Land-atmosphere coupling explains the link between pan evaporation and actual evapotranspiration trends in a changing climate

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[1] Decreasing trends in pan evaporation are widely observed across the world as a response of the climate system to changes in temperature, precipitation, incoming radiation and wind speed. Nevertheless, we only partially understand how trends in actual evapotranspiration are linked to those trends. Here, we use a model to show that regulation of the near-surface temperature and humidity by land-atmosphere feedbacks results in a strong connection between pan evaporation, actual evapotranspiration and vapor pressure deficit (VPD) depending on the climate forcings. When climate change occurs, the feedbacks direct the system towards a different combination of the three variables. If we know the trends in pan evaporation, VPD and wind speed, we can therefore infer the change in the forcings and estimate the trend in actual evapotranspiration. **Citation:** van Heerwaarden, C. C., J. Vilà-Guerau de Arellano, and A. J. Teuling (2010), Land-atmosphere coupling explains the link between pan evaporation and actual evapotranspiration trends in a changing climate, *Geophys. Res. Lett.*, *37*, L21401, doi:10.1029/2010GL045374.

1. Introduction

[2] A widespread decline in pan evaporation has been observed over the second half of the 20th century [*Peterson et al.*, 1995; *Golubev et al.*, 2001]. This was initially regarded as a large controversy—in an environment where temperature is rising, evaporation was expected to increase [*Brutsaert and Parlange*, 1998]. It is, however, only partially understood how pan evaporation is related to the actual evapotranspiration from its surroundings. Only few long term data sets are available for this variable [*Teuling et al.*, 2009; *Seneviratne et al.*, 2010]. Therefore, interpreting trends in pan evaporation is key to inferring past and future changes in the terrestrial water cycle. Three hypotheses [*Brutsaert and Parlange*, 1998; *Roderick and Farquhar*, 2002; *Roderick et al.*, 2007] with very different implications for the actual evapotranspiration have been put forward to explain decreasing pan evaporation.

[3] The first hypothesis stresses the fact that pan evaporation is a measure of the capacity of the atmosphere to take up water—it does not take into account the supply at the land surface. If global warming accelerates the hydrologic cycle, the increase in actual evapotranspiration reduces the atmospheric capacity to take up water, thus suppressing pan evaporation. This effect is likely strongest in water-limited environments.

[4] A second hypothesis links the decline to global dimming, which is the widely observed decrease in incoming short wave radiation due to increased aerosols and/or cloudiness [*Roderick and Farquhar*, 2002]. In humid climates, where evaporation is limited by the available energy rather than by the water supply at the land surface, this explanation is considered to be the main cause of decreasing trends in both pan evaporation and actual evapotranspiration [*Teuling et al.*, 2009].

[5] The most recent hypothesis is based on the observation that in many areas decreasing trends in pan evaporation coincide with decreasing trends in surface winds [*Roderick et al.*, 2007, 2009b]. This phenomenon—stilling—reduces the efficiency of the atmosphere in taking up water. Especially in water-limited regions, the pan evaporation is expected to react strongly to stilling [*Roderick et al.*, 2009b], although the implications for the actual evapotranspiration are yet unsure.

[6] In this paper, we investigate the effects of each of the climate forcings—warming, increasing precipitation, dimming and stilling—separately and provide a method to infer the trend in the actual evapotranspiration by linking trends in forcing with trends in the capacity of the atmosphere to take up water.

2. Methodology

[7] The theoretical basis of our study is that the land surface and the atmosphere form a tightly coupled system and should be analysed as such [*Lyon et al.*, 2008; *Seneviratne et al.*, 2010]. The lowest part of the atmosphere, the turbulent atmospheric boundary-layer (ABL), regulates the surface evaporation by controlling the temperature and humidity of the near-surface air and thus the capacity of the atmosphere to take up water—a quantity usually expressed in terms of vapor pressure deficit (VPD) [*Raupach*, 2000; *van Heerwaarden et al.*, 2009]. The regulating feedbacks have time scales shorter than one day [*Raupach*, 2000], whereas the time scale of the trends in the forcings is much longer. Therefore, pan evaporation, actual evapotranspiration and VPD do not respond proportionally to the climate forcings, because they are controlled by land-atmosphere feedbacks. For this reason, understanding how the climate forcings influence the local dynamics of evaporation on a daily time scale is essential in interpreting observed pan evaporation trends.

