The surface evaporation capacitor (SEC)

Pore scale physics constrain terrestrial surface evaporation

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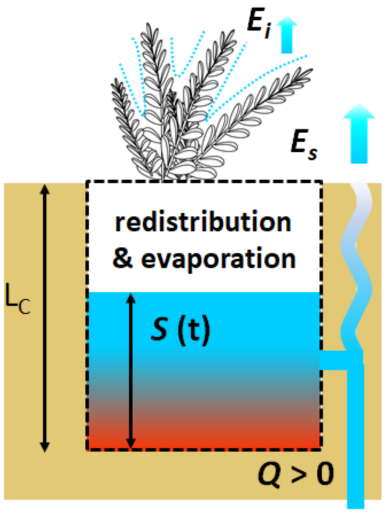

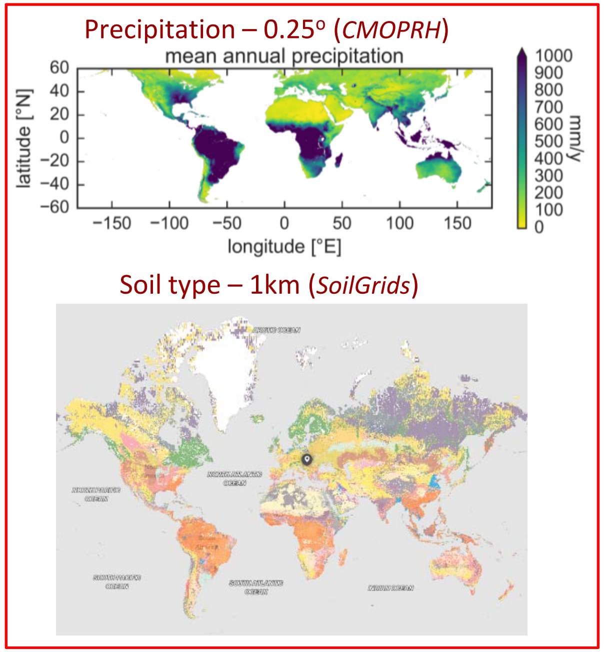
Precipitation – 0.25° (*CMOPRH*)

Soil type – 1km (*SoilGrids*)

TERENO meeting – *Potsdam, September 2019*

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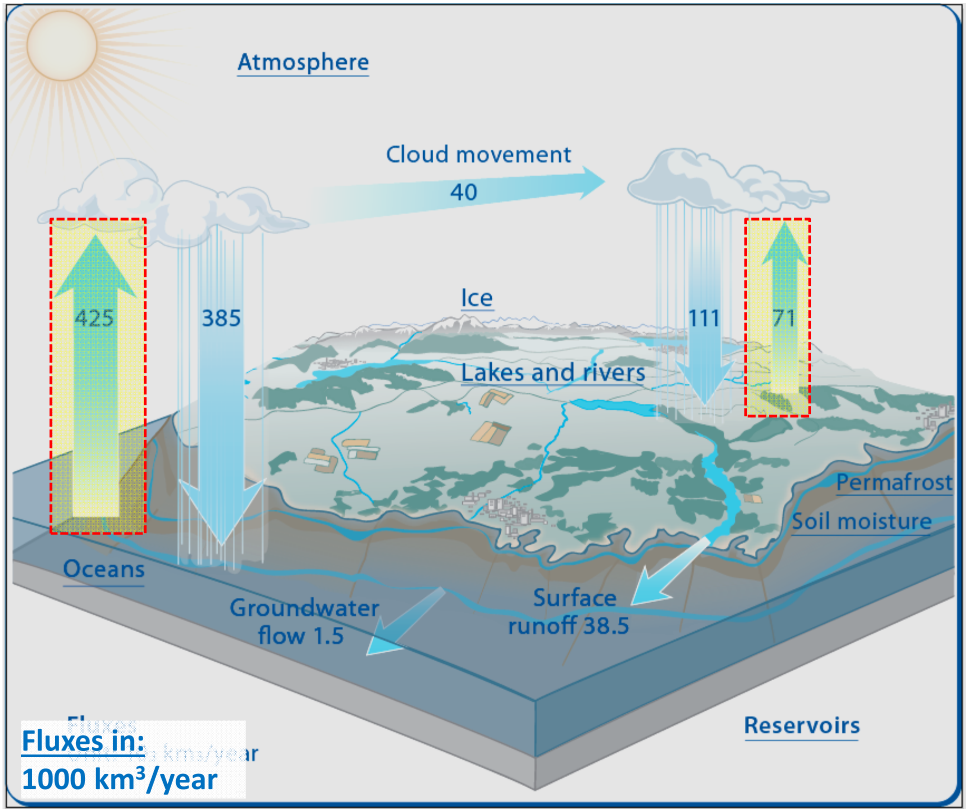
Global evaporation – *an overview*

- *Evaporation is an energy intensive process:* evaporation consumes ~ 25% of global solar energy input (40K TW)

- *Vegetation is important*: 60% of terrestrial precipitation (111×10^3 km^3/yr) returns to the atmosphere via transpiration (40%) or surface evaporation (20%)

- *Pore scale processes are important:* energy and mass exchanges between surfaces and the atmosphere are controlled by pore scale processes (*both on soil surfaces and plant leaves*)



- *The water and carbon cycles are linked:* global water and carbon cycles are intimately linked in plant leaves (*CO_2 uptake and assimilation is associated with loss of water by transpiration*)

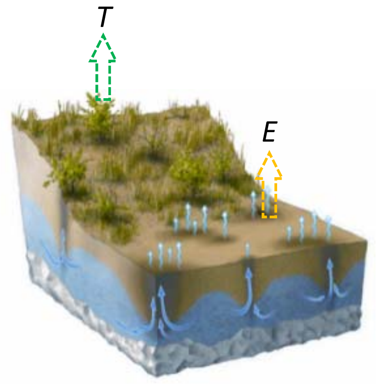
Introduction – *components of **ET (E** and **T)** are difficult to separate*

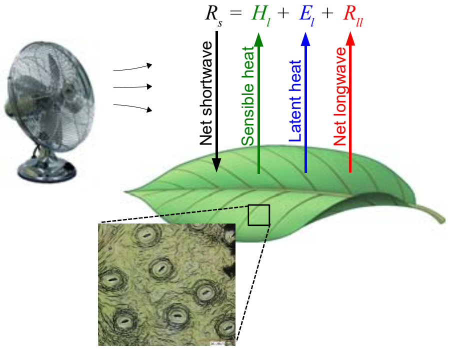
- The separation of *ET* to its components *E* and *T* remains a challenge (*Lawrence et al. 2007; Wei et al. 2017*) – estimates of global mean *T* range from 25% to 90% of mean global *ET*

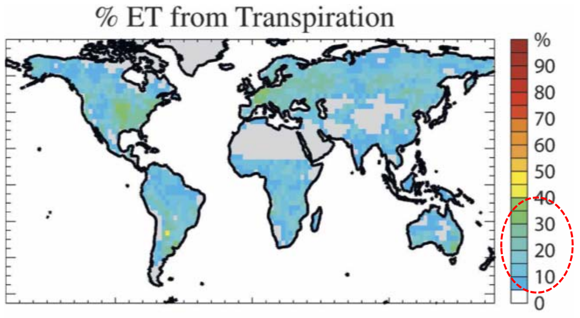
- *Why is this so difficult?* methodological difficulties (*no good measurements*), plant biological control (*stomata, uptake*), empirical coefficients (*Penman-Monteith, canopy resistance*)

- *Why is this important?* surface energy balance, irrigation management, water and carbon cycles, isotope fractionation

- We propose an approach for estimating surface evaporation *E* based on soil and rainfall characteristics independent of *T* or *ET* estimates

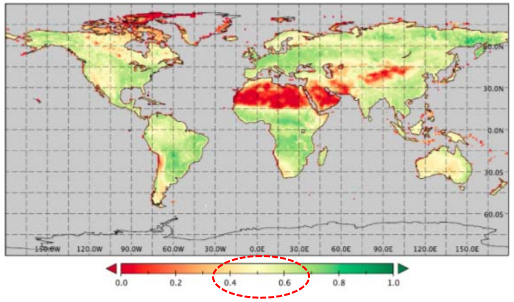




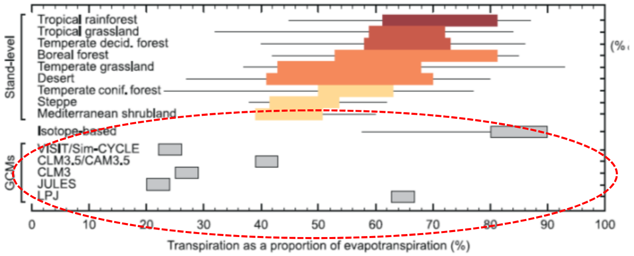


Lawrence et al. 2007

T/(E+T)



