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Developing a feedbacks toolkit for regional water resource assessments

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Abstract There is a need to include the atmospheric feedbacks that alter evaporative demand in a region when water availability is changed. This is because the water resource implications of large-scale irrigation or soil water depletion cannot be assessed unless the subsequent changes to air temperature, humidity and cloudiness are accounted for. Here, we propose a simple tool that can be used to assess such feedback strengths anywhere in the globe, although it will not always be appropriate. The tool is based on a simple box model for the planetary boundary layer, assuming a semi-permeable lid at the top, but taking advection into account as well. Sample calculations with a prototype of the tool and an analysis of atmospheric data in North America showed that atmospheric feedbacks can play an important role in water resource assessments in some regions. If the region has a relatively straightforward feedback regime dominated by one-dimensional feedback processes, this can be quantified using the simple tool.

Key words water resource management; evapotranspiration; land–atmosphere feedback

INTRODUCTION

The rain that falls, the clouds that form above us, the wind patterns and the temperature and humidity of the air around us, are to some extent affected by the roughness, the albedo and the wetness of the land below us (Shukla & Mintz, 1982). A feedback loop is sometimes established between the moisture held on and in the land surface and the evaporation and rainfall that deplete and supply the moisture store.

It is important to quantify this feedback loop, not only in weather forecast models but also in water resource prediction models. For instance, if a Water Resource researcher needed to assess the impact of doubling the extent of an irrigation scheme, he should include the impact that such an increase in wet soil might have on the clouds, rain, humidity and temperature of the region. Ignoring it may cause an error in his estimate of the evaporative demand or the incoming precipitation and lead to an inconsistent estimate of the irrigation required.

BACKGROUND

There are two main changes to the meteorological conditions that could occur as a result of a change in the land-surface state: the change in precipitation (Koster *et al*., 2004; Wang *et al*., 2007) or cloudiness (Ek & Holtslag, 2004), and the change in the evaporative demand (Schubert *et al*., 2004). Precipitation is particularly difficult to predict as it can be affected by large-scale weather patterns or complex processes such as mesoscale circulations or convective processes. The physics involved and the scale and complexity of the processes means that complex numerical atmospheric models are usually necessary to quantify impact of the land surface on cloudiness and precipitation, although a simple, analytical model can sometimes be used to assess the effect of the land-surface state on the likelihood of triggering convective precipitation (e.g. De Ridder, 1997). However, the change in the evaporative demand can sometimes lend itself to a fairly simple analysis. A simple method to take the impact of the feedback loop on evaporative demand into account is proposed in this paper.

There are direct effects of the land surface on the atmosphere such as the moistening/drying and heating/cooling of the Planetary Boundary Layer (PBL, the part of the atmosphere thermodynamically linked to the surface, typically about 1 km in depth at midday). The feedback exerted by this PBL change on the surface fluxes can be calculated directly. Some understanding of the PBL processes is required for this: the state of the (well-mixed dry) PBL is not only dependent on the surface fluxes of heat and moisture, but also on the overlying free atmosphere. For instance, daytime PBL drying can occur due to a mixing-in of dry air, in spite of a positive surface moisture flux. This feedback needs to be considered when trying to estimate diurnal evolution of surface evaporation (e.g. De Bruin, 1983; McNaughton & Spriggs, 1989; Jacobs & de Bruin, 1992).

METHODS

For our purpose, the PBL can be envisaged as a box of air of height h (m) with a semi-permeable lid at the top (McNaughton & Spriggs, 1986). This box grows as the day progresses with heat coming into the box from below and with air being entrained into the box from above. The evolution of the potential temperature ($\theta{\downarrow}m$) and specific humidity ($q{\downarrow}m$) within the boundary layer is governed by the latent heat (λE) and the sensible heat (available energy, A, minus latent heat: $A - \lambda E$) entering the PBL open-box from the surface, and the temperature and humidity of the air being entrained into the box from above as the box grows:

$$\rho c_p h \frac{\partial \theta_m}{\partial t} = (A - \lambda E) + \rho c_p (\theta_s(h) - \theta_m) \frac{\mathrm{d}h}{\mathrm{d}t} \tag{1}$$

$$\rho \lambda h \frac{\partial q_m}{\partial t} = \lambda E + \rho \lambda (q_s(h) - q_m) \frac{\mathrm{d}h}{\mathrm{d}t} \tag{2}$$

where θ_s, and q_s are, respectively, the potential temperature and specific humidity of the entrained air, ρ and c_p ($\approx$1005 J kg^{-1} K^{-1}) are the density and specific heat of the air, respectively, λ ($\approx$2.46 × 10^6 J kg^{-1}) is the latent heat of vaporization, E is the water vapour flux and t is time.

