annual temperature or warmest month temperature would also be possible to characterize high temperature environments; see Prentice et al., 1992), tropical biomes do compete better (for Pampas, it is worth noting that fire frequency increases with temperature). Therefore, the grasslands in Pampas should be considered as tropical grasslands, not extratropical grasslands. DS89 vegetation classification, however, considers both warm (tropical) and cool (extratropical) grasses as belonging to the same category (biome 7).

4. RESULTS

4.1. Potential Vegetation Using CPTEC PVM

The simulated potential vegetation calculated by CPTEC PVM is shown in Fig. 7b. The PVM is able to reproduce the main global biome patterns: tropical forests in Amazonia, Congo and Indonesia; savannas in Brazil and Africa; grasslands in North America (prairies) and Eurasia (steppes); temperate forests in North America, Europe and East Asia; mixed forest in North America and Eurasia; boreal forest in North America and Eurasia; larch in Northeast Asia; deserts in Africa (Sahara), Middle East (Arabia) and Central Asia (Gobi); semi-desert in South Africa (Kalihari), Australia and North America.

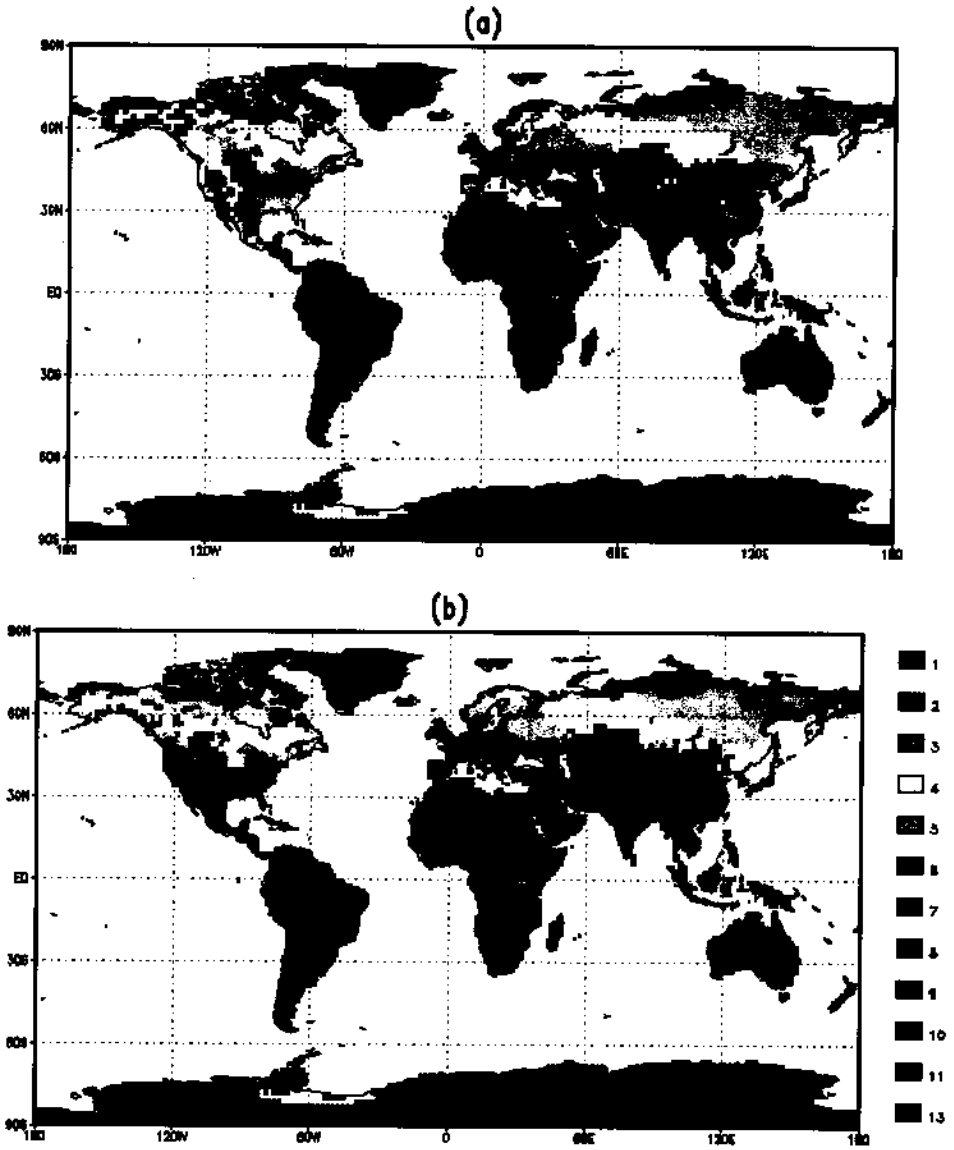


Figure 7: a) Natural and b) potential vegetation map. The numbers refer to vegetation types (see also Table 1): 1, tropical forest; 2, temperate forest; 3, mixed forest; 4, boreal forest; 5, larch; 6, savanna; 7, grasslands; 8, caatinga; 9, semi-desert vegetation; 10, tundra; 11, desert; and 13, ice.

In South America, the PVM is able to reproduce the tropical forests in Amazonia and Atlantic coastal region, the savannas in Central Brazil, the caatinga in Northeast Brazil and Chaco region, the grasslands in the Pampas, and the semi-desert in Patagonia. In other regions, however, differences do occur on a regional level. For example, in North America, the PVM incorrectly predicts larch vegetation across much of Canada and grasslands in southeastern USA. These differences outside South America are expected since the PVM parameter set (thresholds) was calibrated to give an accurate representation of South America vegetation distribution (regional level constraint) while reproducing the main global biome patterns (large scale level constraint).

