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Groundwater convergence as a possible mechanism for multi-year persistence in rainfall

Marc F. P. Bierkens[1] and Bart J. J. M. van den Hurk[2]

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[1] Yearly rainfall totals in wet-to-dry climate transition zones show marked multiyear periods of dry and wet anomalies. These are said to originate from large-scale external forcings (e.g. SST anomalies) and enhanced by land-atmosphere coupling through soil moisture, vegetation and surface albedo. We explore the hypothesis that the degree of persistence in rainfall may be partly caused by groundwater convergence, i.e. the confluence of groundwater to discharge zones that remain wet throughout the year to sustain evaporation for longer periods of time. A simple stochastic model of soil moisture-precipitation feedback augmented with a groundwater component shows that groundwater convergence introduces long-term persistence in rainfall. The degree of persistence (as measured by the Hurst exponent of simulated yearly rainfall totals) increases with groundwater residence time. This notion has important ramifications for multiyear drought forecasting, whereby monitoring or concurrent modeling of groundwater stores may play a role in improving predictability.
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1. Introduction

[2] Many regions that lie between semi-arid and semi-humid climate zones with seasonal rainfall experience prolonged periods of dry and wet spells. Examples of such areas are the Mediterranean, the Sahel, South-Central Asia and the Central United States [*Koster et al.*, 2004]. The *onset* of prolonged periods of wet and dry spells is usually attributed to anomalies in large-scale atmospheric moisture advection. However, the *persistence* in wet and dry periods is often attributed to soil moisture-precipitation feedback, whereby at the onset of a wet spell precipitation causes wetting of soils, which increases evaporation. Evaporation subsequently puts additional moisture into the atmosphere, which increases the probability of precipitation. By the same argument, the decrease of evaporation due to the drying of soils will cause a dry spell to persist [*Koster et al.*, 2003].

[3] Most prominent are the rainfall anomalies in the Sahel and East-Africa. Here, multiyear to even multidecadal persistence of yearly rainfall occurs [*Wang and Eltahir*, 2000; *Zeng*, 2003]. This multiyear persistence in rainfall almost certainly finds its cause in the multiyear variability caused by SST anomalies [*Giannini et al.*, 2003]. However, some studies [e.g., *Zeng et al.*, 1999; *Wang and Eltahir*, 2000] clearly show that the observed persistence can only be explained with additional land surface–atmosphere feedback. These studies also show that in semi-arid seasonal climates (such as the Sahel) soil moisture dynamics alone are unable to induce the multiyear persistence of rainfall anomalies as observed. This because in these regions soil moisture tends to zero in the course of the dry season, regardless of whether the previous rainy season is anomalously dry or wet. Thus, the dry season resets the memory of the system [c.f. *Nicholson*, 2000] and soil moisture dynamics cannot be invoked to explain the multiyear persistence of rainfall anomalies. Additional mechanisms are needed that carry the influence of the land surface state on evaporation over the year. Examples of suggested mechanisms that could explain such multiyear persistence are multiyear changes in vegetation cover [*Zeng et al.*, 1999] and multiyear trends in atmospheric dust [*Nicholson*, 2000]. However, up to now the role of the groundwater system in inducing multiyear persistence in land-surface coupling has been neglected. Therefore, in this paper we modify an existing simplistic model of land-atmosphere coupling [*Entekhabi et al.*, 1992] to show how groundwater convergence may explain the multiyear persistence of rainfall.

[4] Groundwater convergence occurs in regions with renewable groundwater resources and adequate topography where groundwater that is recharged through infiltration and soil percolation, subsequently flows to low lying areas and discharges there in the form of stream discharge, soil evaporation and plant transpiration. As the discharge areas are usually much smaller in size than the recharge areas, a concentration of water occurs due to groundwater flow; hence the use of the term ‘‘groundwater convergence’’, in analogy with ‘‘atmospheric moisture convergence’’ [*Trenberth*, 1999]. Evaporation in groundwater discharge areas may persist during dry spells, even if in the remaining parts of the region soils are dry and evaporation ceases. This prolonged evaporation thus positively influences the probability of rainfall and counteracts droughts. However, as groundwater reservoirs are often large and groundwater flow is slow, groundwater levels and redistribution react slowly on variations in groundwater recharge (which reflect variations in precipitation). Just as vegetation density or dust, groundwater convergence thus imposes a low-frequency (possibly multiyear) component on evaporation into the atmosphere.

