SENSITIVITY EXPERIMENTS ON MULTIPLE EQUILIBRIA OF THE WATER CYCLE

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1. INTRODUCTION

The understanding of the interactions between atmosphere, oceans and continents, which enable the persistence and intensification of hydrologic anomalies in continental climates, is important to assess human impacts on the hydrological cycle and improve forecast skills (Tuinenburg et al., 2011; Brubaker and Entekhabi, 1995).

Bimodality was observed in the probability distribution of soil moisture in Illinois-USA, for the summer season, possibly linked to a positive feedback between soil moisture and precipitation at midlatitudes (D'Odorico and Porporato, 2004). Later, D'Andrea et al. (2006), hereinafter referred as DA, used a soil-atmosphere model and could predict the existence of multiple equilibria in the water balance.

In this study, our objective is to evaluate the sensitivity of the multiple equilibria to variations in key parameters and check whether this phenomenon can still be observed or not.

2. METHODOLOGY

The model developed here is similar to the one developed by DA in that it includes the main processes of mass and heat exchange between soil and atmosphere, as schematized in Figure 1; and the prognostic variables are four: the temperature and humidity of each medium.

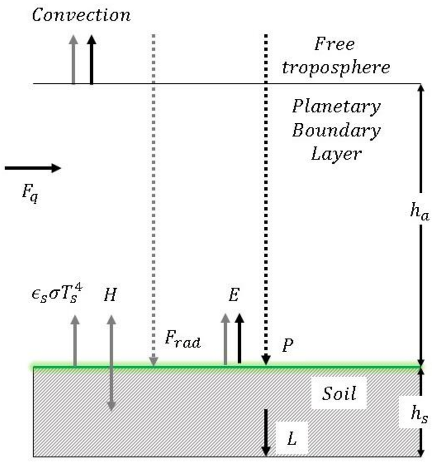

Figure 1 - Schematics of the model. Gray arrows represent energy fluxes and black arrows represent water fluxes.

The evolution equations (hourly time step) for atmospheric potential temperature θa (in K), air humidity qa (in kg of water per kg of air), soil temperature Ts (in K) and soil moisture qs (relative to saturation) are as follows, where H is the surface sensible heat flux and the other symbols are the same as used by DA:

$$\rho c_{pa} h_a \frac{\partial \theta_a}{\partial t} = H + \epsilon_a \epsilon_s \sigma T_s^4 - \rho c_{pa} h_a \left[\frac{\partial \Delta \tilde{\theta}_a}{\partial t} + \frac{1}{\tau_a}(\theta_a^* - \theta_a) \right]$$

$$\rho h_a \frac{\partial q_a}{\partial t} = E - \rho h_a \frac{\partial \Delta \tilde{q}_a}{\partial t} + F_q$$

$$\rho_s c_{ps} h_s \frac{\partial T_s}{\partial t} = F_{rad} - H - \epsilon_s \sigma T_s^4 - L_e E$$

$$h_{sa} \frac{\partial q_s}{\partial t} = P - E - L(q_s)$$

Most parameters remained the same from DA, but some were modified, such as active soil depth and hydraulic conductivity. Also, we had to assume a certain porosity to calculate the soil's water holding capacity. The soil parameters adopted correspond to sandy loam, for that is the type of soil closest to what was used in the previous study, and were taken from Laio et al. (2001 a).

Two stable states were observed when running our model starting from soil moisture conditions varying from 0 to 1 and keeping the initial values for the other three prognostic variables the same. Here, the values associated with each of the equilibrium states for temperature were between 2 and 6% different from DA, and between 1 and 16% different for humidity. Also, the threshold on initial soil moisture separating the two equilibria changed from 0.32 (DA) to 0.26, but we can consider that the final states were nearly the same and the current model is valid.

The dry state is reached for initial qs equal or less than 0.26: in this case, air (25 °C) and soil (26.6 °C) temperatures are high and evapotranspiration (E) equals precipitation (0.3 mm/day). As for initial values of qs above 0.26, the wet state is reached: air (17 °C) and soil (17.8 °C) temperatures are much lower than in the dry case and precipitation (3.4

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mm/day) is slightly higher than E (3 mm/day).

3. RESULTS AND DISCUSSION

3.1. Sensitivity to type of soil

We ran the model for five different types of soil using parameters from Laio et al. (2001 a). The threshold value for initial soil humidity separating the two equilibria states and the final soil moisture vary largely, as can be observed in Figure 2. However, the other three prognostic variables have kept the same values for each final state (wet or dry).

3.2. Sensitivity to evapotranspiration

To evaluate the response to evapotranspiration, we used values for maximum potential evapotranspiration (Emax) and evapotranspiration at wilting point (Ew) for different types of vegetation, taken from Laio et al. (2001 b). In one case, we used values higher than the previously considered, and lower ones in the other case. As shown in Figure 3, the changes in E affect all the prognostic variables for the wet equilibrium, but in the dry case only qs is affected.

3.3. Sensitivity to convergence

If the lateral moisture input Fq is 0.29 mm/day or lower, the final dry state will be reached independent of the initial soil moisture. In other words, even if the soil is initially saturated, the system will tend to the dry state for such low moisture convergence. On the other hand, if the Fq is 0.95 mm/day or higher, the final state will be wet independent of the initial soil moisture – the system tends to the wet state with time even if the initial soil condition is extremely dry.

The multiple equilibria are then observed only for a certain range of lateral moisture input, which is in accordance with the results obtained by DA.

4. CONCLUSION

The persistence of the equilibria states throughout the experiments supports the theory that this phenomenon can

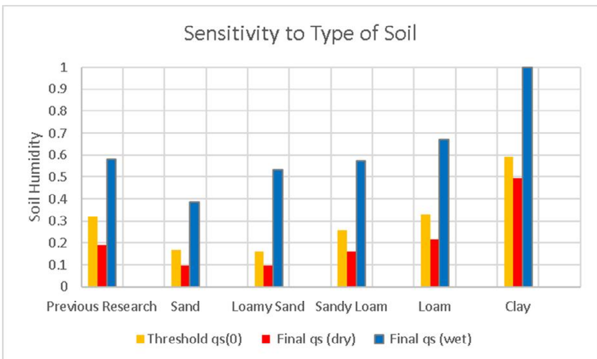

Figure 2 - Model's sensitivity to different types of soil.

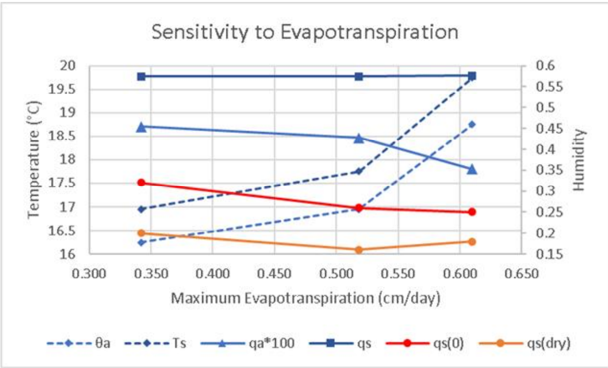

Figure 3 - Model's sensitivity to evapotranspiration. All the different shades of blue refer to the wet state.

explain the observational bimodality within a certain range of lateral moisture input. The type of soil is an important factor determining the soil humidity and the evapotranspiration rates play an important role in the whole water cycle for the wet equilibrium.

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