Role of a simplified hydrological cycle and clouds in regulating the climate–biota system of Daisyworld

By JUAN FERNANDO SALAZAR* and GERMÁN POVEDA, *School of Geosciences and Environment, Universidad Nacional de Colombia, Medellín, Colombia*

ABSTRACT

The role of a simplified hydrological cycle and a physical representation of clouds is investigated in the Daisyworld model, subject to constant and variable solar forcing and varying cloud albedo and height. Under constant forcing, properties of the cloudy hydrologic cycle control the long-term system dynamics to non-oscillatory, oscillatory, abiotic or biotic states. In case of oscillatory solutions, their amplitude and periodicity are controlled by the net cooling or warming effects from clouds. Two conditions are considered under variable forcing—active or neutral—depending on the existence or not of biota–environment feedbacks. Temperature, cloudiness and hydrological variables are self-regulated in the active condition, whereas non-regulated in the neutral condition. Self-regulation is quantified through two measurements (luminosity range and total life), both of which can be larger in our model than in several other variants of Daisyworld, depending on cloud characteristics. The hydrological cycle and clouds can make the planet more habitable for life, independent of the capacity of the system for biological adaptation. Two hypotheses are put forward: (1) beneficial effects for life emerge from biota–clouds interactions, enhancing the global amount of life and extending the life span; and (ii) the existence of a maximum self-regulation capacity principle.

1. Introduction

Gaia theory postulates that life and its environment evolve on Earth as a coupled self-regulated system that maintains the planet in an habitable state for life (Lovelock, 2003), and Daisyworld (DW) constitutes the scientific framework of Gaia theory (Watson and Lovelock, 1983; Lenton and Lovelock, 2001). Daisyworld is a zero-dimensional model of radiative balance at a global scale, which represents an imaginary planet similar in size to Earth, rotating around a Sun, which acts as its energy source, ocean-devoid but containing enough water to sustain life and covered by white and black daisies, whose albedos are greater and lesser than bare ground, respectively. The fundamental idea on the functioning of DW refers to the establishment of self-regulation of the system through feedbacks between biota and its environment.

Even though some consider DW too a simple model to gain understanding of Earth's climate system (Kirchner, 2002; Volk, 2002), it has inspired a number of variants together with analysis (Lenton and Lovelock, 2001 and references therein) and has included different kinds of biological dynamics as well as enhanced biodiversity (Harding and Lovelock, 1996), 'Darwinian

Daisyworlds' including adaptation and competence for multiple resources (Stocker, 1995; Robertson and Robinson, 1998; Cohen and Rich, 2000; Lenton and Lovelock, 2000), as well as different fertile ground colonization strategies by daisies (Seto and Akagi, 2005). Some other variants of DW use diverse explicit representations of space (Von Bloh et al., 1997; Ackland et al., 2003; Adams et al., 2003). On the other hand, Nevison et al. (1999) modify the energy balance equation of the original DW to take account of the planetary heat capacity (details are given in the following section). Results from DW-like models include the existence of chaotic dynamics (Zeng et al., 1992, 1990; Jarcourt and Raymond, 1992) and detailed mathematical elaborations on the biological and physical dynamics (Saunders, 1994; Weber, 2001; Sugimoto, 2002; Weber and Robinson, 2004).

The hydrological cycle is a highly non-linear component of the climate system (Chahine, 1992; Pierrehumbert, 2002; Stephens et al., 2004), and vegetation plays a very important role in the dynamics of the planetary hydrological cycle and climate through regulation of the planetary water, energy and carbon budgets (Hutjes et al., 1998). In spite of the highly relevant role the hydrological cycle plays in climate models of diverse complexity (e.g. Chu and Ledley, 1995; Szilder and Lozowski, 1996), it has been largely ignored in models of DW, with few exceptions. Baldocchi et al. (2005) introduce a 'wet/dry DW' that considers the influence of vegetation (daisies) on the latent

*Corresponding author.
e-mail: salazar.jf@gmail.com

heat flux exchange at the surface, but that fails to take into account an explicit representation of either the hydrological cycle or of clouds. Nordstrom et al. (2005) construct a zero-dimensional Earth-like DW that becomes too complex so as to impede comparisons.

This paper aims to investigate the role of simple albeit sound representations of the hydrological cycle and clouds in a DW model, to further our understanding of the dynamics and self-regulation of the climate–biota system, while keeping the original spirit of DW as a parable with possible implications for the Earth's system (Watson and Lovelock, 1983). Consequently, we develop and implement a DW model involving the dynamics of a simplified hydrological cycle (via precipitation and evapotranspiration) and the most relevant physical characteristics of clouds and study its long-term climatic, hydrological and biotic dynamics. As such, our model is referred to as DAisy World with HYdrological Cycle and Clouds (DAWHYC, hereafter).

2. Model description

Daisyworld is represented by a system of coupled ordinary non-linear differential equations that model the global radiative balance and the dynamics of black and white daisies populations. The original DW (Watson and Lovelock, 1983) assumes an exact energy balance between the planetary net incident short-wave and outgoing long-wave radiations. Afterwards, Nevison et al. (1999) modified this assumption using a time rate of change for the system's internal energy as a function of the planetary mean heat capacity or thermal inertia, c_p, such that

$$c_p \frac{dT}{dt} = SL(1 - \alpha_s) - \sigma T^4,$$
(1)

where S is the present-day constant solar radiation flux reaching the planet, L is a dimensionless measure of the Sun's luminosity relative to present conditions, α_s is the average planetary surface albedo, σ is the Stefan–Boltzmann constant for black-body radiation and T is the average planetary temperature. The model of Nevison et al. (1999) (NGK99, hereafter) is completed with the original equations of DW for the evolution of daisy populations, as well as for variations of the average planetary albedo and the internal distribution of heat within the system, expressed as

$$\frac{da_i}{dt} = a_i[(1 - a_w - a_b)\beta_i - \gamma],$$
(2)

$$\alpha_s = (1 - a_w - a_b)\alpha_d + a_w\alpha_w + a_b\alpha_b,$$
(3)

$$\beta_i = \max\left[0, 1 - \left(\frac{T_i - T_{opt}}{17.5}\right)^2\right],$$
(4)

$$T_i = q(\alpha_s - \alpha_i) + T,$$
(5)

where the subscripts, $i = $ b, w, d refer to black daisies (b), white daisies (w) and bare soil (d), whose area fractions are denoted by a_b, a_w, and a_d, respectively. Likewise, their albedos

are denoted by α_b, α_w, and α_d; whereas β_b and β_w denote the growth rate of black and white daisies, respectively. γ is the mortality rate and T_{opt} is the optimal growth temperature, which are assumed equal for both types of daisies; T_b and T_w represent local temperatures determining the growth rate of each daisies, and q is a coefficient that represents the energy flux among the various land cover types.

The DAWHYC introduces two fundamental modifications with respect to NGK99, as follows: (1) clouds make up part of the planetary energy balance and (2) the hydrological cycle is involved through a simple representation of precipitation and evapotranspiration. As such, DAWHYC's energy balance equation is

$$c_p \frac{dT}{dt} = SL(1 - \alpha_c a_c)(1 - \alpha_s) + \sigma T_c^4 \varepsilon_c a_c - \sigma T^4 \varepsilon_s,$$
(6)

where c_p, T, S, L and σ are defined as in eq. (1). Additionally, the following cloud characteristics are used: albedo (α_c), temperature (T_c, assumed as a single value for the bottom of the cloud layer), emissivity (ε_c) and cloud cover area fraction (a_c). Also, land surface albedo (α_s) and emissivity (ε_s) are considered. Equation (6) expresses that the planetary surface receives energy from the Sun and from its atmosphere by virtue of the natural greenhouse effect. The DAWHYC assumes that the greenhouse effect is solely due to the presence of water in the atmosphere, and also that water is always contributing to cloud formation. To determine T_c, it is necessary to assume a tropospheric temperature lapse rate, $\Gamma = -dT/dz$, such that

$$T_c = T - z_c\Gamma,$$
(7)

where z_c represents cloud height. Figure 1 illustrates our approach.