In the Pampas, the replacement of grasslands by forest is avoided by using a simple constraint: temperate forests are not allowed to develop in regions where the coldest month temperature is greater than 6°C. Together with coldest month temperature constraints for tropical forests and savannas, grasslands are the unique biome that can take place in the Pampas. In NEB, the replacement of caatinga by savanna is avoided using carefully adjusted constraints on both wetness and seasonality indices. This adjustment leads to two fortunate consequences: in South America, the NEB area covered by caatinga is much better reproduced; on global scale, the savanna and caatinga patterns are well reproduced (i.e., the regional adjustment does allow for a global skillful representation of savannas and caatingas).

A limitation of the present model, which also occurs in other PVM's (such as BIOME and BIOME3), is the replacement of dry forests in India and Southeast Asia by savannas. We agree with the explanation given by Haxeltine and Prentice (1996): in monsoon months, there is high rainfall and simple water balance models predict higher runoff; in the dry season, since there is a smaller amount of soil water stored, soil moisture values decrease faster, leading to a sharper decrease of actual evapotranspiration. The pronounced dry season leads the PVM to place savannas in these regions. Apparently, the use of a more comprehensive hydrological model would save more soil water in the wet season (less runoff), thus weakening the severity of the dry season and allowing the presence of forests. On the other hand, the existence of dry forests in those areas may be due to particular ecological adaptations (for instance, existence of resistant deciduous trees) to cope with a pronounced dry season (Eyre, 1968). This type of effect is not captured by this simple climate driven vegetation model.

4.2. Objective Analysis

Two statistics are used to compare objectively the agreement between the natural and the potential biome maps. The first, hereafter referred to as agreement fraction (%; also known as intraclass correlation coefficient), is the fraction of grid points where there is agreement between the maps for a given biome. The second is the kappa (κ) statistics (Monserud and Leemans, 1992), which measures the degree of similarity between two maps. The conventions shown in Table 2 are followed.

κ	degree of agreement
< 0.05	no
0.05 - 0.20	very poor
0.20 - 0.40	poor
0.40 - 0.55	fair
0.55 - 0.70	good
0.70 - 0.85	very good
0.85 - 0.99	excellent
> 0.99	perfect

Table 2: Degree of agreement between maps according to κ statistics (Monserud and Leemans, 1992).