[5] For groundwater to have any influence on precipitation, two conditions should be met: 1) a significant part of

[1]Department of Physical Geography, Utrecht University, Utrecht, Netherlands.
[2]Royal Netherlands Meteorological Institute (KNMI), De Bilt, Netherlands.

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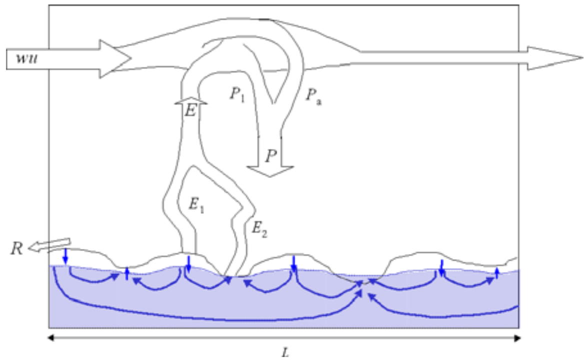

Figure 1. Coupled terrestrial-atmospheric water balance over a large landmass including groundwater convergence.

the precipitation should have a local component derived from evaporation and this evaporation should be dependent on soil wetness; 2) significant groundwater convergence should occur. From studies identifying major areas of precipitation recycling and land surface-precipitation feedback it follows that in particular areas with gradients from wet to dry climate conditions with seasonal rainfall show a strong dependence of precipitation on the soil moisture status [*Trenberth*, 1999; *Koster et al.*, 2004], where hot spots are found in the Sahel, the Mid-Western United States and North India. As recycling ratio's depend on region size [*Trenberth*, 1999] these areas are typically large, i.e. sub-continental in scale. Evidence for considerable groundwater convergence and exfiltrating groundwater in these regions can be found in the literature as well. For instance, *Gutentag et al.* [1984] describe considerable drainage of groundwater from the High Plains Aquifer to the Platte river and the Canadian river (both tributaries of the Mississippi), as well as the discharge of groundwater to springs and streams along the eastern escarpment of the High Plains Aquifer. In North India, along the edge of the Himalayas, very large aquifers of recent and Pleistocene sedimentary deposits can be found. Although recently groundwater levels have dropped due to overexploitation [*Sha et al.*, 2003], shallow groundwater levels and considerable groundwater flow to wetlands, rivers and streams are found in North India [*WHYMAP*, 2004]. *Edmunds et al.* [1999] report an average groundwater recharge of 40–60 mm/year in the Sahel of North-East Nigeria with groundwater convergence to lakes and depressions, while *Thorweihe and Heinl* [2002] describe groundwater convergence and exfiltration in the Nile Valley.

2. Model

[6] To investigate the possible effect of groundwater convergence on rainfall persistence we extended the stochastic soil moisture–evaporation–precipitation feedback model of *Entekhabi et al.* [1992] with a groundwater component. This simple stochastic model is meant to simulate coupled precipitation, evaporation and soil moisture dynamics across a continent at a yearly scale; i.e. seasonality is not taken into account. The modified model is used to investigate how multiyear persistence in rainfall is influenced by groundwater residence time. After the model description, we will present and discuss results of runs with and without the groundwater component included.