It is worth noting that our model does not consider the energy balance equation in the cloud layer, but the role of clouds in the natural greenhouse effect (through the term $\sigma T_c^4 \varepsilon_c a_c$ in eq. 6), and thus the atmospheric column is parametrized through the lapse rate (Γ) and the cloud base height (z_c). Our model leaves z_c as a free parameter since (in an Earth-like atmosphere) it
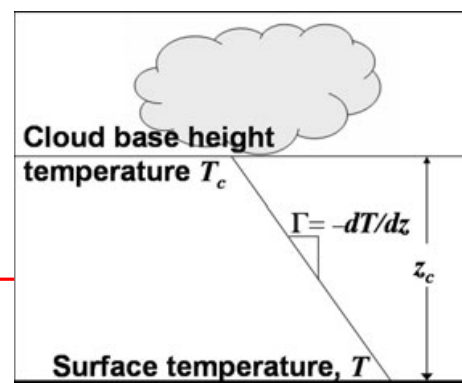

Fig. 1. Schematics of the atmospheric column in DAWHYC including clouds.

depends on the saturation conditions of the atmospheric column, and thus different saturation conditions give rise to different values of z_c. Note that the energy balance in the cloud layer is not violated as it is controlled by changes in variables such as the saturated lapse rate, the vertical depth of the cloud layer and its temperature aloft, all of which are not prescribed in our model. Thus, we fix Γ and vary z_c within a realistic range of values. We avoided an explicit computation of the atmospheric energy balance as it led to unrealistic temperature lapse rates (verified in experiments not shown here), unless the energetic role of water in the atmospheric column is taken into account. Such an explicit representation would imply a complete reformulation of the model in terms of saturation conditions imposed by the Clausius–Clapeyron equation, leading our model far beyond the realm of DW. We aim to keep our model simple enough to allow for comparisons with other variants of DW. This is why the energy balance of the cloud layer is parametrized via eq. (7), which links both cloud and surface temperatures, while allowing albedo, height and cloud cover area to vary independently.

The hydrological cycle is represented by,

$$\frac{da_c}{dt} = E(t) - P(t), \tag{8}$$

with,

$$E = (1 - a_c)E_p, \tag{9}$$

$$P = a_c P_p, \tag{10}$$

where E_p and P_p denote fractions, between 0 and 1, associated with cloud cover growth and demise rates, respectively. For the sake of simplicity, from eq. (9) onwards, we neglect the explicit time dependence representation of $E(t)$ and $P(t)$.

Under the assumption that all atmospheric water contributes to cloud formation, a_c is a measure of the atmospheric water content, and eq. (8) represents the mass conservation law, whereby a_c is a time-varying quantity that depends on the difference between inputs to, $E = (1 - a_c)E_p$, and outputs from, $P = a_c P_p$, the control volume. Therefore, E and P can be qualitatively associated with actual evapotranspiration and precipitation rates, respectively, given that both fluxes affect the rates of cloud cover growth and demise rates, through changes in the atmospheric water content. The form of $(1 - a_c)E_p$ aims to represent the dependence of actual evapotranspiration from two factors: the 'atmospheric available space', or saturation degree of the atmosphere, $(1 - a_c)$, and the available phase transition energy or potential evapotranspiration, E_p. It is implicitly assumed that the planetary surface is not water-limited, but energy-limited. Likewise, precipitation rate, $a_c P_p$, depends on both the atmospheric available moisture, or precipitable water, and P_p, which can be viewed as a 'potential precipitation'. It represents all rainfall-producing processes, such as condensation and water droplet formation. As previously discussed, a further detailing of these processes implies a dynamic representation of atmospheric wa-

ter and energy budgets, thus leading to a much more complicated version of the hydrological cycle. As is, DAWHYC involves the energetic role of clouds and the dynamics of a simple albeit realistic hydrological cycle.

Estimation of E_p and P_p will be based on simple hydrological principles and observations. For precipitation, we use a modified version of the power law between average annual precipitation and cloudiness, found by Nordstrom et al. (2005) with data from Beijing between 1951 and 1990 reported by Wang et al. (1993),

$$P_p = \frac{1}{P_{max}}\left(\frac{a_c}{m}\right)^{1/n}, \tag{11}$$

where m and n are estimated from observations. We fix $n = 0.1$ after Nordstrom et al. (2005), and set $m = 0.35$ to reproduce mean annual global precipitation ($P \sim 1000$ mm yr^{-1}) when cloud cover equals the annual global average ($a_c \sim 0.7$; Hartmann, 1994). We introduce P_{max} (maximum possible precipitation) to express precipitation as a dimensionless quantity. We assume that this value is reached when $a_c = 1.0$, so that $P_{max} = 36\,251$ mm yr^{-1} is estimated from eq. (11) with $P_p = 1.0$. Note that a maximum precipitation value of over 36 m yr^{-1} might be in excess of anywhere to be found on the Earth. In fact, the rainiest place on Earth is located on the Pacific coast of Colombia, exhibits mean annual rainfall rates of 12 700 mm yr^{-1} and some years like 1974 experiencing 26 m of rainfall (Poveda and Mesa, 2000)! However, note that the maximum precipitation value corresponds to a cloudiness of 100% ($a_c = 1.0$), that is a planet completely covered by clouds, which is also unlikely on Earth. Thus, P_{max}, as well as $a_c = 1.0$, should be understood as theoretical upper limits.

To relate E_p with surface temperature, T, we use a simplified version of the Thornthwaite equation within the interval from 277 to $\sim$313 K,

$$E_p = ETP/ETP_{max}, \tag{12}$$

with

$$ETP = 192(10T/I)^k, \tag{13}$$

$$I = 12(T/5)^{1.5}, \tag{14}$$

$$k = 6.7 \times 10^{-7}I^3 - 7.7 \times 10^{-5}I^2 + 1.8 \times 10^{-2}I + 0.49, \tag{15}$$

assuming that temperature remains constant throughout the year. T is measured in $^\circ$C, I is the annual caloric index and ETP_{max} is the maximum possible potential evapotranspiration which is assumed equal to P_{max}. We define $E_p = 0$ if $T \leq 277$ and $E_p = 1$ if $ETP \geq ETP_{max}$. The Thornthwaite equation is based on the Gaian-like idea that evaporation is related to plant growth and growth to temperature (John Gash, personal communication, 2007).

The formulation of DAWHYC is completed with eq. (2)–(5) from the original DW. Note that NGK99 is the particular case

of DAWHYC devoid of a hydrological cycle and clouds, that is, $a_c = P = E = 0$.

3. Results

Two experiments are performed on DAWHYC. The first one studies the influence of clouds on the planetary physical and biological dynamics, under constant external solar forcing. The second experiment studies the evolution of DAWHYC's climate-biota system under increasing solar forcing, while considering diverse combinations of clouds characteristics. Table 1 shows those parameters that are kept constant in both experiments. From those values it is worth noting that DAWHYC's $c_p = 3.0 \times 10^{10}$ J m^{-2} K^{-1} is high in comparison with that of the Earth (the heat capacity per unit area of a 2.4-m ocean mixed layer is about 1.0×10^7 J m^{-2} K^{-1}). However, we use that value after Nevison et al. (1999) for the sake of comparison. Implications of the chosen value of c_p are addressed in the discussion section. Solutions were obtained using a fourth order Runge–Kutta method, with time steps of 0.01 yr and solar forcing increments of 0.004.

3.1. The influence of clouds under constant external solar forcing

The first experiment aims to study the equilibrium states of the climatic, hydrological and biotic variables and their dependence on the characteristics of clouds. These equilibrium states are arrived at by running the model during a time horizon of 10 000 yr, in which solar forcing remains equal to its present value ($L = 1.0$). Variables at equilibrium state are denoted with the superscript 'eq' (e.g. T^{eq}). Results in Table 2 show the appear-

Table 2. Types of equilibrium states in DAWHYC with $L = 1.0$, depending on cloud albedo (α_c) and height (z_c)

z_c (km)	α_c							
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	1+	1+	1+	1+	1+	3−	6−	6−
2	1+	1+	1+	2+	3−	6−	6−	6+
3	1+	1+	2+	3−	6−	6−	6+	6+
4	1+	2+	3−	6−	6−	6+	6+	4+
5	2+	2−	6−	6−	6−	6+	6+	4−
6	2−	6−	6−	6−	6+	6+	5+	4−
7	6−	6−	6−	6+	6+	6+	4+	4−
8	6−	6−	6−	6+	6+	6+	4−	4−

Note: 1, abiotic; 2, only white daisies; 3, both daisies ($a_w^{eq} \gg a_b^{eq}$); 4, only black daisies; 5, both daisies ($a_w^{eq} \ll a_b^{eq}$); 6, both daisies and oscillations. Signs indicate whether mean temperature ($\overline{T}$) in DAWHYC is higher (+) or lower (−) than in NGK99.

ance of both steady non-oscillatory and oscillatory equilibrium states, depending on the values of the cloud parameters α_c and z_c. We vary α_c between 0.2 and 0.9, with increments of 0.1, and z_c between 1 and 8 km, each 1 km, and considering all possible combinations. Such ranges correspond to typical values of the albedo of clouds on Earth (Fu, 2003) and tropospheric heights which include low (<2 km), mid-level (2–7 km) and high (>7 km) clouds (Rangno, 2003).