Wei et al. 2017



Schlesinger and Jasechko, 2014

Soil evaporation characteristic length – *a brief overview*

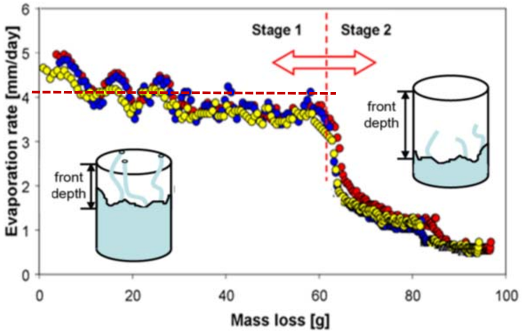
- The initial stage of soil evaporation (*stage-1*) is sustained by capillary flow to the vaporization plane at soil surface

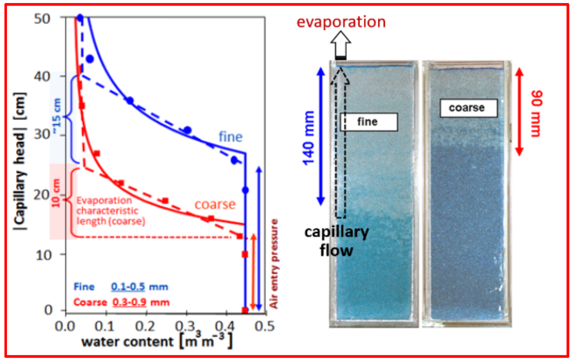
- Transition from *stage-1* (capillary) to *stage-2* (diffusion) evaporation is determined by soil-specific characteristic length (*L_c*) at which capillary continuity is disrupted

- The evaporation characteristic length varies with soil type and marks the depth below which soil water is largely sheltered from surface evaporation (certain losses in *stage-2*)

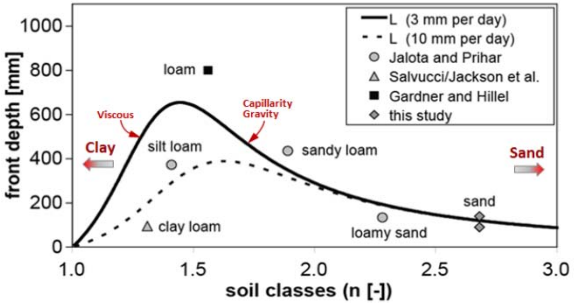
- The evaporation characteristic length is affected by atmospheric demand (evaporation rate) and soil hydraulic conductivity (*clay → short L_C due to viscous resistance*)

Main point – for each soil type a characteristic length defines the depth of evaporable water (deepest for loamy soils)





$$L_{cap} = \frac{1}{\alpha(n-1)} \left(\frac{2n-1}{n}\right)^{\frac{2n-1}{n}} \left(\frac{n-1}{n}\right)^{\frac{1-n}{n}}$$



Lehmann et al. *PRE 2008*

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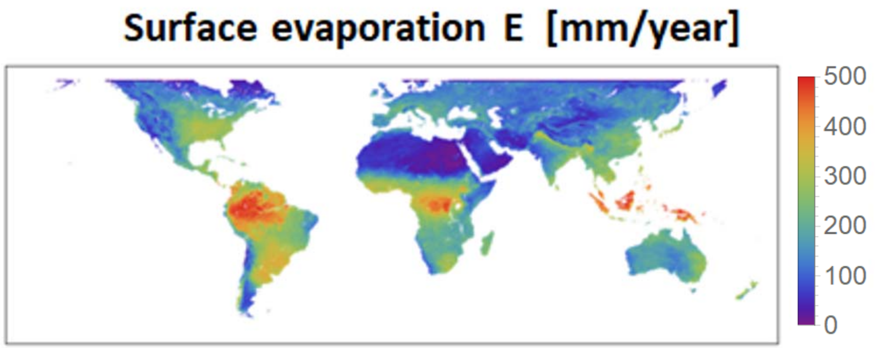
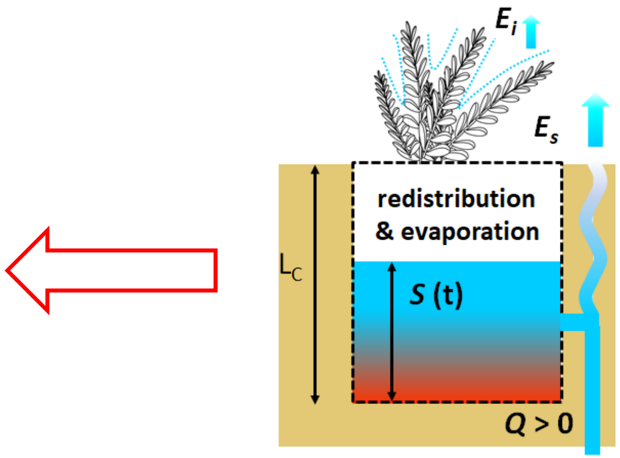
Objectives

1. To extend representation of evaporation from porous media to consider concurrent evaporation-redistribution effects on soil-specific evaporative losses - *analytical model*
2. To define near-surface "active evaporation region" using the concept of evaporative characteristic length to estimate surface evaporative losses from different soil types under different rainfall patterns – *surface evaporation capacitor (SEC)*
3. To evaluate the *SEC* concept using literature and lysimeter data and extend to global evaporation estimation using resolved global soil maps, potential ET and rainfall data

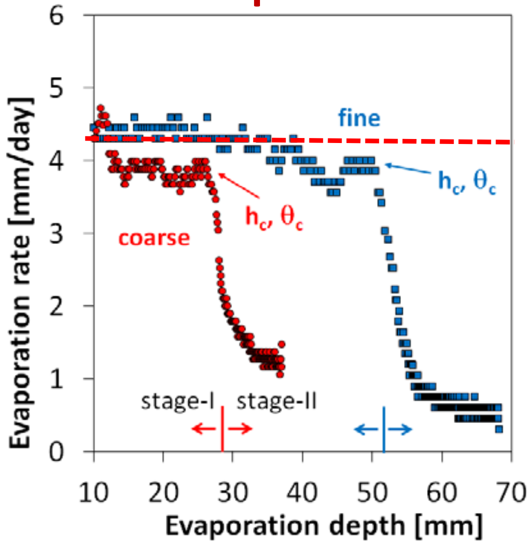


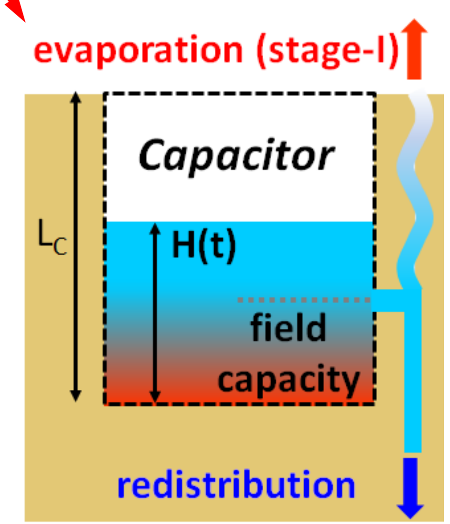


Evaporation–redistribution dynamics – *analytical solution*

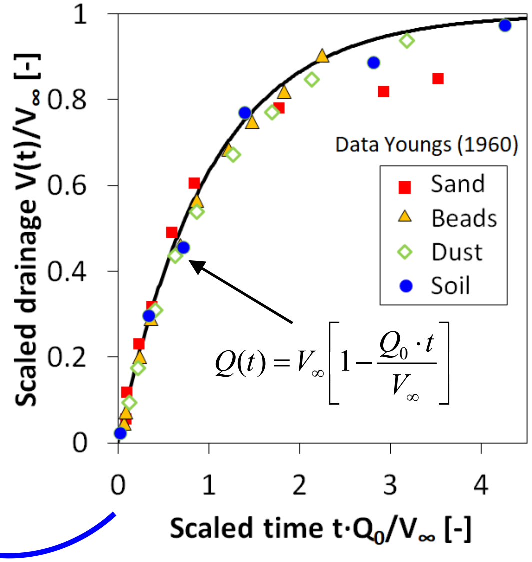
- We seek an analytical representation of water fluxes during ***stage-1*** evaporation with simultaneous internal redistribution following a wetting event (i.e., a rainfall event)
  - The transition to ***stage-2*** evaporation occurs at a soil-specific characteristic length L_C marked by critical capillary pressure h_c and water content θ_c at the surface
  - During ***stage-1*** evaporation, redistribution or drainage below L_C is described analytically based on the *Youngs (1960)* model
  - The two processes are analytically combined to represent how BC affect evaporation dynamics