[8] We investigate the impact of feedbacks by using a coupled land-atmosphere model that features a slab model for the ABL, the Penman-Monteith equation for solving the surface energy balance and a two-layer force-restore soil

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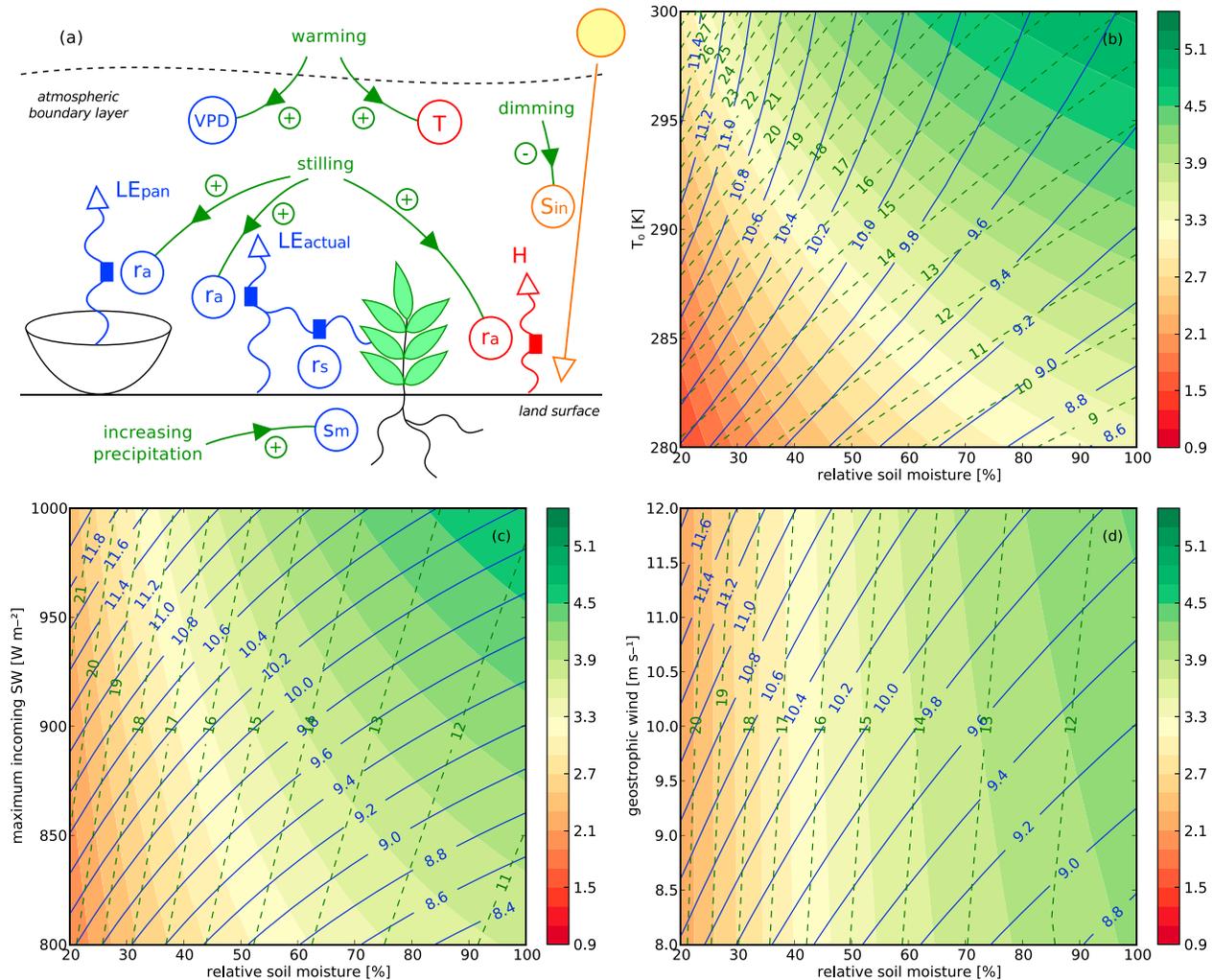
Figure 1. Impact of climate forcings on pan evaporation and actual evapotranspiration. (a) How climate forcings enter the daily cycle of evapotranspiration. Here, LE_{pan} is the pan evaporation, LE_{actual} is the actual evapotranspiration, VPD is the vapor pressure deficit, T the temperature, S_{in} the incoming short wave radiation, r_a the aerodynamic resistance, r_s the surface resistance and s_m is the soil moisture. (b–d) Daytime sums (over 10 h) of actual evapotranspiration in mm (shades), pan evaporation in mm (blue contour lines) and the daytime average in vapor pressure deficit in hPa (green contour lines) as a function of the soil moisture and the early morning temperature (Figure 1b),the incoming short wave radiation (Figure 1c) and the geostrophic wind (Figure 1d). All model runs have $T_0 = 290$ K, relative soil moisture = 60 %, maximum incoming short wave radiation = 900 W m^{-2} and geostrophic wind = 10 m s^{-1} as a reference, which is inspired on the Great Plains climatology. Figures 1b–1d therefore share identical values at their center coordinates.

