SENSITIVITY EXPERIMENTS ON MULTIPLE EQUILIBRIA OBSERVED IN A SOIL-ATMOSPHERE MODEL

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1. INTRODUCTION

Hydrologic anomalies tend to persist and intensify in continental climates due to interactions between atmosphere, oceans and continents. The understanding of these is important to assess human impacts on the hydrological cycle and improve forecast skills (Tuinenburg et al., 2011; Brubaker and Entekhabi, 1995).

Observational data from Illinois-USA showed a bimodal shape for the probability distribution of soil moisture in the upper 50 cm layer during the warmer season, possibly linked to the existence of a positive feedback between soil moisture and precipitation at the midlatitudes (D'Odorico and Porporato, 2004). A physical mechanism for the existence of this bimodality has been proposed by means of a coupled soil-atmosphere model, that could predict the existence of multiple equilibria in the water balance of the atmospheric boundary layer and the upper soil layer (D'Andrea et al., 2006, hereinafter referred as DA).

In the present study, the objective is to assess the model's sensitivity to variations in some key parameters and check if the bimodality can still be observed.

2. METHODOLOGY

2.1. Model description

The base model developed by DA includes the main processes of mass and heat exchange between soil and atmosphere (Figure 1). The prognostic variables are four, representing temperature and humidity conditions of soil layer and planetary boundary layer and the four resultant evolution equations are solved at an hourly timestep starting from various initial soil moisture conditions until the system reaches one of the equilibria states – that can be either wet or dry depending mainly on the initial humidity conditions.

The model developed for the current study features a slightly different approach for the soil layer and has been validated based on a comparison between its results and those obtained by the base model – we could conclude that the outcomes were very approximate in terms of the observed final equilibria states. Furthermore, sensitivity experiments were conducted by introducing modifications including adoption of different soil types, evapotranspiration rates and lateral moisture input.

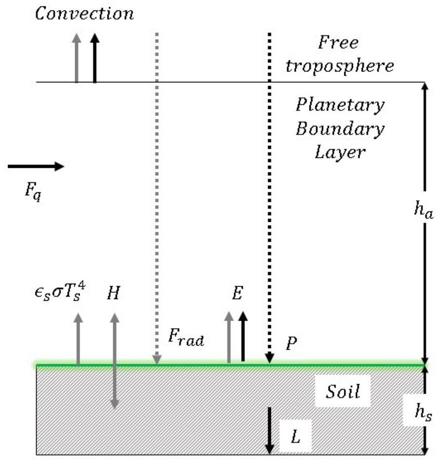

Figure 1 - Schematics of the model. Gray arrows represent energy fluxes and black arrows represent water fluxes.

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:

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

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

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

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

H is the surface sensible heat flux and the other symbols are the same as used by DA.

2.2. Model validation

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 the results 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 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 mm/day) is slightly higher than evapotranspiration (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). Depending on the type of soil, 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. The other three prognostic variables have the same values for each final state (wet or dry) independent of the type of soil.

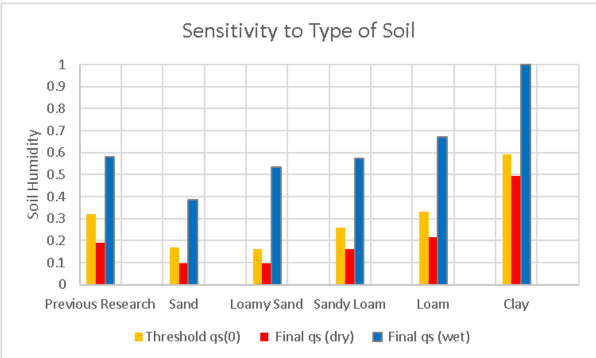

Figure 2 - Model’s sensitivity do different types of soil.

3.2. Sensitivity to evapotranspiration

To evaluate the model’s 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 ET rates 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 towards the dry state for such low moisture convergence. On the other hand, if the Fq is 0.95

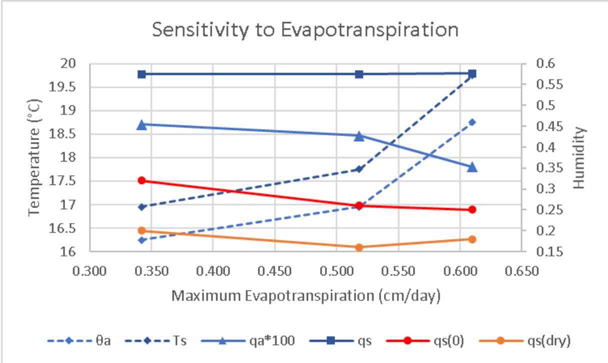

Figure 3 - Model’s sensitivity to evapotranspiration. The different shades of blue all refer to the wet state.

mm/day or more, 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 is then observed only for a certain range of lateral moisture input, according to the results obtained by DA.

4. CONCLUSION

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