Evaporation



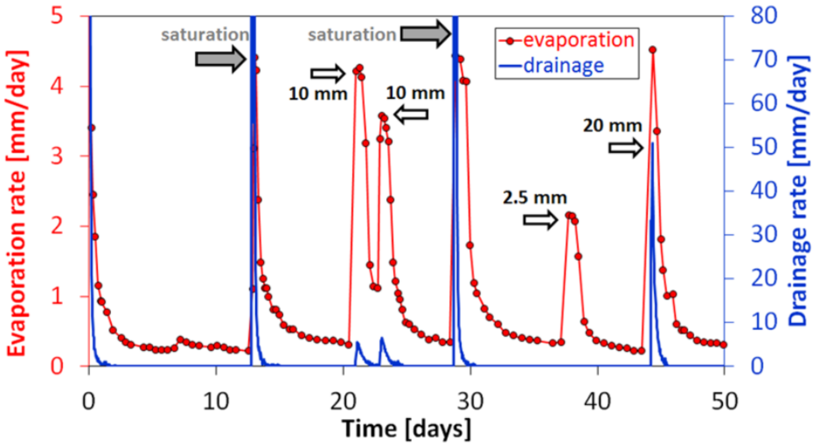


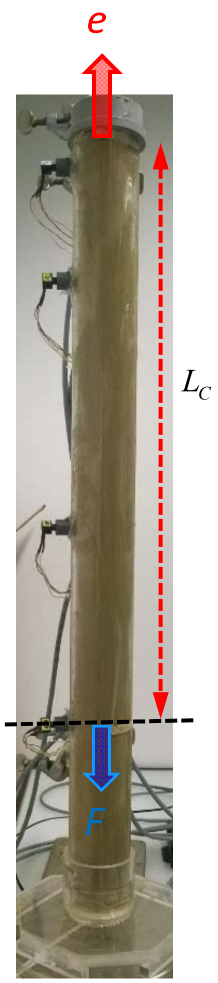
Drainage



Evaporation-Redistribution - *experiments and analytical estimates*

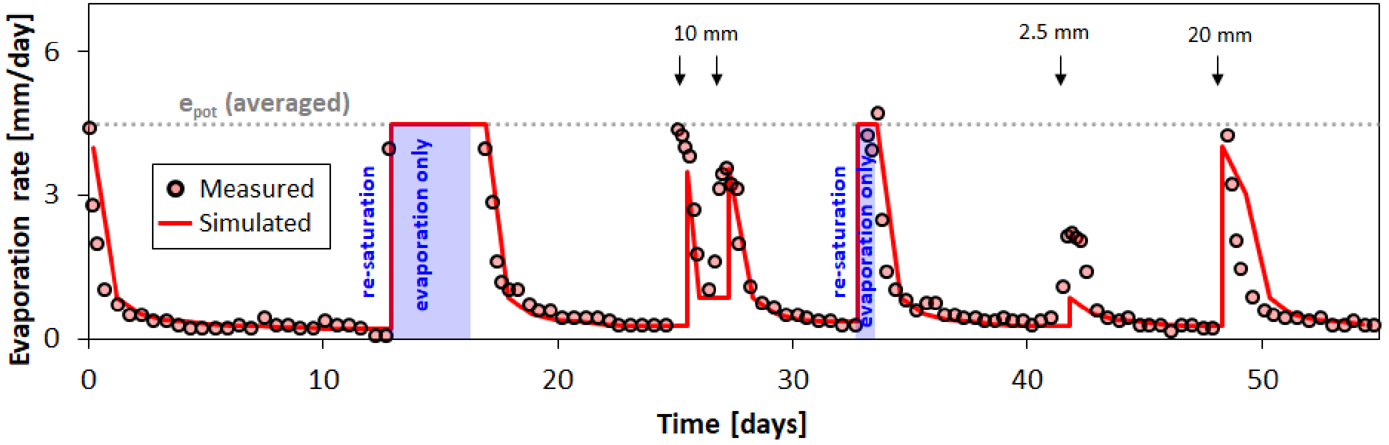
- To understand the interplay of evaporation-redistribution dynamics, we conducted a series of wetting-drying events of fine-sand column
- Time scale separation between rapid drainage and slow evaporation
- Flux dynamics were reasonably well described by analytical evaporation-redistribution model





Surface evaporation-redistribution analytical model

(cumulative evaporation 95% measured value)



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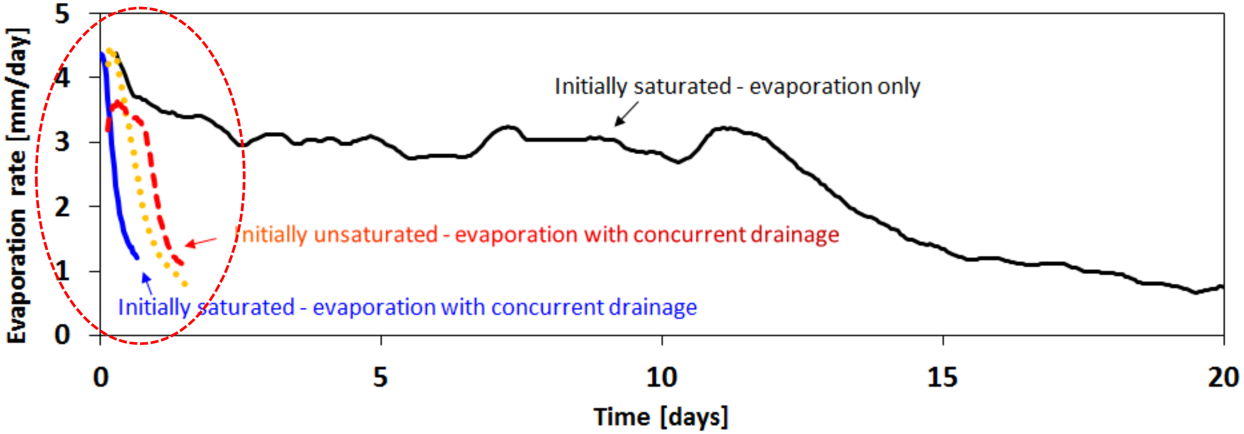
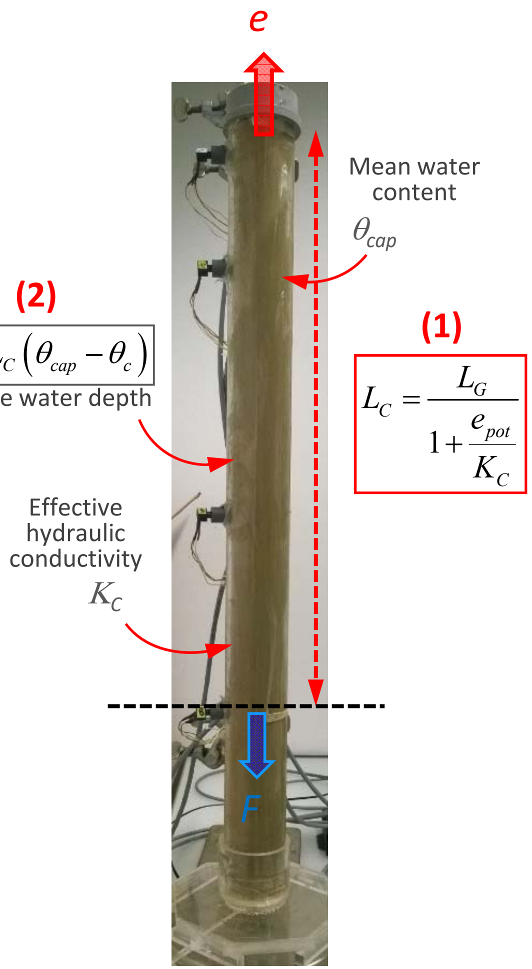
Evaporation–redistribution dynamics – *analytical solution*

- Following wetting (rainfall event), *stage-1* evaporation (*e*) from the surface and a redistribution flux *F(t)* occur simultaneously – key steps: *(1)* define depth of evaporation active region L_C with mean water content θ_{cap}; *(2)* estimate the amount of drainable water F_∞; *(3)* calculate time of transition to *stage-2*