[7] Figure 1 depicts the coupled terrestrial-atmospheric water balance over a large land mass of size L [L] (area per unit width). The influx (advection) of atmospheric moisture is given by wu with w the vertical integral of precipitable atmospheric moisture [L] and u the vertical average of the wind speed [LT^{-1}]. The precipitation that falls over the region partly comes from advected moisture (P_a) and partly from evaporation (P_l) from the landmass itself. If it is assumed that full mixing occurs in the atmosphere above the land, a relationship between precipitation, advection and evaporation can be obtained [*Budyko*, 1974] (E denotes evaporation [LT^{-1}]):

$$P = P_a\left(1 + \frac{EL}{2wu}\right) \tag{1}$$

When writing up the large-scale terrestrial water balance we split the land surface into two areas: groundwater recharge areas and groundwater discharge areas. The fraction of the land surface where groundwater discharge occurs is denoted by f_g, where by the definition of a groundwater *con*vergence zone $f_g < 0.5$. The terrestrial water balance is then given by:

$$nz_r\frac{ds_i}{dt} = P - E_i - R_i \pm Q_i \qquad i = 1, 2 \tag{2}$$

with n the drainable porosity, z_r the thickness of the active root zone, s_i the average soil saturation (-) of the recharge zone (i = 1) and discharge zone (i = 2), E_i the evaporation from each of the zones [LT^{-1}], R_i the surface runoff [LT^{-1}], and Q_i [LT^{-1}] groundwater recharge ($-Q_1$) or groundwater advection ($+Q_2$). Evaporation is modelled as:

$$E_i(S_i) = E_p S_i^c \qquad i = 1, 2 \tag{3}$$

with E_p potential evapotranspiration, and c a shape parameter for the dependence of evaporation on soil saturation. With equation (1), (3) and the notion that the total evaporation is given by $E = (1 - f_g)E_1 + f_g E_2$, the rainfall in terms of soil moisture feedback is given by:

$$P = P_a\left\{1 + \alpha\left[\left(1 - f_g\right)s_1^c + f_g s_2^c\right]\right\} \tag{4}$$

with $\alpha = LE_p/2wu$ a parameter determining the strength of the soil moisture – rainfall feedback (see *Entekhabi et al.* [1992] for details). Surface runoff is modelled as a fraction of precipitation and dependent on soil moisture content:

$$R(s_i) = \varepsilon P s_i^r \qquad i = 1, 2 \tag{5}$$

with ε, r parameters. Percolation Q_1 is parameterised as a function of soil moisture as follows:

$$Q_1(s_1) = k_s s_1^b \tag{6}$$

with k_s the saturated conductivity and b a shape parameter. Finally, the groundwater convergence term Q_2 represents groundwater advection, whereby groundwater recharge water converges to discharge zones, possibly with considerable delay and attenuation. *Krayenhoff van de Leur* [1958] shows that groundwater discharge from thick

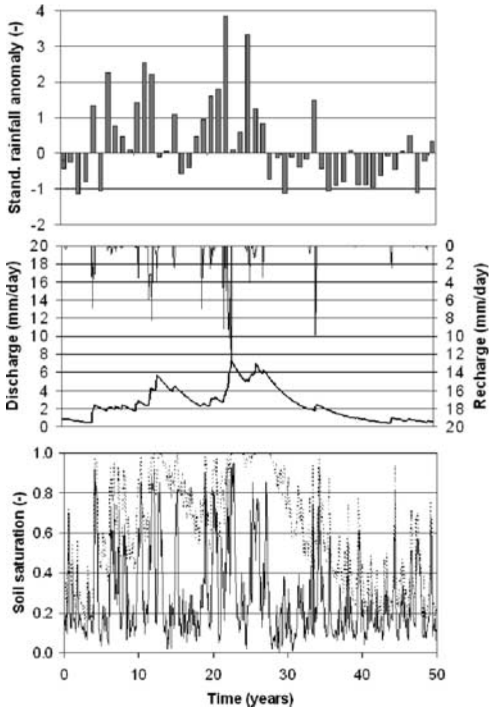

Figure 2. Variation of standardized anomalies of simulated yearly rainfall totals (yearly minus average rainfall divided by the standard deviation of yearly rainfall), groundwater recharge and discharge and soil saturation (varying between 0 for dry soils and 1 for saturated soils) of groundwater recharge areas (solid line) and groundwater discharge areas (dashed line). Groundwater residence time is 5 years.