To avoid an artificial increase of model skill, the grid points covered by ice are not taken into account. Table 3 summarizes the CPTEC PVM skill. The average value of κ is 0.58, which means a good agreement between the maps. This value is comparable to the values found in the literature. For instance, BIOME obtained 0.49; Monserud and Leemans, using a modified version of Holdridge's model, obtained 0.43. In about 62% of the grid points the model is able to correctly predict the vegetation type. This value is better than the 38-40% obtained by Prentice (1990), who used 4 simple PVM's. For each biome, the agreement is very good for tropical rainforest and deserts; good for boreal forests, larch, savannas, semi-deserts and tundra; regular for temperate forests, grasslands and caatinga; and poor for mixed forest. These degrees of agreement, thus, compare well to other PVM's. In particular, for savannas, it is worth mentioning that the good agreement obtained by CPTEC PVM is comparable to BIOME PVM results (and better than BIOME3 PVM results). Thus, a better regional representation for South America has not affected the global simulation of savannas.

biome	agreement fraction (%)	κ
1	71	0.73
2	52	0.49
3	26	0.26
4	55	0.56
5	70	0.65
6	66	0.60
7	76	0.50
8	53	0.41
9	55	0.56
10	62	0.67
11	70	0.74
average	62	0.58

Table 3: CPTEC PVM skill.

5. CONCLUSIONS

A simple potential vegetation model (i.e., a model which diagnoses the biome in equilibrium with a given climate), named CPTEC PVM, was developed. Given a set of environmental variables derived from climatological mean surface temperature and precipitation - namely, growing degree-days, temperature of the coldest month and two moisture indexes (one to distinguish between wet and dry climates and the other to represent the soil moisture seasonality) - the model was designed to identify a biome among those used in the vegetation classification of SiB (or SSiB) land surface scheme. In order to calculate the two moisture indices, a water balance model - which includes the possibility of soil water freezing and evaluates the actual evapotranspiration using the Penman-Monteith formulation - was developed. The water balance model produces a consistent global distribution of soil moisture.

The potential vegetation model was able to represent reasonably well the global biome patterns. On a regional level in South America, the model was able to reproduce the Pampas grasslands of southeastern South America and avoid the replacement of caatinga by savannas in Northeast Brazil (NEB). In the Pampas region, the replacement of grasslands by forest is avoided by using simple constraints on coldest month temperature. To reproduce the NEB caatinga area, a careful adjustment in the wetness and seasonality indices was carried out. This adjustment does not affect the savannas and caatinga simulation on a global scale. A limitation of the model, which is also found in other potential vegetation models, is the replacement of forests in India and Southeast Asia by savannas.

The global κ (kappa statistics) is 0.58. It means good agreement between the potential and the natural biomes map. There is agreement of biomes in 62% of the grid points (excluding ice covered regions). This performance is comparable to other potential vegetation models currently in use for climate studies. Objective analysis for individual biomes showed very good agreement for tropical forests and deserts; good agreement for boreal forests, savannas, semi-deserts and tundra; regular agreement for temperate forest, extratropical prairies and "caatinga-like" vegetation; and poor agreement for mixed forest. Overall, this degree of agreement does compare well with other PVM's. Subsequently, the CPTEC PVM was asynchronously coupled to the CPTEC/COLA AGCM to study vegetation-climate equilibrium under present-day climate forcings (in a similar way to Claussen, 1997). Oyama (2002) found a second stable vegetation-climate equilibrium for South America in which there are much larger extent of savannas covering Amazonia in comparison to the current vegetation-climate equilibrium.

The development of a PVM and its coupling to CPTEC/COLA AGCM may be regarded as a first step towards a fully coupled climate model. This kind of model - albeit not useful for weather forecasting or seasonal climate prediction - is necessary for global climate change assessments, paleoclimate studies and, in particular, for studying past, present and future vegetation-climate interactions on South America.

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