Results summarized in Table 2 show that all equilibrium states can be classified into six categories, depending on the characteristics of clouds. (1) A steady non-oscillatory abiotic state ($a_b^{eq} = a_w^{eq} = 0$) where the planet is too hot ($T^{eq} > 80\,°C$) to be habitable because of the strong greenhouse effect enhanced by clouds of low albedo and height. (2) A steady non-oscillatory state where only white daisies survive in a not too hot planet warmed by a greenhouse effect due to clouds with low to middle height and albedo. (3) A steady non-oscillatory state for both species of daises, whereby $a_w^{eq} \gg a_b^{eq}$. (4) A steady non-oscillatory state where only black daisies survive in a not too cold planet cooled by clouds with middle to high albedo and height, thus enhancing the reflection of short-wave radiation to the space. (5) A steady non-oscillatory state for both species of daises, whereby $a_w^{eq} \ll a_b^{eq}$. Finally, (6) a self-sustained oscillatory equilibrium state in the dynamics of area fractions of black daisies ($a_b(t)$), white daisies ($a_w(t)$), cloudiness ($a_c(t)$), temperature ($T(t)$), evapotranspiration ($E(t)$) and precipitation ($P(t)$). This latter equilibrium state points out a remarkable result from DAWHYC: the amplitude and periodicity of self-sustained oscillations are strongly controlled by the clouds' characteristics. Table 3 shows the period with the maximum power in the Fourier spectrum of the resulting temperature record. Figures 2–4 show different examples of the identified self-sustained oscillations, with their corresponding power spectrum at the inset.

Table 1. DAWHYC parameters

Parameter	Units	Value	Data source
c_p	J m^{-2} K^{-1}	3.0×10^{10}	(Nevison et al., 1999)
S	J m^{-2} yr^{-1}	2.89×10^{10}	(Nevison et al., 1999)
σ	J m^{-2} yr^{-1} K^{-4}	1.79	(Nevison et al., 1999)
α_b	dimensionless	0.25	(Nevison et al., 1999)
α_w	dimensionless	0.75	(Nevison et al., 1999)
α_d	dimensionless	0.50	(Nevison et al., 1999)
ε_s	dimensionless	1.0	fixed
ε_n	dimensionless	1.0	fixed
γ	dimensionless	0.3	(Nevison et al., 1999)
q	K	20	(Nevison et al., 1999)
T_{opt}	K	295.5	(Nevison et al., 1999)
Γ	K km^{-1}	6.5	(Hartmann, 1994)
EVP_{max}	mm yr^{-1}	36251	estimated
P_{max}	mm yr^{-1}	36251	estimated
n	dimensionless	0.10	(Nordstrom et al., 2005)
m	dimensionless	0.35	estimated

Table 3. Period in years of the temperature oscillations with the maximum power in the Fourier power spectrum, depending on cloud albedo (α_c) and height (z_c). Note that self-sustained oscillations just appear for certain cloud characteristics, which in turn define their periodicity.

z_c (km)	α_c							
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	–	–	–	–	–	–	1250	833
2	–	–	–	–	–	1250	714	833
3	–	–	–	–	1000	714	625	1250
4	–	–	–	1000	714	556	556	–
5	–	–	1250	714	556	556	1000	–
6	–	1250	714	556	500	625	–	–
7	1000	833	556	500	500	833	–	–
8	833	556	455	455	556	1250	–	–

For the sake of simplicity, hereafter we neglect the explicit dependence of variables with respect to time (t). Note in Figs. 2–4 that values of E and P evolve at the same pace, owing to the expected steady-state that emerges from the small capacity of the atmosphere/clouds to store water at the annual timescale.

For all combinations of α_c and z_c, two bio-physical characteristics are evaluated: (1) the average spatial and temporal planetary temperature ($\overline{T} = \overline{a_b T_b + a_w T_w + a_d T_d}$), which is a measure of the mean energy stored in the system throughout time, and (2) the biologic predominance, B_p, defined as the mean difference between the total cumulative populations of black and white daisies,

$$B_p = \frac{1}{t_f - t_i} \int_{t_i}^{t_f} (a_b - a_w)\,dt, \tag{16}$$

where t_i and t_f are the limits of the modelling time horizon for which B_p is evaluated. Such measurement is relevant insofar the system's ecological dynamics varies significantly in cumulative terms depending on the predominant species of daisies. Figures 5 and 6 show results of the two biophysical characteristics in DAWHYC, estimated from time-series of 10 000 yr, whose 5000 initial years are discarded to get rid of numerical noise. Estimates in NGK99 are $\overline{T} = 22.12\,°C$ and $B_p = -0.11$. The negative value of B_p indicates predominance of white daisies. Signs in Table 2 indicate whether $\overline{T}$ in DAWHYC is higher ($+$) or lower ($-$) than in NGK99, which allows to quantify the effect of the cloudy hydrological cycle presence (DAWHYC) or absence (NGK99) on the planetary climate.

3.2. The influence of clouds under variable external solar forcing

The second experiment aims to study the evolution of DAWHYC's climate–biota system while varying the external solar forcing (luminosity) from $L = 0.2$ to $L = 3.3$. Two con-
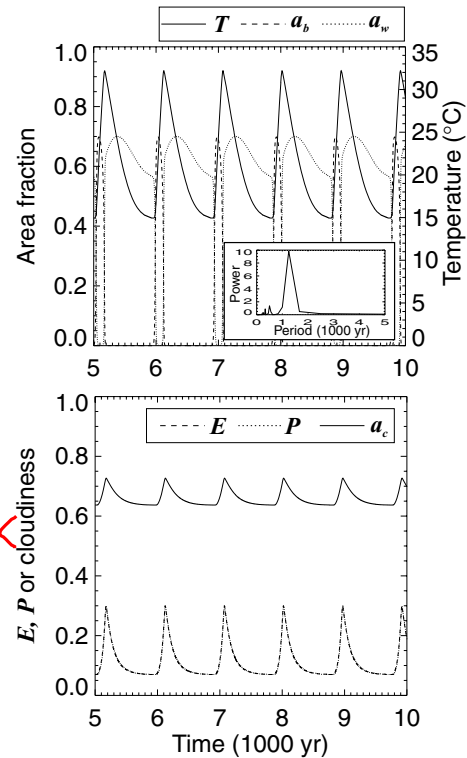

Fig. 2. Results of Experiment 1 (constant external solar forcing) with $L = 1.0$, $\alpha_c = 0.7$ and $z_c = 2$ km. (Top panel) Time evolution of temperature (T) and biota (a_b and a_w). The Fourier power spectrum of temperature is shown at the inset. (Bottom panel) Time evolution of the variables representing the hydrological cycle (E, P and a_c). Values of E and P are augmented ten-fold to improve visualization.

ditions depending on the specific role of biota are considered: (1) an 'active' condition, owing to biota–environment feedbacks arising from albedo differences between both species of daisies and bare ground and (2) a 'neutral' condition whereby both daisies and bare ground exhibit the same albedo value ($a_b = a_w = a_d = 0.5$), so that the radiative balance is indifferent to the presence of biota. Note that this neutral condition does not imply the absence of life, but of an abiotic condition in radiative terms. A comparison between the active and neutral conditions points out the role of life on the system's self-regulation capacity. To further investigate the role of the hydrological cycle and clouds, we also consider the condition by which temperature is solely determined by solar forcing due to the total absence of life, water and clouds, referred to as a 'dead planet' condition.