Using the method proposed by Huntingford & Monteith (1998), the rate of growth ($\mathrm{d}h/\mathrm{d}t$) is determined by the energy going into the PBL from the surface and the thermodynamic stability of the original morning profile:

$$\frac{\mathrm{d}h}{\mathrm{d}t} = \frac{(A - \lambda E) + 0.07 \lambda E}{\rho c_p (\mathrm{d}(\theta_\mathrm{s}(1 + 0.61 q_s)) / \mathrm{d}h} \tag{3}$$

The simplest expression for the morning profiles is a linear slope with lapse rates Γ_θ and Γ_q:

$$\theta_s(z) = \theta_{s0} + \Gamma_\theta z \tag{4}$$

$$q_s(z) = q_{s0} + \Gamma_q z \tag{5}$$

where z is height. This can be estimated from, for example, observed (radiosoundings), forecasted or re-analysed atmospheric profiles. According to Monteith (1965), we can calculate the evapotranspiration rate using:

$$\lambda E = \frac{\Delta A + \rho c_p \partial q / r_a}{\Delta + \gamma (1 + r_s / r_a)} \tag{6}$$

where δq is specific humidity deficit, Δ is the rate of change with temperature of the saturated humidity, γ is the psychrometric constant (= c_p/λ), r_a is the aerodynamic resistance and r_s the surface resistance.

Using the morning profiles to define the initial conditions regarding specific humidity, potential temperature and boundary layer height, these equations (1)–(6) can then be solved with a time varying A to give the evolution of the PBL with mixed-layer temperature, humidity and growth. The morning profiles are used to define the initial conditions. This simple tool that takes into account fundamental feedbacks between the atmosphere and the surface fluxes can be used to account for the impact of the feedbacks on the evaporative demand, for any changes to the land surface moisture content. The evaporative demand (*ED*) is defined to be the Penman-Monteith equation with $r_s = 0$, thus:

$$ED = \frac{1}{\Delta + \gamma}(\Delta A + \rho c_p \partial q / r_a) \tag{7}$$

ED for some sample profiles and sample surface moisture conditions are given in Table 1. The examples include the evolution of the temperature and humidity and subsequent *ED* with the default surface resistance (θ_{1D} and q_{1D}) as well as the *ED* with the temperature and humidity with the changed surface conditions ($\theta_{1D\text{new}}$ and $q_{1D\text{new}}$) for different lapse rates.

If the surface resistance in this simple PBL model is kept at roughly the value of the surface from which the observed profiles come, then, in the absence of lateral advection of air, the simulated evolution of the temperature and humidity should follow that observed. By assuming that deviations of the air temperature and humidity from this simple one-dimensional evolution are caused by of the advection of air from surrounding regions, it is possible to estimate the effect of this advection as follows:

$$\theta_{\text{adv}} = \theta_{\text{obs}} - \theta_{1D} \tag{8}$$

$$q_{\text{adv}} = q_{\text{obs}} - q_{1D} \tag{9}$$

These advected values of θ and q are assumed to ramp up linearly over the time from the morning profiles and can then be applied to any modelled value of θ and q in equation (7), to estimate the likely effect including this estimate of the advection of air. By recalculating the value of I*adv* and δadv it is possible to compare the influence of the local PBL feedbacks on the evaporative demand (equations (1)–(6)) to the influence of advected air (equations (8)–(9)) *EDadv*:

$$EDadv = \frac{1}{\Delta adv + \gamma}(\Delta adv A + \rho c_p \partial q adv / r_a) \tag{10}$$

Initial conditions are defined from morning atmospheric profiles of the temperature and humidity. The impact of advection of air on the feedback can then be assessed from afternoon profiles.

To demonstrate the utility in assessing the PBL structure for use in feedback studies, we computed the Priestley-Taylor parameter α (Priestley & Taylor, 1972) from ERA40 reanalysis fields (Uppala *et al*., 2005) for the USA and parts of Mexico and Canada. The parameter α is related to evaporative fraction ($EF = \lambda E/A$) by (Priestley & Taylor, 1972):

$$EF = \alpha \frac{\Delta}{\Delta + \gamma} \tag{11}$$

EF was estimated from the ERA40 latent and sensible heat flux fields, taking for each day the values corresponding to the maximum A for that day. Furthermore, Δ was computed from the midday air temperature at a height of 2 m. For these analyses, we used data for the summer months (June, July and August) of the years 1991–2000 (920 days).

RESULTS

To assess the possible influence of advection, in the example we use the values found by Santanello *et al.* (2009) of an advected increase of 4 degrees in potential temperature and a 0.001 kg/kg increase in humidity. Table 1 displays the new evaporative demand for the day, with and without the advected air for the different changes in surface conditions and different theoretical initial lapse rates.