- Lab experiments in various soils (0.75 m column) with different boundary conditions have shows → very short duration of active drainage (redistribution) at high rates

Main point - Concurrent drainage shortens the duration of *stage-1* and may reduce overall evaporative losses





(2)

$$F_\infty = L_C\left(\theta_{cap} - \theta_c\right)$$

Drainable water depth

(1)

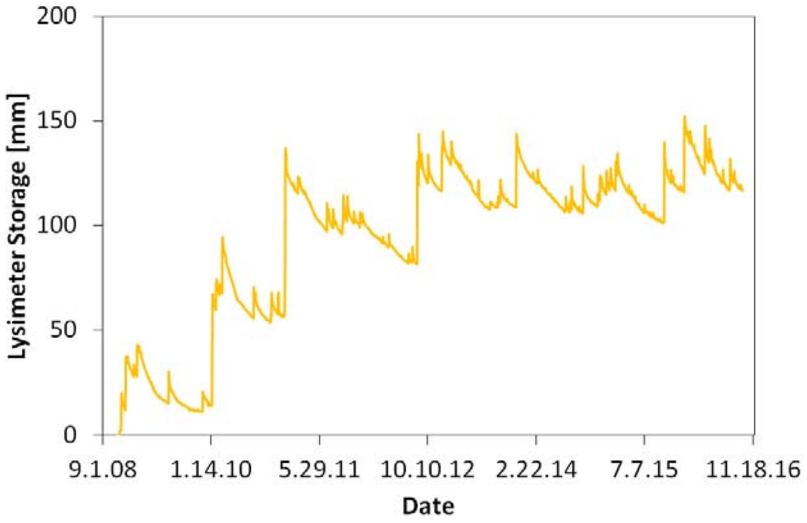
$$L_C = \frac{L_G}{1 + \frac{e_{pot}}{K_C}}$$

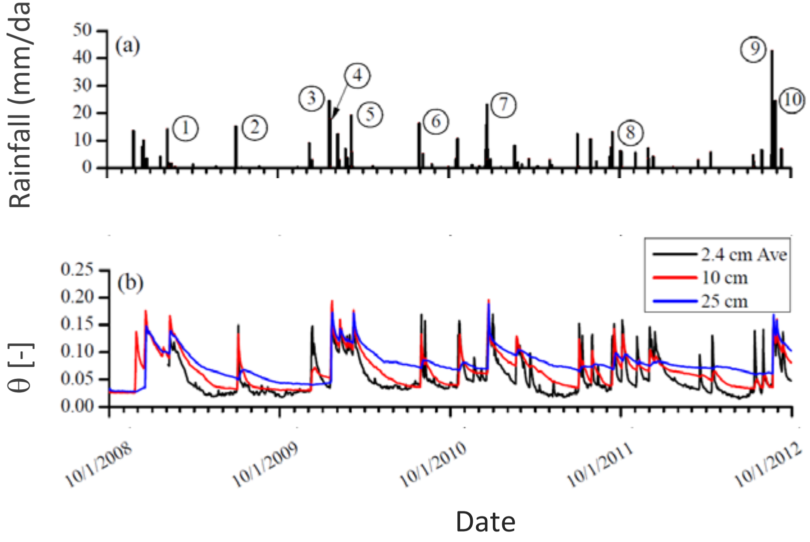
(3)

$$F(t) = F_\infty\left[1 - \exp\left(-\frac{K_0 \cdot t}{F_\infty}\right)\right]$$

Decade-long study of bare soil lysimeter – DRI Las Vegas

- The SEC model was evaluated using data from 3-m deep lysimeter filled with local sandy soil (*Las Vegas, DRI*)
- We used a decade-long time series of rainfall events, potential ET, surface evaporation (*no vegetation*), water content and total storage measurements



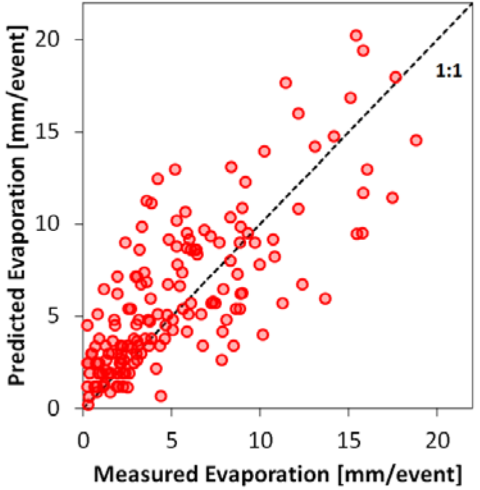


Surface evaporation from desert lysimeter

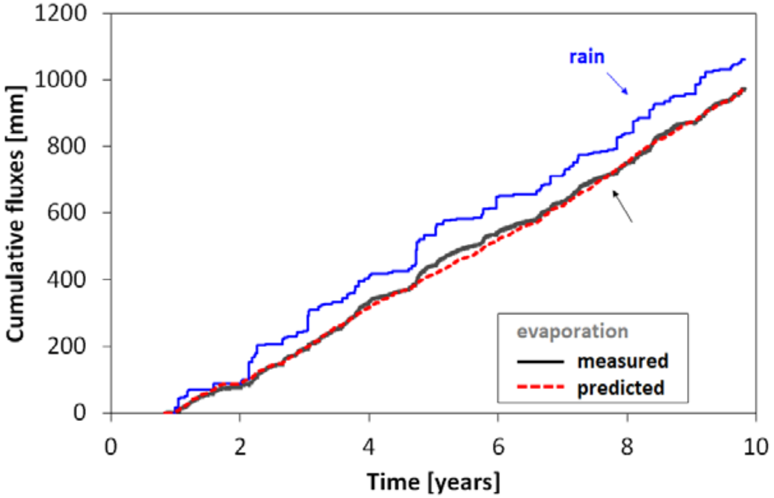
- The decade-long cumulative rainfall depth of 1 m was partitioned into surface evaporation (0.9 m) and inter-seasonal storage in the lysimeter (0.1 m)

- Despite high potential evaporation (cumulative $ET_0=18$ *m*; aridity index ~0.05), a fraction of rainwater (11%) remained stored in the lysimeter across years (*no plant uptake*)