Likewise, our results from this experiment describe the equilibrium states of the system as a function of solar forcing (L), for all combinations of α_c and z_c used in Experiment 1 under a constant solar forcing. We determine the equilibrium values of T, a_b, a_w and a_c for each value of L. Note that in terms of the theory of dynamic systems, the set of these four variables defines the phase-space of the model. An oscillatory equilibrium
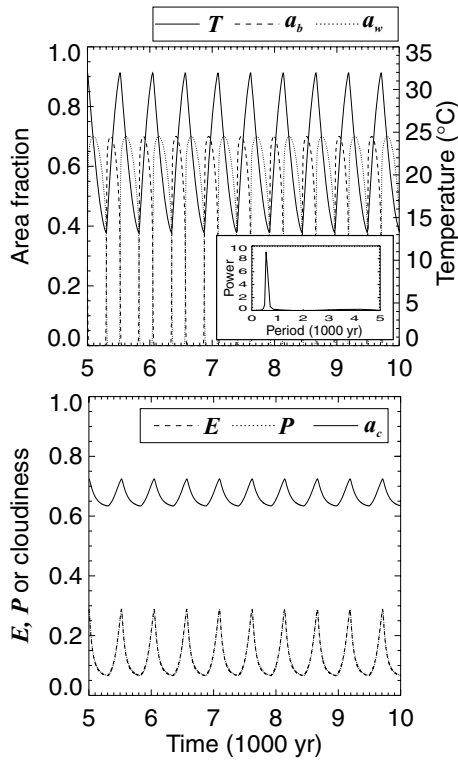
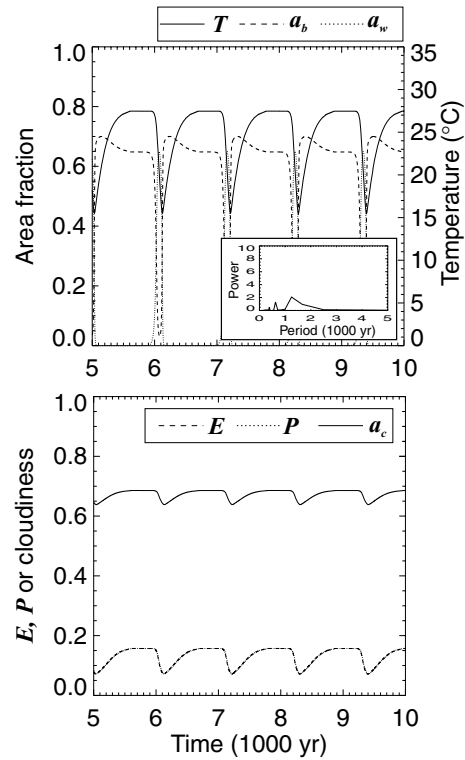Fig. 3. Same as Fig. 2 with $z_c = 4$ km.

Fig. 4. Same as Fig. 2 with $z_c = 8$ km.

state can be described by average and extreme values. Likewise, equilibrium states are obtained from time series of 10 000 yr, whose initial 5000 yr are discarded to get rid of numerical noise. Figure 7 shows the dynamics of temperature (T), area fractions of daisies (a_b and a_w) and cloudiness (a_c). The corresponding figures (not shown) for evapotranspiration (E) and precipitation (P) are quite similar to that of a_c. Similar results were found for different combinations of α_c and z_c.

Two measures were introduced by Lenton and Lovelock (2001) to quantify DW's self-regulation capacity. The first one is the 'luminosity range', L_R, defined as the difference between the maximum (L_M) and minimum (L_m) luminosity by which the planet is habitable. And the second one is the 'total life', (V_T), defined as the total amount of life present in DW over the whole luminosity range, estimated by integration over all populations (average area in DAWHYC) and for the full range of luminosity values. The higher the values of both measures, the higher the system's self-regulation capacity. Values of L_m, L_M, L_R and V_T are reported by Lenton and Lovelock (2001) for different variants of DW.

The DAWHYC's equilibrium values of L_m, L_M, L_R and V_T depend on the combination of cloud characteristics (α_c and z_c), as well as on the biological condition type (active or neutral). Figures 8 and 9 show estimates of L_R and V_T for the active condition. Extreme and average values of L_R, V_T, L_m and L_M during DAWHYC's active condition
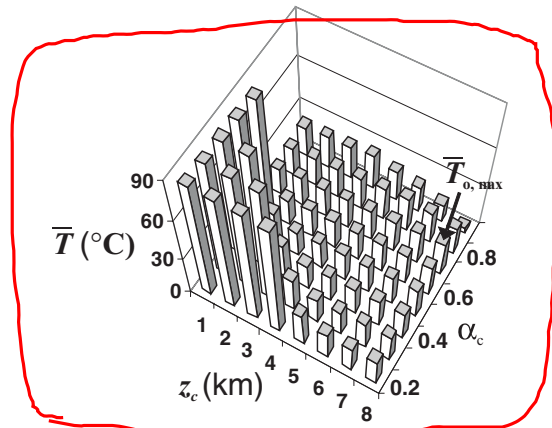

Fig. 5. Results of experiment 1 with $L = 1.0$. Average temperature ($\overline{T}$) in equilibrium in DAWHYC as a function of cloud albedo (α_c) and height (z_c). The arrow indicates $\overline{T}_{o,\max} = 24.92\,°C$, which corresponds to the maximum average temperature for which self-sustained oscillations occur.

are $L_{R,\max} = 2.32$, $L_{R,\min} = 0.36$, $\overline{L}_R = 0.89$, $V_{T,\max} = 1.449$, $V_{T,\min} = 0.227$, $\overline{V}_T = 0.584$, $L_{m,\min} = 0.30$, $L_{m,\max} = 0.94$, $L_{M,\max} = 3.26$, $L_{M,\min} = 0.66$. All maximum values of L_R, V_T, L_m and L_M correspond to $\alpha_c = 0.9$ and $z_c = 8.0$ km (coldest clouds), and all minimum values occur for $\alpha_c = 0.2$ and $z_c = 1.0$ km (warmest clouds). Note that L_m is the minimum luminosity value required for the appearance of life in DAWHYC,
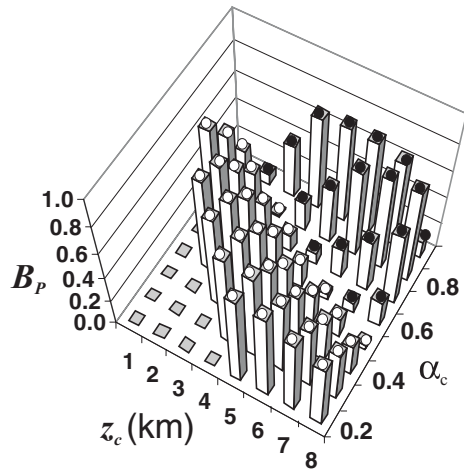
Fig. 6. Results of Experiment 1 with $L = 1.0$. Biologic predominance (B_p) in DAWHYC as a function of cloud albedo (α_c) and height (z_c). Bars marked with black (white) dots indicate predominance of black (white) daisies. Unmarked bars correspond to those cases for which all daisies become extinct.

given certain characteristics of clouds, while L_M is the value at which life becomes extinct. Thus, $L_{m,min}$ is the minimum among all values of L_m obtained for different combinations of cloud characteristics. $L_{m,max}$, $L_{M,min}$, and $L_{M,max}$ are defined in a similar way. Corresponding estimates for NGK99, computed by fixing $a_c = P = E = 0$ in DAWHYC, are the following single values due to the absence of clouds: $L_R = 0.95$, $V_T = 0.626$, $L_m = 0.62$ and $L_M = 1.57$.

4. Discussion

Analysis of results from both experiments will focus on three major issues: (1) physical consistency of the couplings between biota and climate with the hydrological cycle and clouds, (2) plausible interpretations of DAWHYC results in the context of the Earth's system and (3) major differences between the long-term biophysical dynamics of DAWHYC and NGK99, explained by the presence of a cloudy hydrological cycle.