model [*van Heerwaarden et al.*, 2010]. Canopy resistance is parameterized for grass. We set up the model to reproduce one day that is based on the climate of the Great Plains and compute the daytime sums of actual and pan evaporation and the average VPD at 2 m. To investigate the impact of changes in the climate forcings, we perform sensitivity analyses on the early-morning temperature (warming), soil moisture (increasing precipitation), incoming short wave radiation (dimming) and geostrophic wind speed (stilling). These variables are all either initial or boundary conditions of our model. In Figure 1a we show how the climate forcings enter into the daily dynamics of evaporation. Three of the climate forcings, respectively temperature, wind speed and the amount of incoming short wave radiation, can be of similar magnitude in other regions, both arid and humid, where decreasing pan evaporation has been observed.

Therefore, by taking soil moisture as one of the two free variables in each sensitivity study, our results estimate the impact of the climate forcings from arid to humid conditions, despite being based on the Great Plains climatology.

[9] While our research focuses on local feedbacks according to the recent framework of *Shuttleworth et al.* [2009], our setup also covers partly nonlocal changes in the atmosphere, as increases in early morning temperature are merely related to global warming, while changes in the geostrophic winds are associated with modifications to the global atmospheric circulation.

3. Separate Impact of Climate Forcings

[10] First, we find that both actual and pan evaporation respond positively to warming (Figure 1b). The former,

however, is more sensitive to the rise than the latter and at high temperatures in arid conditions (low soil moisture), pan evaporation even becomes insensitive to temperature variations, something that has been observed in data sets over Australia [*Roderick et al.*, 2009a]. VPD is found to increase strongly with temperature if other conditions are kept constant (moving from bottom to top in Figure 1b), whereas pan evaporation becomes relatively insensitive to temperature change at high temperatures. Under such conditions, the atmosphere takes up evaporated water so efficiently, that only the available energy limits the pan evaporation.

[11] Second, if we move from left to right in Figures 1b–1d to find the impact of increasing precipitation, it is clear that changes in pan evaporation are not in line with changes in the actual evapotranspiration. Instead, we reproduce the complementary relationship between pan evaporation and actual evapotranspiration that formed the basis of the first hypothesis [*Brutsaert and Parlange*, 1998]. At all temperatures and from arid to humid conditions an increase in soil moisture leads to an increase in the actual evapotranspiration and a reduction in pan evaporation. This confirms the observations of *Lawrimore and Peterson* [2000], who show that in the USA the complementary relationship between pan evaporation and actual evapotranspiration even holds for the wettest soils. Therefore, evaporation never becomes fully controlled by radiation. Note that in sharp contrast with the effects of temperature rise, increasing precipitation largely reduces the VPD. While *Roderick and Farquhar* [2002] introduced global dimming as the essential mechanism behind decreasing pan evaporation at constant VPD, we find that VPD could remain constant without dimming, given the right combination of warming and wetting. Nevertheless, we will show in section 4 that *Roderick and Farquhar* [2002] are correct in their interpretation that dimming is essential in linking measured trends in pan evaporation and VPD.

[12] A reduction in short wave radiation (dimming) leads to uniform decreases in both actual and pan evaporation that follow our intuition—less energy, less evaporation (Figure 1c). A comparison of actual evapotranspiration between arid and humid places hints at the existence of a water-limited regime. In arid places, namely, actual evapotranspiration is barely sensitive to the incoming short wave radiation [*Teuling et al.*, 2009], but responds strongly to an increase in soil moisture. This is not the case for pan evaporation. The sensitivity of this variable to dimming is independent of soil moisture. With this result, we show that decreasing pan evaporation trends in water-limited areas such as India [*Roderick et al.*, 2009b] are strongly influenced by dimming.