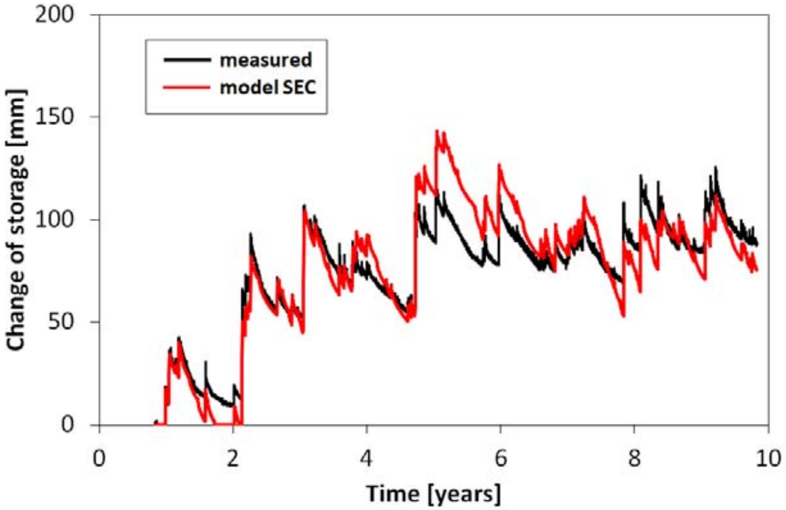
Event-based evaporation



Cumulative surface evaporation



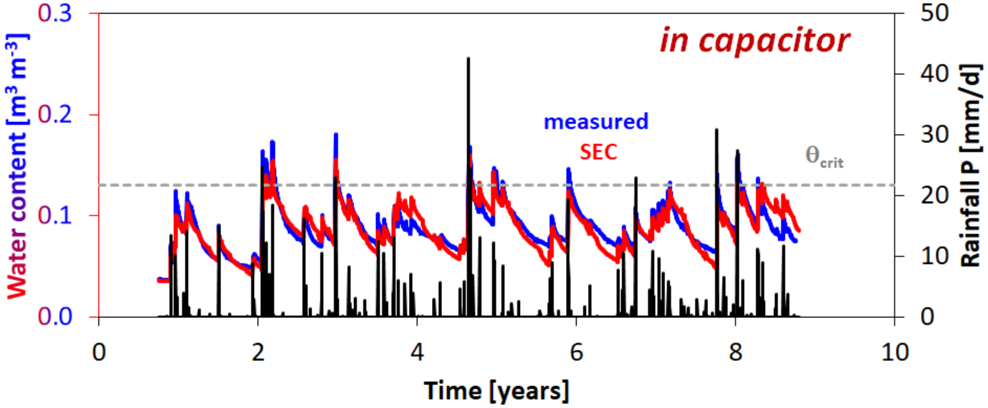
Soil water storage

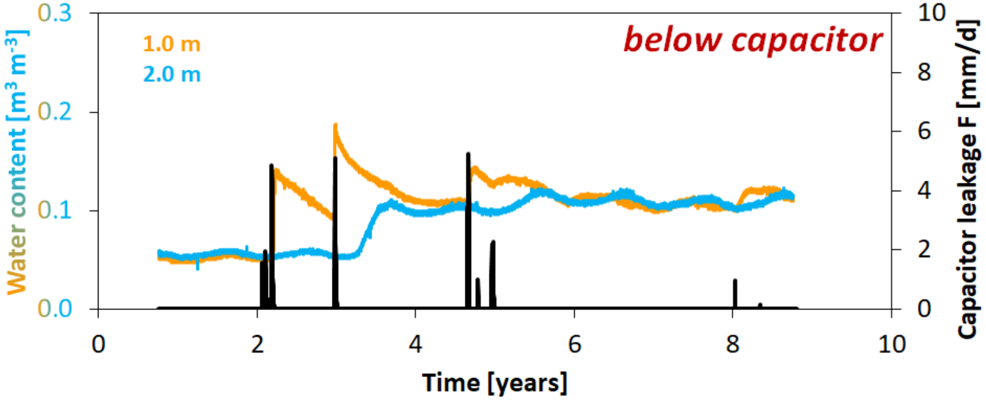


(Lehmann et al. 2019 GRL)

Soil water dynamics (***no plants***) – *arid region characteristics*

- The lysimeter surface evaporative capacitor (SEC) layer of *0.5 m* was estimated from soil properties (i.e., the evaporation characteristic length)
- Rainwater percolated into deeper layers only when the SEC layer water content exceeded a critical water content θ_{crit} of 0.13 m^3 m^{-3}
- The arrival of rainwater to deeper layers was delayed with increasing soil depth
- The estimated redistribution "events" were in agreement with increased soil water content in deeper layers

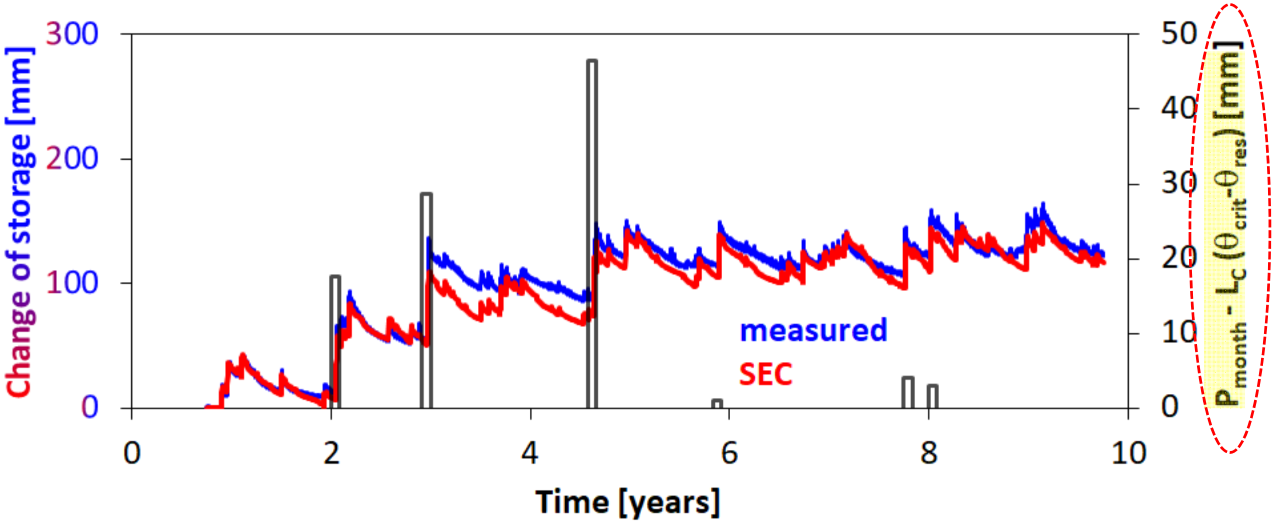


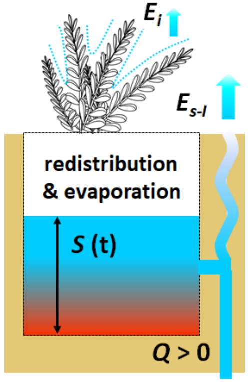


(Lehmann et al. 2019 GRL)

Deep soil water storage determined by 3 rainfall events

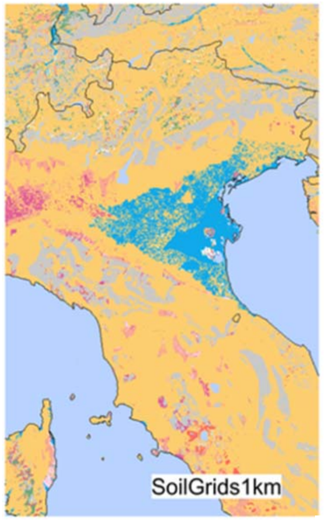
- The increase of inter annual water storage in the lysimeter occurred in three large rainfall events that exceeded SEC critical capacitance (generating leakage *F*>0!)
- Other rainfall events evaporated back to the atmosphere within one season
- SEC estimates of critical storage capture the salient features of arid region soil water storage dynamics using soil type and rainfall information only



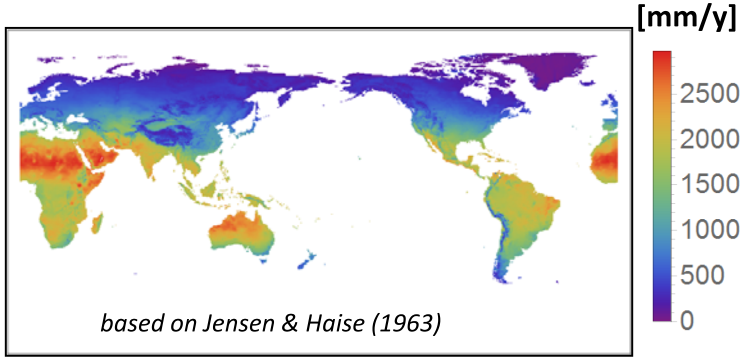


Surface evaporation capacitor – *global applications*

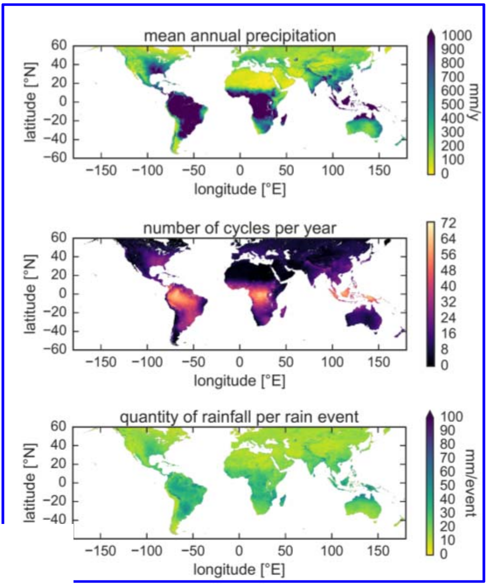
High resolution soil maps
→ characteristic depths (L_c)



Local atmospheric demand (ET_0)
(affects dynamics small effect on losses)