4.1. On the influence of clouds under constant external solar forcing

The most remarkable result from the first experiment on DAWHYC is the appearance of diverse equilibrium states, arising from the presence of the hydrological cycle and clouds, which depend on cloud characteristics (albedo and height), despite having a constant solar forcing. Such equilibrium states can be either of steady non-oscillatory nature (fixed set point attractor) or oscillatory nature (limit cycle), biotic (with one or two species of daisies present) or abiotic nature (uninhabitable planet). For most but not all states (see Table 2), self-sustained
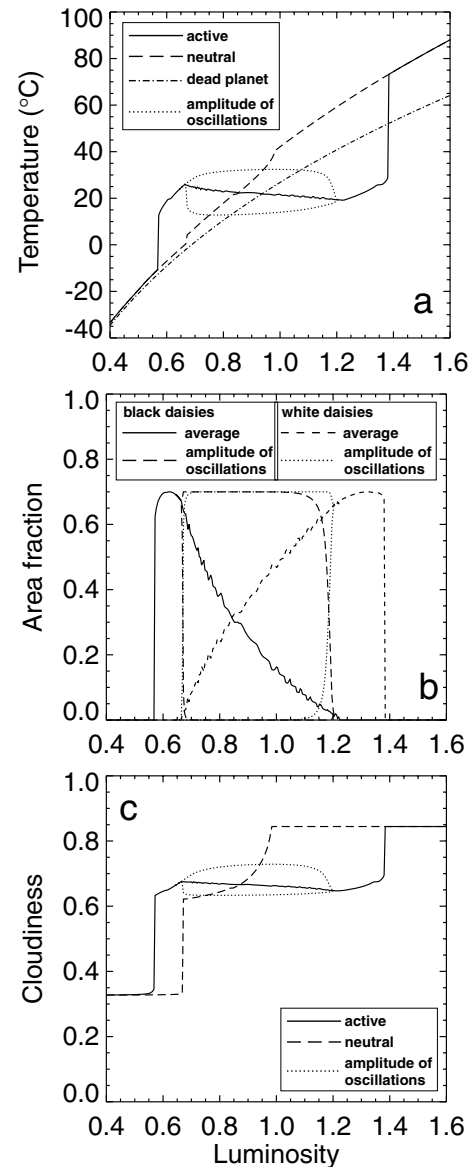

Fig. 7. Evolution of DAWHYC under variable solar forcing (luminosity) using $\alpha_c = 0.6$ and $z_c = 4$ km: (a) climate (temperature) for the 'active', 'neutral' and 'dead planet' conditions; (b) populations (area fraction) of daisies for the 'active' condition and (c) cloudiness for the 'active' and 'neutral' conditions.

coupled oscillations emerge among climatic, hydrological and biotic variables (T, E, P, a_c, a_b, and a_w). Such oscillations resemble those found by NGK99 in temperature and daisies populations (see fig. 2 of Nevison et al., 1999). They are referred to as self-sustained in the sense of periodic oscillations around a homeostatic mean value, which emerge from the system's internal dynamics rather than from some external forcing (Nevison et al., 1999). In this context, 'homeostasis' refers to regulation towards a fixed set point (Lenton, 2002). These
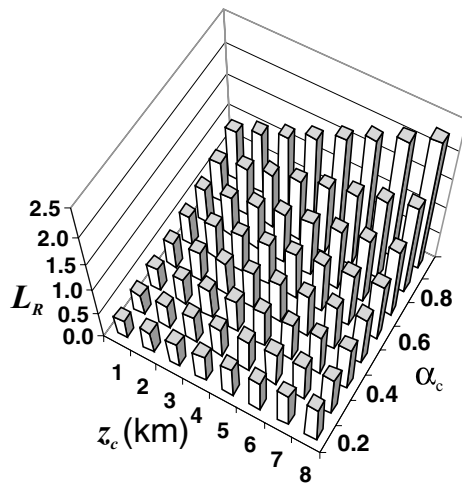
Fig. 8. Luminosity range (L_R) in DAWHYC as a function of cloud albedo (α_c) and height (z_c) during the active condition and a varying solar luminosity.
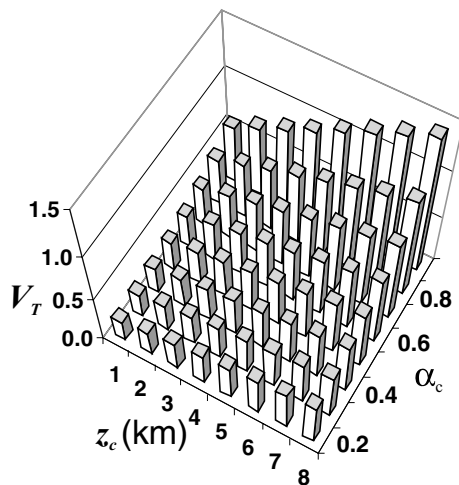

Fig. 9. Total life (V_T) in DAWHYC as a function of cloud albedo (α_c) and height (z_c), during the active condition and a varying solar luminosity.

oscillations are consistent with clear-cut oscillatory dynamics in the Earth's hydroclimatic processes (see fig. 1 of Ghil, 2002).

   Oscillations in DAWHYC emerge out of the couplings and feedbacks between the model variables representing the energy balance, the hydrological cycle and biota. All these components are coupled through temperature, since it depends on the energy balance and affects both biological and hydrological dynamics. Note that T is present in the equations modeling the energy balance, the growth rate of the daisies and evapotranspiration. Consequently, two main feedbacks take place in DAWHYC: biota–climate and clouds–climate feedbacks. The first one is the fundamental feedback of the DW models, established between

temperature (T) and the area fraction occupied by daisies (a_b and a_w) through albedo. Daisies thus regulate the average planetary albedo by varying their areal extent, which in turn affect the planetary radiative balance and average temperature, thereby controlling the growth rate of daisies. Hence, the occurrence of oscillations requires the existence of the biota–climate feedback resulting from the presence of both species of daisies throughout time; in other words from the maintenance of the planetary biodiversity.

   The clouds–climate feedback is established among evapotranspiration, clouds and precipitation, through the hydrological cycle represented by eq. (8). To understand further this feedback mechanism let us consider the case for which $a_c = 1$, and then $E = 0$ due to the full saturation of the atmosphere. When $a_c = 1$, precipitation reaches its maximum value and $da_c/dt < 0$, thus reducing the saturation degree of the atmosphere, which in turn allows for an increased evapotranspiration flux ($E \neq 0$). On the other hand, for $a_c = 0$ then $P = 0$ because the atmosphere is devoid of water vapour. Nonetheless, if $a_c = 0$ then evapotranspiration reaches its potential rate ($E = E_p$) and $da_c/dt \geq 0$, thus increasing the atmospheric water content, which in turn allows for an increased precipitation flux ($P \neq 0$). Given the non-linear dependence of E_p on T, the described mechanism intrinsically depends on the energy balance, and therefore it is coupled with the whole system. The functioning of the hydrological cycle on Earth's system involves similar albeit much more complex mechanisms.

   In this regard, let us consider a simple example. For an energy-limited environment, an increase in surface temperature implies an increase in evapotranspiration flux, which in turn increases the atmospheric water vapour content. Also, there is an exponential dependence of the atmospheric water vapour content with respect to temperature, as stated by the Clausis–Clapeyron equation (e.g. the water vapour content of the terrestrial atmosphere doubles per 10 K of surface temperature rise; Raval et al., 1989). Then, clear-cut positive feedback mechanisms exist between the greenhouse effect and the atmospheric water vapour, which in turn increase the land surface temperature, and so on (p. 156 Barry and Carleton, 2001).

   Gorshkov et al. (2004) hypothesize that such a positive feedback mechanism could lead the Earth to a complete evaporation state of the hydrosphere, if it were not for the role of life. Furthermore, they argue that the existence of a liquid hydrosphere in the Earth's surface implies an inherent thermodynamically unstable state whose persistence through geological time points to the existence of a 'biotic regulation of the environment' (Gorshkov et al., 2000), which in our opinion extends Gaia theory. In this regard, Figure 5 shows a region of parameter values for which high mean temperatures are produced by a runaway greenhouse effect, similar to that undergone by Venus. On the other hand, most studies on the controls over the habitable zone suggest that Earth has not yet reached the inner boundary of the habitable zone even in the absence of life. In other words, the positive

feedback would not yet have reached runaway, even without life (Tim Lenton, personal communication, 2008).

The occurrence and nature of oscillations are controlled by the planetary heat capacity and also by cloud albedo and height. An exhaustive identification and description of all of the possible equilibrium states (whether oscillatory or not) requires studying the system's non-linear dynamics, which goes much beyond the goals of this work. However, our numerical results allow us to conclude on the roles of heat capacity and cloud characteristics on the identified oscillations, as follows.