The upper map of Fig. 1 shows the mean summertime (JJA) value of α. The lower map shows the number of days with $\alpha > 1$, representing days on which the evapotranspiration is (nearly) equal

Table 1 Evaporative demand (ED) under different conditions, using A = 500 W m^{-2}, θ_m = 293 K, q_m = 0.01 kg kg^{-1}, $\Delta\theta$ = 1 K, Δq = 0.01, r_a = 20 s m^{-1}, r_s = 60 s m^{-1}, h = 200 m.

Background r_s (s m^{-1})	Lapse rate, Γ (K m^{-1})	ED no feedbacks (mm d^{-1})	ED with feedbacks (mm d^{-1})	ED with advection – no feedbacks (mm d^{-1})	ED with advection and feedbacks (mm day^{-1})
60	0.003	9.45	6.38	10.51	7.43
60	0.005	9.53	9.39	10.59	10.46
500	0.003	13.22	6.38	14.29	7.43
500	0.005	14.25	9.39	15.33	10.46

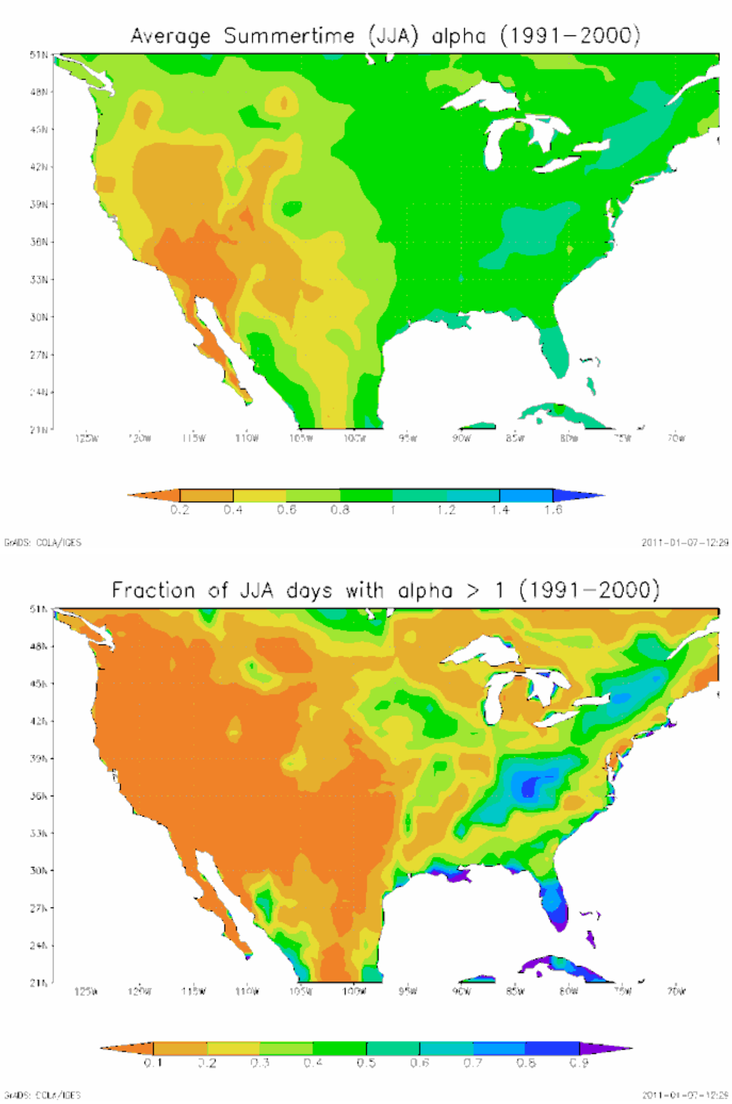

Fig. 1 Maps of the Priestley-Taylor parameter α for the USA from ERA40 data.

to the potential rate. That is the case only on a limited number of summer days in the domain considered here. These results are similar to the maps developed by Findell & Eltahir (2003a,b) and demonstrate where the land has the greatest influence over the atmospheric state (see also Conil *et al*., 2009, and D'Odorico *et al*., 2004, for a similar analysis). It is in the areas with low α where it is more likely that irrigation has to be applied and where large feedback effects are expected.

CONCLUSIONS

This tool can be used to assess feedback strengths anywhere in the globe, although it will not always be appropriate. Atmospheric feedbacks can play an important role in water resource assessments in some regions. In the example data set, it made a 30% decrease in evaporative demand in some cases. If the region has a relatively straightforward feedback regime dominated by one-dimensional feedback processes, this can be quantified using a simple model. The appropriateness of this depends on the spatial scale of the land-surface change.

The ERA40 profiles or profiles from other reanalysis fields can be used to make this analysis for the present-day climate, but the regions that are sensitive to the feedbacks may change with a new climate (Seneviratne *et al*., 2006). Water managers could obtain forecasted profiles from any weather forecast model to apply the tool in practice and assess *ED* for their specific situation.

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