Spatially and temporally
resolved precipitation input

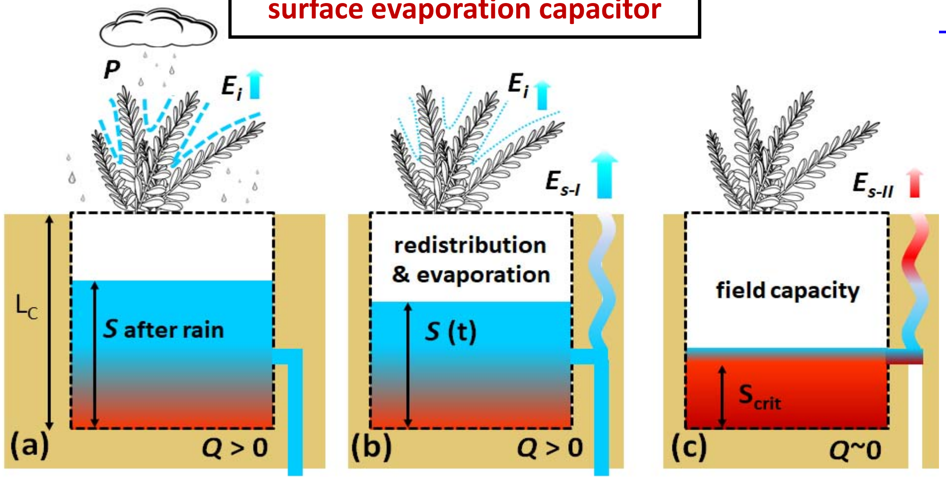


soil

climate/ET_0

rainfall

Define a local and dynamic surface evaporation capacitor



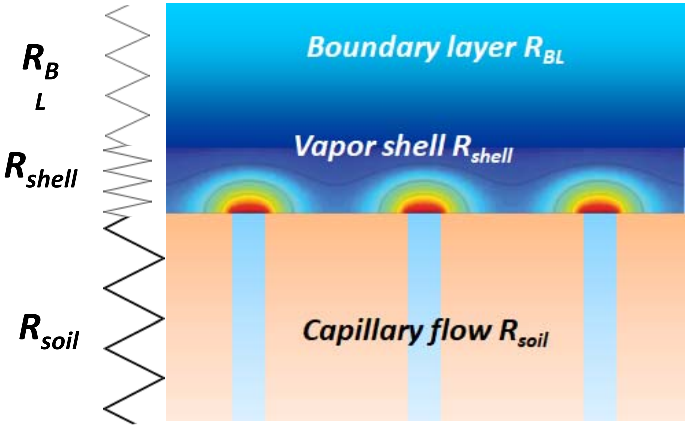
$$I = LAI \cdot h^*$$

Surface resistance – *pore scale processes and soil type matter…*

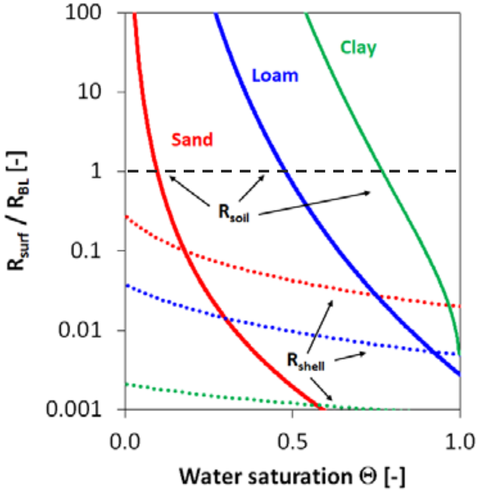
- *Lehmann et al. (2018)* incorporated pore-scale physics to estimate surface evaporative resistance as a function of water content and soil texture (*generalization and reducing empiricism*)
- Relative evaporation rate E_{surf}/ET_0 reflects how surface resistance varies with water content and soil type – *agree with observations*
- Surface evaporation data from *Fluxnet sites* differing in soil texture were used to evaluate surface evaporation vary with water content

$$\boxed{\frac{E_{surf}}{ET_0} = \frac{4K(\theta_{surf})\left[1+{ET_0}/{4K(\theta_C)}\right]}{ET_0 + 4K(\theta_{surf})\left[1+{ET_0}/{4K(\theta_C)}\right]}}$$

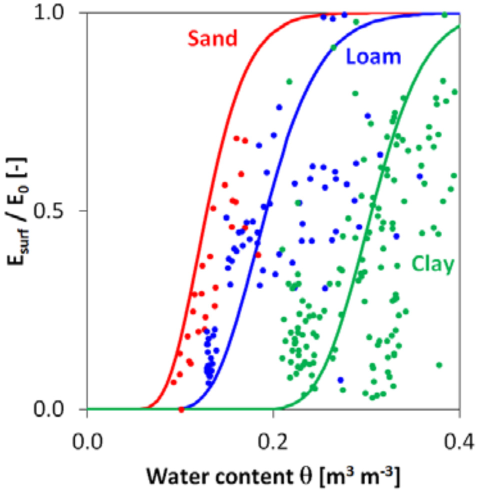
Three resistances to surface evaporation - in series



Relative importance of viscous and diffusion



In line with the findings of Merlin et al. (2016)



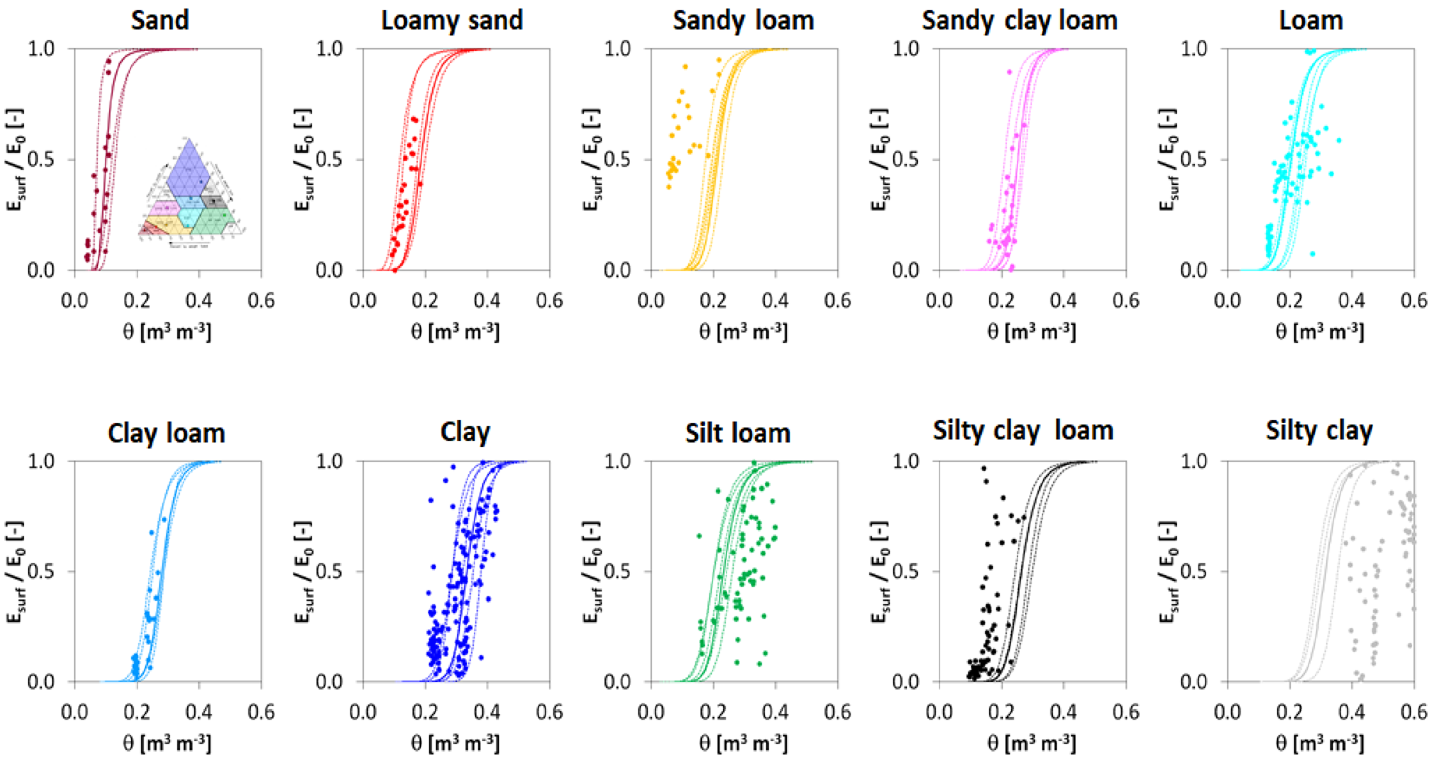
$$R_{shell} = \xcancel{\frac{1}{D_{air}} \cdot \frac{r_{pore}\left(\pi - 2\sqrt{\theta_{surf}}\right)}{4\theta_{surf}}}$$

$$E_{surf} = \frac{1}{R_{BL} + R_{shell} + R_{soil}} \cdot \frac{M_W}{\Re \cdot T} \cdot \frac{(p_{sat} - p_{air})}{\rho_{water}}$$