A null heat capacity in DAWHYC cause the collapse of oscillations for all combinations of cloud characteristics ($1 \leq z_c \leq 8$ km, and $0.2 \leq \alpha_c \leq 0.9$), as temperature tends to stabilize at a fixed point rather than in a limit cycle. Mathematically, removal of the heat capacity substantially changes DAWHYC by eliminating the ordinary differential equation for T. Thus, for $c_p = 0$, solutions for T are to be obtained from a fourth order polynomial function and the time rate of change of temperature tends to infinity ($dT/dt \rightarrow \infty$ as $c_p \rightarrow 0$, see eq. 6), which means that the planet instantly responds to solar forcing by changing its temperature.

Contrary to NGK99, a positive heat capacity value in DAWHYC is a necessary but not a sufficient condition for the occurrence of oscillations. The DAWHYC shows that the hydrological cycle and clouds can explain the occurrence of six different equilibrium states in the system (see Table 2), including oscillatory and non-oscillatory dynamics, for a fixed heat capacity (similar to that in NGK99). This implies that the sole presence of $c_p > 0$ does not necessarily cause the emergence of self-sustained oscillations in DAWHYC, and that cloud characteristics strongly control the occurrence and nature of oscillations.

Results from both DAWHYC and NKG99 show that oscillation period increases with the heat capacity, as seen in their fig. 4 and in our Fig. 10. Also, for fixed values of cloud albedo and height, a reduction in c_p turns the system from a limit cycle (oscillatory) to a fixed point (non-oscillatory) attractor. Sensitivity of the oscillation period to heat capacity is consistent with the fact that a thermodynamic system with a larger (lower) heat capacity is more (less) resistant to change its internal energy, which is reflected in DAWHYC's and NGK99's lower (higher) frequency oscillations. Such longer-period (shorter-period) oscillations point to higher (lower) climatic persistence, consistent with higher (lower) heat capacity values. This is clearly seen in the energy balance eq. (1), whereby dT/dt is inversely proportional to c_p.

When oscillations occur in DAWHYC, their amplitude and period are strongly controlled by cloud characteristics. Differences in the amplitude and period of oscillations can be understood as self-adjustment mechanisms that maintain the system in an oscillatory equilibrium state, or that stabilize the system in spite of the imposed changes in cloud characteristics, which in turn are external drivers as long as they are prescribed and do
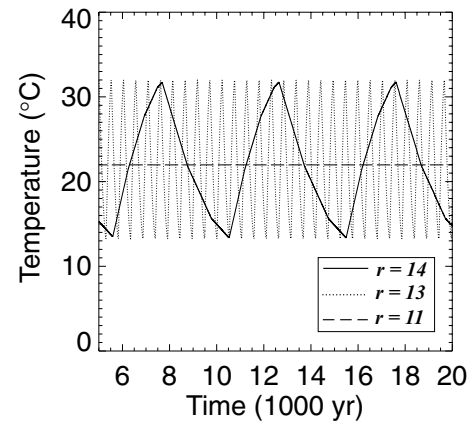

Fig. 10. Temperature oscillations with $L = 1.0$, $\alpha_c = 0.7$ and $z_c = 4$ km, depending on $c_p = 3.0 \times 10^r$. Values of the power r are specified for each line. The corresponding plot for $c_p = 3.0 \times 10^{12}$ is represented by very high-frequency less amplitude oscillations (not shown for improving visualization).

not depend on the system's dynamics. The hydrological cycle and clouds allow for the existence of different limit equilibrium states in DAWHYC. In this regard, the existence of diverse equilibrium states in the Earth's climate system has been discussed by several authors (e.g. Lenton and Lovelock, 2001).

Three different kinds of temperature oscillations can be distinguished depending on the isolated influence of cloud characteristics (α_c and z_c) on the climate system: an increase (decrease) in cloud albedo induces a higher (lower) amount of radiation being reflected to space and a lower (higher) cloud height induces a stronger (weaker) greenhouse effect owing to higher (lower) cloud temperatures. The first kind of oscillations is associated with 'warming clouds', with either very low albedo or very low height, or a combination of low albedo and height, as shown in Fig. 2. The dynamics is characterized by shorter, rapidly rising limbs and longer, concave descending limbs, thus giving rise to longer periods of white daisies' predominance over black ones. On the other hand, either very high albedo or very high clouds, or a combination of high albedo and height ('cooling clouds'), give rise to the appearance of the second kind of oscillations, as shown in Fig. 4. These oscillations show longer convex rising sections and shorter rapidly descending sections, associated with longer periods of black daisies' predominance over white ones. The described differences between oscillations from warming or cooling clouds can be explained in terms of the climatic (temperature) persistence, so that the planet is more prone to warming or cooling depending on the existence of warming or cooling clouds, respectively. Figure 3 shows that the third kind of oscillations are characterized by quasi-linear ups and downs (as in NGK99), resulting from the contrasting effects of warming and cooling clouds.

Our distinction between 'warming' and 'cooling' clouds is based upon the isolated influence of each parameter (α_c and z_c) on the climate system, so that warming (cooling) clouds do not imply higher (lower) planetary average temperature (as estimated in Fig. 5), because this temperature, which represents climate in DAWHYC, results from the non-linear interactions among all components of the climate system. The role of life tends to counteract the warming and cooling effects from clouds. Such conclusion arises from the signs in Table 2. Whenever life becomes extinct at equilibrium state 1, the system's response to the presence of warming clouds always increases its temperature beyond that without clouds (NGK99). If only one of the species survive, as in equilibrium states 2 and 4, the system's response to the presence of warming (cooling) clouds tends to warm (cool) the planet more than in NGK99. In contrast, for the co-existence of both daisies species (equilibrium state 6), signs in Table 2 show that warming (cooling) clouds tend to produce oscillations around a lower (higher) mean temperature than those in the cloud-lacking NGK99. This latter result points out a biologically mediated counteraction resulting from the prescribed biological advantage of black (white) daisies to proliferate under low (high) temperatures, as is generally assumed in DW and its variants, so that cooling (warming) clouds tends to favour black (white) daisies, which in turn tend to warm (cool) the surface. Implications of this assumption are discussed in Lenton (2004) and Gorshkov et al. (2004). As a matter of fact, Fig. 5 shows that the maximum average temperature for the occurrence of self-sustained oscillations ($\overline{T}_{o,\max} = 24.92\,°C$), is associated with values of $\alpha_c = 0.7$ and $z_c = 8\,km$, which correspond to cooling clouds. Such maximum occurs because oscillations with the largest predominance of black daisies ($B_{p,\max} = 0.56$ in Fig. 6) occur for $\alpha_c = 0.7$ and $z_c = 8\,km$, which maximizes the warming effect from black daisies.

In summary, the net global effect from clouds in DAWHYC can be either to cause warming or cooling (see signs in Table 2). These effects do not arise as a separate consequence of the greenhouse effect and the reflection of short-wave radiation, but from the non-linear interactions between clouds and the rest of the climate system components. In the Earth's system, it has been suggested that the overall radiative influence of clouds leads to cooling the planet (Ramanathan et al., 1989).

Beyond the identified effects on climate dynamics (temperature), the presence of the hydrological cycle and clouds control the biological dynamics. In NGK99, the maximum area fraction that can be occupied by each type of daisy is always 0.7, which corresponds to the system's carrying capacity, estimated as the maximum of the difference $(1 - \gamma/\beta_i)$, with $\beta_i = 1.0$ and $\gamma = 0.3$ (Lenton and Lovelock, 2001). Such a constant value does not hold any longer in DAWHYC, even though the growth and mortality rates of daisies remain unchanged. For instance, for $\alpha_c = 0.2$ and $z_c = 7\,km$, the maximum area fraction occupied by black daisies is about 0.4 at any time (oscillations not shown), as their growth rate is strongly restricted by the presence of very

dark clouds. This result can be interpreted in terms of an environmental constraint for life imposed by the combined role of the hydrological cycle and clouds. Thus, and opposed to NGK99 and other variants of DW, the ecosystem's carrying capacity of DAWHYC is not solely determined by the maximum growth rate and the constant mortality rate of daisies, but it is also restricted by environmental conditions driven by the hydrological cycle and clouds. Clear-cut restrictions for life from environmental conditions do appear in the Earth's climatic system (e.g. Budyko, 1974; Olff et al., 2002). Also, predominance of either species of daisies is sensitive to the presence of the hydrological cycle and clouds, as shown in Fig. 6. Therefore, changes in cloud albedo and height within DAWHYC can significantly modify the ecological dynamics. With regard to the Earth's system, this can be related to the fact that environmental conditions are determinant in establishing the predominance amongst species, and even more that the coupling between climate and ecosystem structure and function leads to complex behaviour (Solé and Bascompte, 2006, p. 295).