permeable aquifers can be modelled (at first order) by a simple linear reservoir. Following their findings groundwater advection is modelled with the following convolution integral:

$$Q_2(t) = \left(\frac{1-f_g}{f_g}\right)\frac{k_s}{J}\int_{-\infty}^{t} s_1^b(t-\tau)e^{-\tau/J}d\tau \tag{7}$$

with J the average groundwater residence time [T]: $J = (S_Y l^2/\pi^2 T)$ [*Krayenhoff van de Leur*, 1958]. Here S_Y is aquifer specific yield [−], T aquifer transmissivity [L^2T^{-1}] and l the average distance between groundwater discharge areas (i.e. the drainage density). The two parameters J and f_g in (7) thus summarize the underlying hydrogeology (aquifer properties) and geomorphology (density and extent of discharge areas) of the land surface. Note that the factor $(1 - f_g)/f_g > 1$, which ensures a closed water balance, i.e. long-term average groundwater recharge equals long-term average groundwater discharge.

[8] Potential evapotranspiration E_p and atmospheric moisture advection wu are not constant but fluctuate in time. If we model the fluctuations of soil moisture content on a multi-year scale (discarding seasonal variation) then variations of E_p and wu can be considered as being of high frequency and the feedback parameter α can be modelled as:

$$\alpha(t) = \langle\alpha\rangle + \sigma\xi(t) \tag{8}$$

where brackets $\langle\ \rangle$ denote the expected value and $\xi(t)$ are random fluctuations, modelled as a unit variance white noise process, with σ^2 the variance of the fluctuations. With relationships (3)–(8) inserted into (2) the following system of coupled stochastic differential equations (Itô−interpretation; c.f. *Rodriguez-Iturbe et al.* [1991a]) is obtained:

$$ds_1 = A(s_1, s_2)dt + B(s_1, s_2)dW_t \tag{9a}$$

$$ds_2 = C(s_1, s_2)dt + D(s_1, s_2)dW_t \tag{9b}$$

where dW_t, which represents fluctuations in α, is an increment of a Wiener process (also called Brownian motion) with statistical properties: $\langle dW_t\rangle = 0$, $\langle dW_t\, dW_{t'}\rangle = 1$ if $t = t'$ and 0 otherwise. The functions $A(s_1,s_2)$ to $D(s_1,s_2)$ are given by:

$$A(s_1,s_2) = \frac{P_a}{nz_r}\left\{1+\langle\alpha\rangle\left[(1-f_g)s_1^c + f_g s_2^c\right]\right\}\left(1-\varepsilon s_1^r\right) - \frac{E_p}{nz_r}s_1^c - \frac{k_s s_1^b}{nz_r} \tag{10a}$$

$$B(s_1,s_2) = \frac{P_a}{nz_r}\left[(1-f_g)s_1^c + f_g s_2^c\right]\left(1-\varepsilon s_1^r\right)\sigma \tag{10b}$$

$$C(s_1,s_2) = \frac{P_a}{nz_r}\left\{1+\langle\alpha\rangle\left[(1-f_g)s_1^c + f_g s_2^c\right]\right\}\left(1-\varepsilon s_2^r\right) - \frac{E_p}{nz_r}s_2^c + \frac{Q_2(t)}{nz_r} \tag{10c}$$

$$D(s_1,s_2) = \frac{P_a}{nz_r}\left[(1-f_g)s_1^c + f_g s_2^c\right]\left(1-\varepsilon s_2^r\right)\sigma \tag{10d}$$

Because the coupling term $Q_2(t)$ not only depends on the current state $s_1(t)$ but also on all the previous states $s_1(t' < t)$ (see Equation 7), Equations (9) are so-called stochastic delay differential equations (SDDEs) whose solutions (the underlying stochastic processes) are non-Markovian [*Frank and Beek*, 2001] (see also *Rodriguez-Iturbe et al.* [1991b] for a first application of SDDEs in hydrology). This means that theoretically the solution to (9), as well as the rainfall derived from it through (4), is an infinite memory process. Long-term persistence can thus be expected from the very form of Equations (9).