[13] Stilling is the last phenomenon that entered the pan evaporation trends discussion [*Roderick et al.*, 2007]. This phenomenon is, similar to increasing precipitation, an excellent example to show that pan evaporation trends are not a good proxy for trends in actual evapotranspiration (Figure 1d). Pan evaporation is strongly correlated to the wind speed as a 1 m s^{-1} lower geostrophic forcing can lead up to a 0.4 mm d^{-1} reduction in pan evaporation. The actual evapotranspiration and the VPD, however, show only a very minimal sensitivity to stilling. Despite the fact that our figure confirms the finding that pan evaporation is particularly sensitive to variations in wind speed in arid climates where a large VPD is common [*Roderick et al.*, 2009a], the

sensitivity of the actual evapotranspiration to stilling is largest in humid conditions. If there is only little soil moisture, the evaporation is water-limited, and stilling does not feed back on actual evapotranspiration or VPD because the evaporation is insensitive to the atmospheric demand for water and the evaporation flux is too small to influence the VPD. When there is ample soil water, the demand of the atmosphere to take up water becomes relatively more important, which results in an actual evapotranspiration that is sensitive to wind speed.

4. Combined Impact of Climate Forcings

[14] With the previous analyses we have demonstrated that each of the climate forcings has a very distinct effect on the relationship between pan evaporation, actual evapotranspiration and VPD. We proceed now by showing that with a set of surface measurements that contain pan evaporation, VPD and wind, we can give a reliable indication of the change in the actual evapotranspiration. We assume that from the four climate forcings we know the temperature rise and the stilling, while we perform a sensitivity analysis on the soil moisture changes and the incoming short wave radiation, since the impacts of these two forcings forms the basis of the debate on the pan evaporation trends. To demonstrate this approach, we apply it to the Great Plains region.

[15] We have taken the forcings for 1950 [*Trenberth et al.*, 2007; *Klink*, 1999; *Hobbins et al.*, 2004] to run a reference case with our model. Subsequently, we have rerun the model with the temperature (+0.5 K) and wind speed (−0.5 m s^{-1}) characteristic for the year 2000 and a range of soil moisture and incoming radiation values that vary around their magnitudes in the reference case. From these runs, we have subtracted the reference case to get an indication of the trends from past to present as a function of the trend in soil moisture and the trend in incoming radiation (Figure 2).

[16] Using the observed changes in temperature and wind speed, but assuming no changes in soil moisture and short wave radiation (center of Figure 2a), our model produces increasing trends in pan evaporation (+0.15 mm d^{-1}), actual evapotranspiration (+0.13 mm d^{-1}) and VPD (+0.7 hPa). More importantly, wind and temperature changes alone would have led to an increase in actual evapotranspiration that would resemble the increase in pan evaporation. With dimming and increasing soil moisture, however, that relationship vanishes, emphasizing the importance of taking into account all forcings and feedbacks when interpreting pan evaporation trends. In Figure 2b we show the same results as in Figure 2a, but here we highlight in colored bands possible combinations of trends in soil moisture and short wave radiation that match trends in measured variables.

[17] The pan evaporation over the Great Plains has decreased in the range of 0.4 to 0.5 mm d^{-1} over 50 years [*Golubev et al.*, 2001]. Therefore, there is a large range of combinations of soil moisture and short wave radiation trends that are able to reproduce this decrease. The blue band in Figure 2b shows that this trend is possible with a strong dimming of 60 W m^{-2} without any soil moisture change, but also with a strong soil moisture increase without any significant dimming. The trend in VPD constrains the possible solutions. Over the Great Plains the VPD has approximately decreased by 1.2 to 1.5 hPa over 50 years [*Hobbins et al.*, 2004]. The red band in Figure 2b shows the
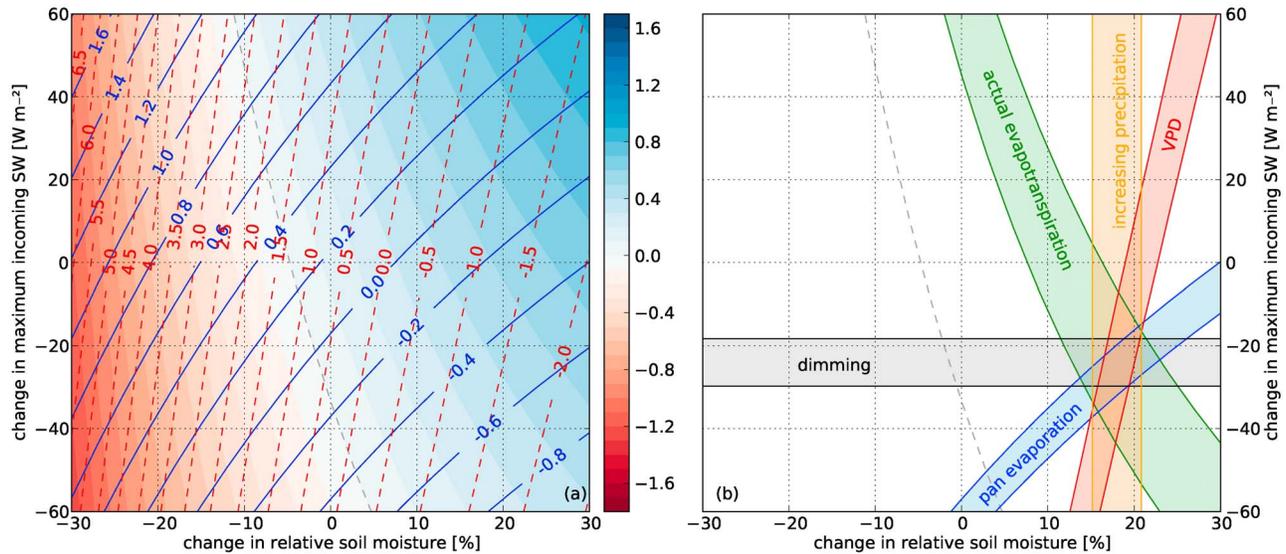
Figure 2. Impact of changes in climate forcings on changes in pan evaporation and actual evapotranspiration. (a) Long term changes in daytime summed actual evapotranspiration in mm (shades), in daytime summed pan evaporation in mm (blue contours) and daytime mean VPD in hPa (red contours) as a function of the change in soil moisture and the change in maximum incoming short wave radiation over the Great Plains (left). The gray dashed line shows the combinations that result in zero trend in actual evapotranspiration. On the left side of the line there is a decreasing trend in actual evapotranspiration, on the right an increasing one. (b) Colored bands for combinations of changes in soil moisture and short wave radiation (see Figure 2a) that reproduce the long term change of a specific variable.