To further elucidate and summarize the influence of the hydrological cycle and clouds on the climate–biota system dynamics of DW (DAWHYC) under constant external solar forcing, let us make the following considerations. The original DW assumes an exact balance between the system's input and output radiation, which means that the internal energy of the system is kept constant, and that the system responds instantly to changes in the external forcing. Such an assumption is modified in NGK99 by introducing the heat capacity (c_p) to represent the temporal variability of the system's internal energy and its response. In this context, the overall effect of the hydrological cycle and clouds on DAWHYC's dynamics becomes clear-cut: the internal energy is affected through energy redistribution by clouds (warming greenhouse effect and cooling by short-wave reflection), which in turn depends on precipitation and evapotranspiration, as these fluxes control the amount of clouds. Thus, DAWHYC's dynamics is not only governed by the external forcing (as in DW) or by the external forcing and heat capacity (as in NGK99), but also by the role of the hydrological cycle and clouds. The presence of clouds modify the time rate of change of the system's internal energy, and thus the hydrological cycle operates as the mechanism whereby cloud dynamics are coupled with the energy balance. In this manner, oscillations found in diverse variables of DAWHYC depend on both the external forcing and the heat capacity, as in NGK99, but also on the hydrological cycle and clouds. Given that such oscillations correspond to possible equilibrium states of the system, our previous conclusion allows for the occurrence of diverse equilibrium states in DAWHYC, including those of oscillatory and non-oscillatory nature, which in turn represent different physical and biological dynamics, even under constant values of solar luminosity or heat capacity. For those equilibrium states of oscillatory nature, the presence of the hydrological cycle and the characteristics of clouds in DAWHYC strongly control the frequency and amplitude of oscillations, which means that

the cloudy hydrological cycle modifies the system's response by controlling its internal energy, regardless of variations in solar external forcing and heat capacity.

4.2. On the influence of clouds under variable external solar forcing

The most remarkable result of the second experiment is the maintenance of the system's self-regulation capacity in the presence of an active cloudy hydrological cycle for a large range of solar luminosity values. Self-regulation goes beyond temperature and involves the hydrological cycle and clouds altogether. This is quite an interesting and novel result, since it allows us to extend the original DW idea of temperature self-regulation to that of hydrological cycle and cloud self-regulation, in the average sense suggested by Jarcourt and Raymond (1992), depicted for temperature (Fig. 7a) and hydrological cycle and clouds (Fig. 7c). It can be seen that for a wide range of luminosity values, the corresponding attractors are not fixed points, rather limit cycles translated into finite amplitude oscillations around a mean state. Thus, temperature self-regulation (climate homeostasis), which constitutes an emergent property in DW and NGK99 (see their fig. 5), is extended in DAWHYC to self-regulation of the hydrological cycle and clouds.

The extent to which the hydrological cycle influences DAWHYC's long-term dynamics depends on equilibrium values of potential evapotranspiration and precipitation. Therefore, a detailed interpretation of Figs. 7a and c is in order. The solar forcing value (L, luminosity) acts as a control parameter of the system's equilibrium states, which in turn are associated with values of equilibrium temperature (T^{eq}). Let us focus the analysis of Figures 7a and c to the case of neutral condition, to isolating the effects of the hydrological cycle, although these effects are also present during the active condition.

All the possible equilibrium states of potential evapotranspiration and precipitation can be classified into three groups: $F^{eq} = 0, 0 < F^{eq} < 1$ and $F^{eq} = 1$, where F^{eq} represents either E_p^{eq} or P_p^{eq} (at equilibrium). Each of these states are determined by their physical constraints, for example, the condition that maximum possible cloudiness is 100%, (recall how P_{max} is estimated in eq. 11), and that potential evapotranspiration (E_p) has lower and upper limits determined by those temperatures for which E_p reaches minimum (0 at $T = 4\,°C$) or maximum (1 at $T \sim 40\,°C$) values. Therefore, three different ranges can be distinguished for the curves representing the equilibrium values of temperature (T^{eq}) and cloudiness (a_c^{eq}) as functions of luminosity, as follows:

(1) For $L < \sim 0.67$, equilibrium states correspond to those for which $T^{eq} \leq 4\,°C$, and potential evapotranspiration is null, ($E_p = 0$).

(2) For $\sim 0.67 < L < \sim 0.98$, equilibrium states correspond to those for which $4\,°C < T^{eq} < \sim 40\,°C$, which are precisely those temperature values for which equilibrium potential evapotranspiration smoothly transits from $E_p = 0$ to 1. Such a transition is characterized by a monotonous increase in the behavior of the variables representing the hydrological cycle and clouds (a_c shown in Fig. 7c; E and P not shown).

(3) For $L > \sim 0.98$, equilibrium states correspond to those for which $T^{eq} > \sim 40\,°C$, which in turn correspond to those for which $E_p = 1.0$ and $P_p = 1.0$.

Therefore, during the neutral condition, an increasingly active and non-regulated (yet bounded) hydrological cycle arises as a consequence of an increasing solar forcing value. In contrast, during the active condition, both the temperature and the hydrological variables are self-regulated for a wide range of solar luminosity values as a result of biota-environment feedbacks. Note that for the 'dead planet' condition the transition described in item (2) does not occur because of the absence of hydrological cycle and clouds. Moreover, note that differences between the neutral and dead planet conditions in Fig. 7a, are entirely due to the presence of the hydrological cycle and clouds in the former one.

For better grasping the roles of the hydrological cycle and clouds, self-regulation characteristics can be compared among DAWHYC, NGK99 and other variants of DW. In terms of luminosity range and total life, the self-regulation capacity of DAWHYC can be either stronger or weaker than NGK99's, depending on cloud characteristics. Estimates of the luminosity range and total life in DAWHYC during the active condition differ from those values of different variants shown by Lenton and Lovelock (2001) (see their table 1). Such variants differ from DAWHYC not only in their lack of the cloudy hydrological cycle, but also in those functions representing the energy balance and the growth rate of daises. Therefore, it is not possible to determine the isolated role of the hydrological cycle and clouds in explaining the observed differences in L_R and V_T between DAWHYC and other DWs. However, generally speaking, it is worth noting that the maximum luminosity range and total life in DAWHYC ($L_{R,max} = 2.32$ and $V_{T,max} = 1.449$) are only lower than L_R and V_T in the variant of 'Extended albedo mutation' ($L_{R,max} = 2.46$ and $V_{T,max} = 1.712$), developed by Lenton and Lovelock (2001). This variant involves an extended adaptation capacity responsible for high values of L_R and V_T. Given that such adaptation capacity is missing from DAWHYC, the appearance of larger values of L_R and V_T than almost all those identified by Lenton and Lovelock (2001), points to DAWHYC's potentially high self-regulation capacity increase owing to the combined action of the hydrological cycle and clouds. There is no *a priori* reason for which one would expect such a wide range of habitability in DAWHYC as in the 'extended albedo mutation' model. That means that the dynamics of the hydrological cycle and clouds can make the planet more habitable for life,

independent of the capacity for biological adaptation. This is a key finding of DAWHYC.

Differences between DAWHYC and NGK99 also include the luminosity range limits (L_m and L_M). Whereas in NGK99 daises do not survive outside the range $0.62 \leq L \leq 1.57$, in DAWHYC the span of life ranges from $L_{m,min} = 0.30$ to $L_{M,max} = 3.26$, which means that under certain conditions set forth by cloud albedo and height, the planet would be habitable for such a wide range of values of L. In all cases, both the total life and luminosity range in DAWHYC are much larger during the active condition than during the neutral one (not shown), which highlights the importance of life on the system's self-regulation capacity.