Soil type affects surface evaporation in several ways…

- The soil textural class and rainfall patterns play important roles in surface evaporation *E*
- The effects of soil type are manifested in: (**a**) **surface resistance** to evaporation; (**b**) evaporation **characteristic length**; and (**c**) **drainage dynamics** (affect overall response)
- The surface evaporation resistance model was in good agreement with flux tower data (*Merlin et al. 2016*) showing soil texture effects

$$\frac{E_{surf}}{ET_0} = \frac{4K(\theta_{surf})\left[1+{ET_0}/{4K(\theta_C)}\right]}{ET_0+4K(\theta_{surf})\left[1+{ET_0}/{4K(\theta_C)}\right]}$$



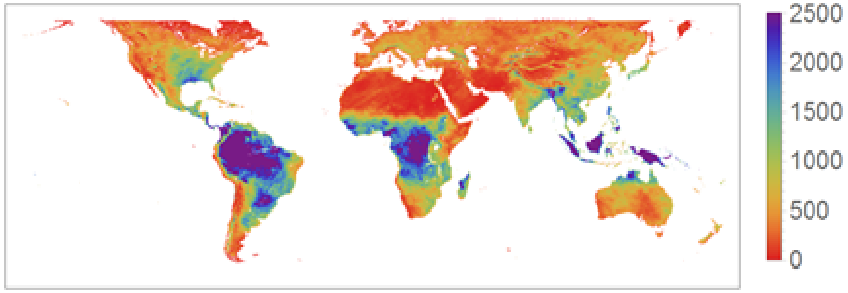
(Lehmann et al. 2018 GRL)

Global application of the SEC - *input information and parameters*

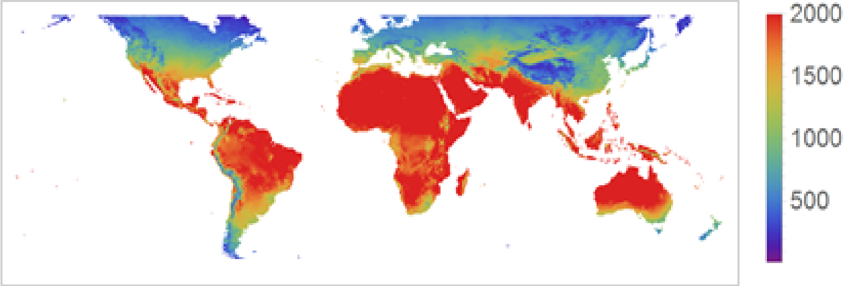
- For global application of the *SEC* we use SoilGrids to derive a characteristic length L_C and surface resistance; climatic data for precipitation *P*, annual ET_0 and plant cover expressed as *LAI* (for canopy interception and surface evaporation shading)

- Data at various resolutions – the *SEC applied at 1/4⁰ (~25 km) resolution and daily time step*

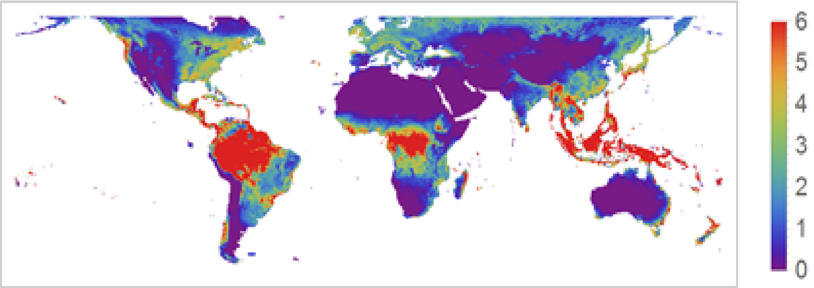
Precipitation [mm/year]



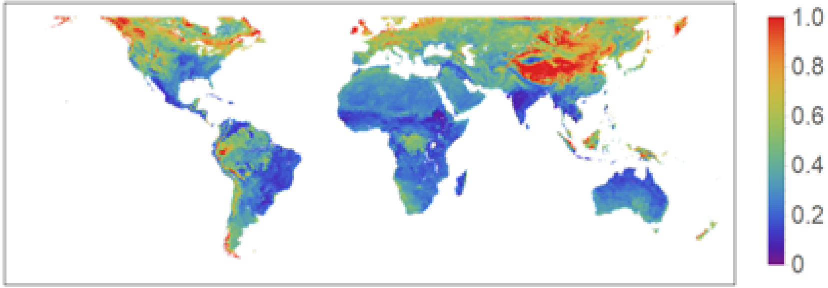
Annual ET_0 [mm/year]



Average LAI [m^2 m^{-2}]



Characteristic length L_C [m]

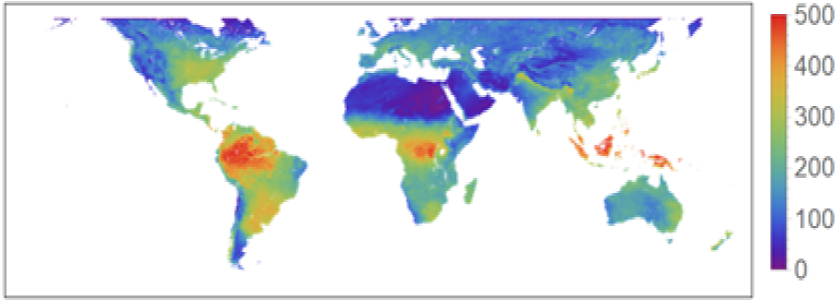


(Or and Lehmann, 2019 WRR)

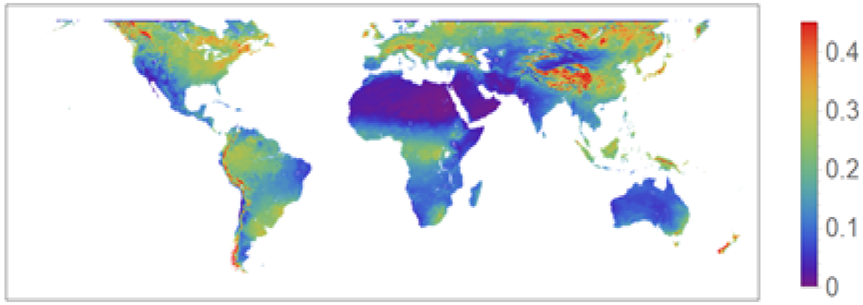
Global SEC estimates - *surface evaporation characteristics*

- Global scale application of the *SEC* for annual surface evaporation (***E***) and “leakage” (***F***) a decade of climatic data linking local soil properties, vegetation *LAI*, precipitation (***P***) and potential ET (***ET_0***)

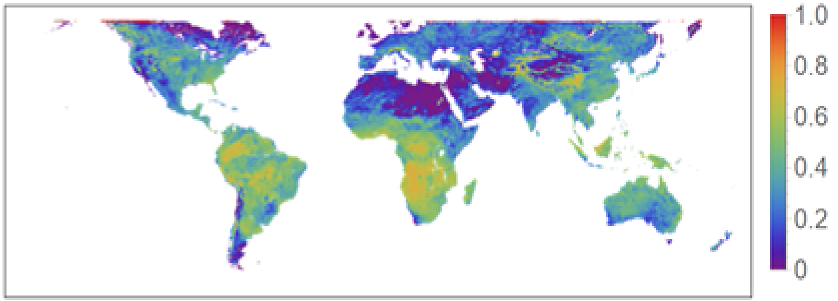
Surface evaporation E [mm/year]



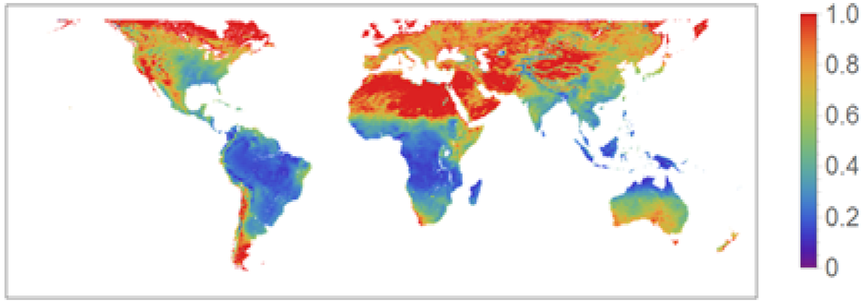
Ratio E/ET_0 [-]



Ratio F/P [-]