3. Results

[9] Because the SDDEs (9) are non-linear and of infinite delay, they can only be solved with Monte Carlo integration [*Frank and Beek*, 2001]. We used an Euler scheme with an integration step of 0.0001 year and a random number generator to simulate a time series of 50,000 years of soil saturation degree (in recharge and discharge zones) and the diagnostic variables groundwater recharge $Q_1(t)$, groundwater discharge $Q_2(t)$ and rainfall $P(t)$. Simulations were performed for a case without groundwater and with groundwater with increasing values of the groundwater residence time J (between 1 and 100 years) and discharge area-ratio f_g (between 0.01 and 0.3). Climate and soil parameters were obtained from *Entekhabi et al.* [1992], with climatology

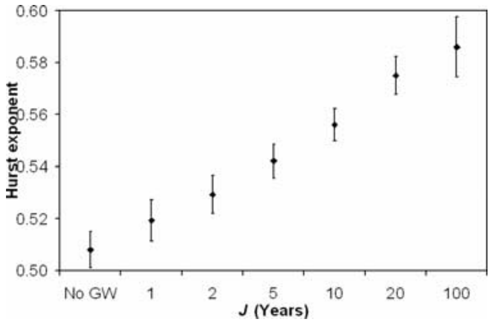

Figure 3. Hurst exponents of simulated time series of yearly rainfall totals for a system without groundwater and systems with different values of groundwater residence time J and groundwater discharge area fraction f_g = 0.1. Hurst exponents have been estimated by re-scaled range analysis. Error bars show estimated values ± 1 standard deviation of estimation error.

indicative for tropical wet-to-dry transition zones, e.g. the Sahel: P_a = 0.4 m, E_p = 2.2 m, w = 0.01 m, u = 0.4 m/s, $L = 2.5 \times 10^6$ m, nz_r = 0.5 m, ε = 1, r = 6, c = 1, k_s = 0.02 m/d, b = 10 (feedback parameter: α = 2.18).

[10] Figure 2 shows the variation of state and diagnostic variables for a fragment of 50 years. The top panel shows the normalized rainfall anomalies, i.e. yearly rainfall totals minus the yearly average rainfall and divided by the standard deviation of yearly rainfall totals. It can be seen that due to soil moisture-precipitation feedback persistent anomalies of multiple years with timescales up to a decade occur, even though the forcing is purely random. The middle panel shows the variation of groundwater recharge (which occurs intermittently during heavy rain showers) and groundwater discharge. In this example, f_g = 0.1 and J = 5 years, such that a considerable delay and attenuation in groundwater variation can be observed. The lower panel shows the relative soil saturation of the recharge and discharge zones. Clearly, the discharge zones show higher saturation values and thus allow for considerable evaporation up to 5 years after the termination of a wet period. The long-term yearly water balance for this particular case is given by (between brackets the distribution between recharge and discharge zone): P = 646 mm, E = 620 mm (567,1100), R = 26 mm (16,113). Groundwater recharge is 63 mm/year, which is similar in magnitude as found by *Edmunds et al.* [1999] for the Sahel. Average groundwater discharge is −567 mm/year (in discharge zones only), balancing the recharge.

[11] Results show that average yearly rainfall is only slightly influenced by the presence of groundwater and increased groundwater residence time: an increase from 638 mm/year (case without groundwater) to 647 mm/year (case with groundwater with residence time J = 100 years). We expect an increase because the evaporation slightly increases due to the wetter soils in the discharge areas, which has an effect on the local rainfall portion P_l. However, the effect is small because the discharge area is small in size. However, groundwater does have a notable impact on the amplitude of the year-to-year variation of rainfall, with the standard deviation of yearly rainfall totals decreasing from 115 mm/year (no groundwater) to 96 mm/year (groundwater with J > 20 years).