Our results show that the presence of the hydrological cycle and clouds can either augment or diminish the planetary system's self-regulation capacity, depending on cloud characteristics. Hydrological cycle, clouds and biota are mutually coupled in DAWHYC through temperature; yet there are no mechanisms whereby life could have an influence on, say, the characteristics of clouds. In the Earth's system, these characteristics are influenced by biological processes. At this point, it is worth asking whether discernible relations between the hydrological cycle, clouds and life have evolved on Earth, and, if so, whether such interactions support Gaia theory, in the sense that feedbacks contribute favourably to the existence of life itself. This question can be approached from two viewpoints. First, it has been thoroughly established that life on Earth affects the hydrological cycle and clouds (e.g. Hutjes et al., 1998; Miller and Rusell, 2004; Marzeion and Timmermann, 2005; Makarieva and Gorshkov, 2007). Evapotranspiration becomes the most important mechanism by which biota influences the hydrological cycle and clouds, which in turn affect the atmospheric water and energy budgets. Probably, the second major influence of biota on clouds results from the production of cloud condensation nuclei (CCN), which affect cloud's formation and radiative properties (e.g. Shaw, 1983; Charlson et al., 1987; Andreae et al., 2004; Claeys et al., 2004; Meskhidze and Nenes, 2006; Vallina and Simó, 2007). Second, the existence of biota–clouds and/or biota–hydrological cycle (biota–environment) interactions, which give rise to 'beneficial' effects for life, and whether such interactions could have been evolved through natural selection, is still an open debate (e.g. Lenton, 1998, 2002, 2004; Betts 1999; Downing and Zvirinsky, 1999; Kirchner, 2002, 2003; Volk 2002, 2003, 2004; Lenton and Wilkinson, 2003; Gorshkov et al., 2004; Wilkinson, 2004). In light of these and inspired in our results, we propose two hypotheses, as discussed next.

First, under the Gaia theory and using the aforementioned notion of the 'biotic regulation of the environment' (Gorshkov et al., 2000), we propose that the influence of biota on clouds is not inadvertent and therefore not merely the result of random effects: in the Earth's system, the biota affects the formation and radiative properties of clouds, so that beneficial effects for life emerge from biota–clouds interactions, by enhancing the global amount of life and extending the life span. A first observation

supporting this hypothesis might be the net cooling effect from clouds (Ramanathan et al., 1989) in the face of global warming. Several additional predictions and observations support the proposed hypothesis. For instance, Betts (1999) suggests the existence of vegetation–climate feedbacks producing 'beneficial' effects for life, by increasing continental precipitation, reducing temperature extremes, increasing net primary productivity and increasing biota's self-sustaining capacity. Also, Miller and Rusell (2004) suggest that interactions between biota and the hydrological cycle improve the environmental conditions required for the existence of vegetation in northern Africa. Although finding counter-examples might also be possible, it is at least plausible to conjecture a Gaian-like coupling of the biota–clouds–hydrological cycle system.

Second, we hypothesize the existence of a maximum self-regulation capacity principle that acts on certain cloud characteristics, which are associated with environmental conditions necessary to sustain life (e.g. Kleidon, 2004). The net result is to increase the occurrence of those combinations of cloud albedo and height, which together produce a higher degree of self-regulation. Were such a maximization principle to exist, then cloud albedo and height would be those which maximize the luminosity range and total life. Different optimization principles have been studied in DW. Pujol (2002) assumes that the horizontal heat transport in DW obeys the principle of maximum entropy production (MEP) and finds that this assumption increases DW's self-regulation capacity with respect to the original version. A similar, yet more general approach is used by Toniazzo et al. (2005). They show that the applicability and consequences of MEP in regulating DW depends on factors such as the number of co-existing species of daisies (two or more) and on the relation between the rate of change of daisy coverage (adjustments) and heat fluxes. On the other hand, Ackland (2004), working with a 2-D DW, argues that the long-term dynamics of DW is governed by a principle of 'maximization of the amount of life', rather than a MEP. In a much broader sense, Toniazzo et al. (2005) and Kleidon and Fraedrich (2005) connect the MEP principle with Gaia theory and show evidence that the outcome of the coupled atmosphere–biosphere system may lead to environmental homeostasis, under the assumption that biosphere adjusts to MEP when environmental conditions change.

5. Conclusions

We have constructed a DW model that involves a simplified hydrological cycle and an explicit representation of clouds, both of which play a decisive role in regulating the internal energy of the system. In a constant solar forcing and planetary specific heat scenario, the presence of the cloudy hydrological cycle gives rise to different equilibrium states of either a steady non-oscillatory nature (fixed point attractor) or oscillatory (limit cycles), biotic (housing one or two species of daisies) or abiotic (uninhabitable planet). For most cases, the equilibrium state consists of

self-sustained oscillations in the dynamics of variables associated with clouds and hydrological cycle, as well as in those associated with biota and climate. The most relevant features of those oscillations can be summarized as follows: (1) they appear as an emergent property of the system's coupled physical and biological dynamics; (2) they reflect physically consistent couplings between the system components; and (3) they constitute a robust result in the sense that they appear for most combinations of cloud characteristics. Similar oscillations are found in NGK99, whose frequency is sensitive to changes in the planetary specific heat. Contrary to NGK99, $c_p > 0$ is a necessary but not sufficient condition for the occurrence of self-sustained oscillations in DAWHYC. The hydrological cycle and clouds in DAWHYC produce different equilibrium states of oscillatory or non-oscillatory nature, even when $c_p > 0$. When oscillations occur, their dynamics are consistent with those in the hydroclimatic and biological records on Earth. The identified equilibrium states are associated with different conditions of habitability and biological predominance, such that the cloudy hydrological cycle affects the general ecological dynamics of DW.

One of DW's fundamental results is the emergence of self-regulation arising from biota–environment feedbacks, in spite of a variable energy input. It also holds for DAWHYC in an average sense, as the long-term dynamics of the planetary temperature oscillate around an average value. Moreover, DAWHYC's self-regulation is also witnessed in the variables representing the hydrological cycle and clouds. The presence of life becomes a necessary condition for the system to maintain its self-regulation capacity in light of changes of the external forcing (solar luminosity). By the same token, the presence of both species of daisy, or maintenance of biodiversity, is also necessary for the occurrence of self-sustained oscillations in constant solar luminosity scenarios. This latter result demonstrates the fundamental role of life's amount and diversity on DAWHYC's self-regulation. Such self-regulation is a consequence of both positive and negative feedbacks, whose occurrence is another fundamental emergent feature of DAWHYC.

Clouds play the dual role of either cooling or warming DAWHYC. The net outcome depends on the balance between warming from the greenhouse effect of water vapour and the cooling from albedo-mediated short-wave reflection. A similar dichotomy is seen in the Earth's system. Its definite long-term outcome is still an unsettled matter (Washington, 1995), thus posing a fundamental question for the future Earth climate in light of anthropogenic greenhouse warming.

The most important role that the hydrological cycle and clouds play is through reducing or augmenting the self-regulation capacity of DAWHYC's climate–biota system. A remarkable finding of this work is that the dynamics of the hydrological cycle and clouds can make the planet more habitable for life, independent of the capacity for biological adaptation. Whether the hydrological cycle and clouds increase or decrease the Earth's system self-regulation capacity is an open question. Also, whether the

evolution of the climate–biota system on Earth obeys some optimization principle remains as an open question. If so, what is such a principle, and does it act as a single principle throughout time? Or rather does it evolve, say, with solar luminosity, and could it be that multiple optimization principles act alternatively or indeed even compete with one another. The DAWHYC constitutes a simple framework to explore possible answers to such questions regarding the Earth system. Although results from the two experiments performed on DAWHYC do not give us a single answer, for instance on the existence of a single specific optimization principle, they do suggest that the hydrological cycle and clouds play decisive roles in controlling the Earth climate system dynamics. In this regard, we conjectured that biota affects the formation and radiative properties of clouds in the Earth's system, so that beneficial effects for life emerge from biota-clouds interactions, in terms of enhancing the global amount of life and extending the span of life. Furthermore, we hypothesized the existence of a maximum self-regulation capacity principle acting on certain cloud characteristics, associated with environmental conditions necessary to sustain life. Results from DAWHYC cannot be conclusive about the Earth's system, and therefore our hypotheses are proposed in the same spirit of Lenton and Lovelock (2001), for whom DW provides a model for answering what-if questions and to inspire multiple questions regarding the Earth's system.

6. Acknowledgments

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