combination of forcings that correspond to the observed VPD trend. By introducing this trend, we limit the possible solutions to a small range of changes in the forcings.

[18] Measurements show that a dimming of approximately 20 W m^{-2} has taken place [*Hobbins et al.*, 2004], while soil moisture increased by nearly 20 per cent [*Sheffield and Wood*, 2008]. These measured quantities fall within the range of possible changes in the climate forcings, which are inferred from the intersection of the bands of pan evaporation and VPD. This confirms the important role of local feedbacks between the land surface and the ABL in mitigating the impact of changes in forcing and proving the consistency of the measurements. Now, we can make a reliable estimate of the sign and the magnitude of the trend in actual evapotranspiration. Based on the area where the blue and the red band cross, we estimate the trend to be positive with values ranging from 0.3 to 0.45 mm d^{-1} over 50 years. This is in line with water balance studies of the Mississippi basin [*Milly and Dunne*, 2001].

[19] It should be noted that the crossing of the measurements is located far right of the line that splits the combinations of dimming and increasing precipitation into negative and positive trends. This strengthens the interpretation that the trend in actual evapotranspiration is positive. In addition, the line is nearly vertical. This indicates that despite the large influences that dimming has on pan evaporation, the actual evapotranspiration trend in this region is barely sensitive to it [see *Teuling et al.*, 2009].

5. Summary and Perspective

[20] In this study we showed using a model how pan evaporation, actual evapotranspiraation and VPD are interrelated due to land surface-atmosphere feedbacks. Each climate forcing, such as global warming, increasing precipitation, global dimming or stilling, has a distinct impact on these variables. Therefore, we can interpret which climate forcing drives pan evaporation trends and infer the trend in actual evapotranspiration from data sets containing pan evaporation, VPD and wind speed. This we showed for the Great Plains, USA.

[21] Our findings can help in interpreting whether actual evapotranspiration is increasing or decreasing as an effect of climate change. One of our main conclusions is that an increase in soil moisture leads to more actual evapotranspiration and less pan evaporation under all conditions (Figure 1b). If we combine that with our finding that, except over wet soils, the actual evapotranspiration is more sensitive to changes in soil moisture than to changes in short wave radiation (Figures 1b and 1c), we expect the global evaporation to have increased. Nevertheless, *Wild et al.* [2004] speculate that in the second half of the 20th century an increased moisture advection from the oceans enhanced the precipitation over land, but suppressed the evaporation—opposite to our expectations. In most places where increasing precipitation has been observed, such as in the central part of the USA and Russia, evaporation is water-limited and/or strongly coupled to soil moisture [*Koster et al.*, 2004]. Since we showed that under these conditions the atmospheric demand for water barely influences the actual evapotranspiration (Figure 1d), it is hard to believe that advection is able to suppress evaporation to such an extent that it can compensate for the enhancing effect of increasing precipitation.

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