[12] To study the multiyear persistence in yearly rainfall we estimated Hurst exponents of the simulated 50,000 year time series using Rescaled Range analysis (R/S-analysis) [*Hurst*, 1951; *Karagiannis et al.*, 2003]. The Hurst exponent is a measure of long-term persistence in time series. For stationary Gaussian time series with finite temporal correlation its value is 0.5. For most hydrological time series however, it is larger than 0.5, indicating statistically self-affine (fractal) long-memory behavior [*Mandelbrot and Wallis*, 1968]. Figure 3 shows the Hurst exponents estimated from the simulated series for the case with and without groundwater convergence with increasing residence times. The figure clearly shows that Hurst exponents increase with groundwater residence time, and therefore the long-term persistence in rainfall. In Figure 4 the relationship between the Hurst exponent and the area fraction of groundwater discharge areas f_g is shown for three different groundwater residence times. Again, these Hurst exponents were estimated from 50,000-year simulations with the model, but now for increasing values of f_g. Clearly, for groundwater convergence to have a significant effect on the persistence in annual rainfall f_g (next to J) should be large enough (>0.05). If the discharge areas are too small, they are constantly wet and provide maximum evaporation but their impact on the total evaporative signal is small. Figure 4 also shows that for larger discharge areas the Hurst exponents flatten out and even slightly decrease again. This can be explained by the fact that a larger f_g results in soils in discharge areas that are less wet such that the evaporative signal starts to resemble that of the recharge areas.

4. Discussion

[13] In this study we coined the hypothesis that groundwater convergence may have an effect on rainfall persistence and illustrated this hypothesis with a simple model applied to a specific case [i.e., *Entekhabi et al.*, 1992]. We realise that in our simple model many processes are not taken into account, such as seasonality, the connection between continental soil moisture status and Monsoon

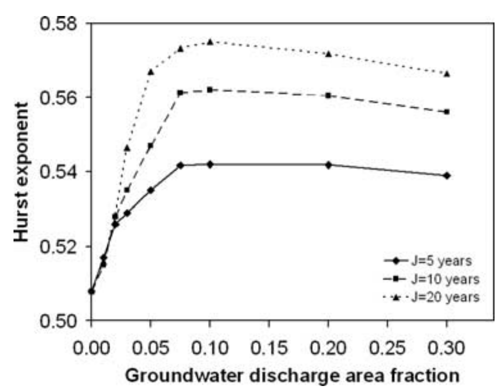

Figure 4. Hurst exponents of simulated time series of yearly rainfall totals for three different residence times J = 5, 10, 20 years and different values of groundwater discharge area fraction f_g (f_g = 0 is the case without groundwater). Hurst exponents have been estimated by re-scaled range analysis. We have omitted the error bars for readability of the Figure (standard deviation on average 0.0065).

strength [*Zhu et al.*, 2005], atmospheric boundary layer dynamics [*Ek and Holtslag*, 2004] and the effect of land surface heterogeneity in relation to meso-scale processes [*Pielke et al.*, 1998; *Rodriguez-Iturbe et al.*, 1998]. However, we believe that at the larger temporal and spatial scales at which this model claims to operate, the average effect of increased soil moisture content and evaporation on precipitation will be positive, and that groundwater redistribution can positively influence average soil moisture status. Our stochastic model should thus be regarded as a tool describing a first order effect of groundwater convergence on the statistical properties of annual rainfall. Given these limitations we realize that further analysis is required to assess the relative importance of the effect in the context of full atmospheric dynamics. This would require runs with an atmospheric circulation model that is coupled with a realistic representation of the terrestrial hydrological cycle, including full groundwater flow dynamics. Apart from limited experiments with a single atmospheric column model (*York et al.* [2002], who showed that for a Kansas catchment 20% of the evaporation is groundwater based during dry periods) such runs have not been performed at this time.

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M. F. P. Bierkens, Department of Physical Geography, Utrecht University, P.O. Box 80115, Utrecht 3508 TC, Netherlands. (m.bierkens@geo.uu.nl)

B. J. J. M. van den Hurk, KNMI Royal Netherlands Meteorological Institute, P.O. Box 201, NL-3730 AE De Bilt, Netherlands. (bart.van.den.hurk@knmi.nl)