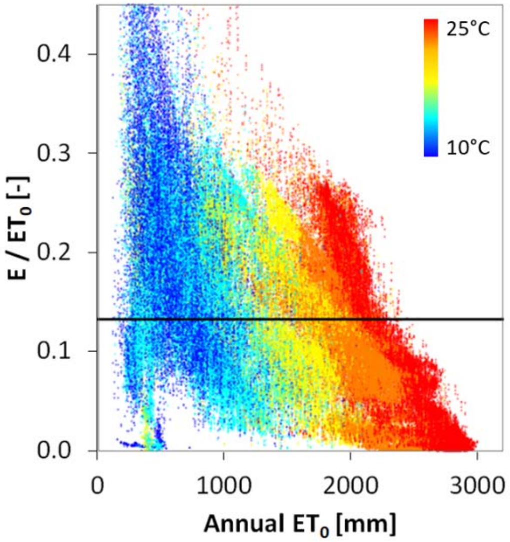
Ratio E/P [-]

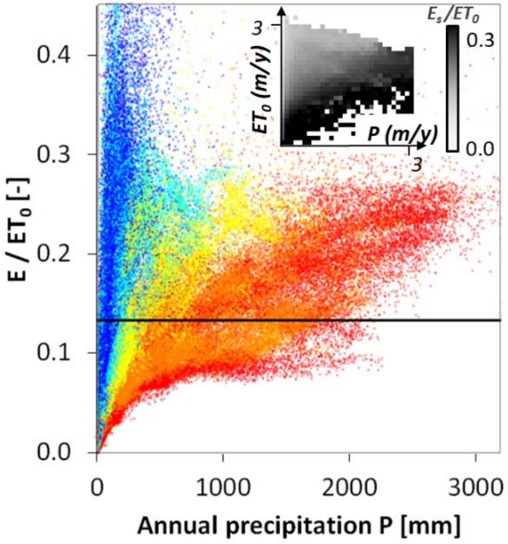


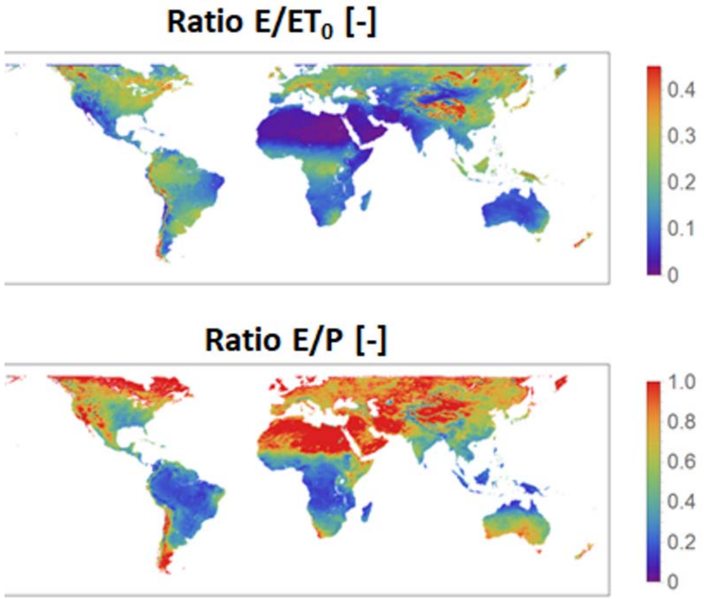
(Or and Lehmann, 2019 WRR)

Global SEC estimates - *surface evaporation characteristics*

- Global scale application of the *SEC* for annual surface evaporation (*E*) and “leakage” (*F*) a decade of climatic data linking local soil, *LAI*, precipitation (*P*) and potential ET (ET_0)
- A narrow range of values: $E/ET_0 < 0.2$ (*global median* ≈ *0.15*)
- High values of E/ET_0 for cooler temperatures and low ET_0







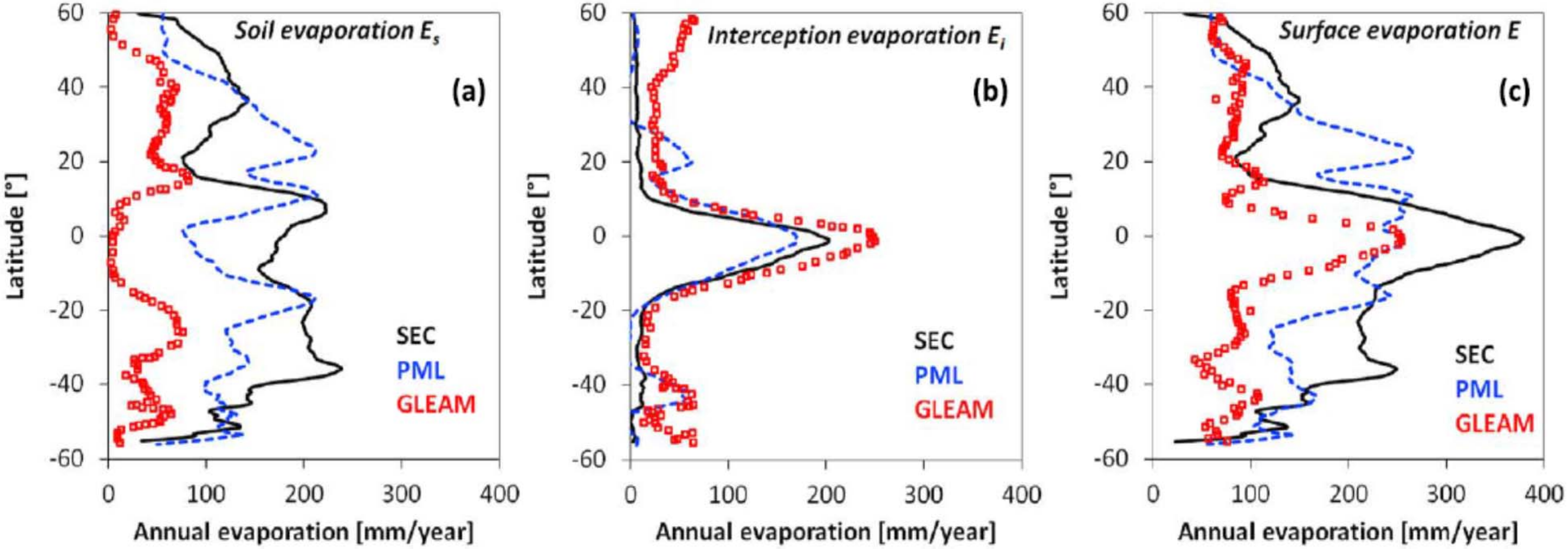
(Or and Lehmann, 2019 WRR)

Latitudinal comparison with other global *E* estimates

- The *GLEAM* and *PML* models estimate daily land evaporation (0.25°); GLEAM uses a multilayer bucket forced by satellite surface moisture; PML uses *PM-Leuning* formulation

- We separate canopy interception losses (*Ei*) and bare soil evaporation (*Es*)

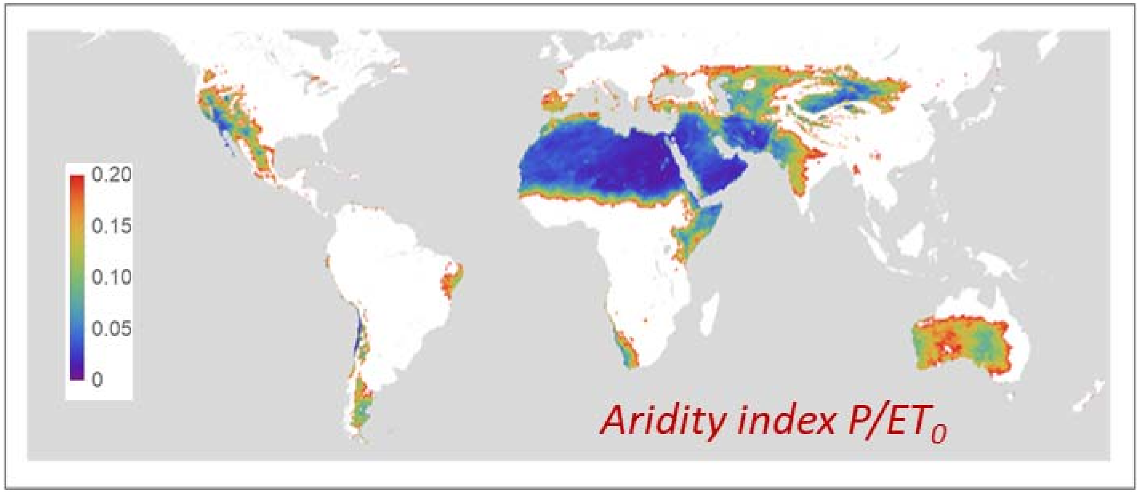
- Latitudinal values of soil evaporation by SEC were different than *GLEAM* predictions due to attribution of E_S to no-vegetation pixels only! SEC estimates closer to *PML* (*PML tend to overestimate E in Tropical regions due to ignoring surface shading by evaporation*)



Or and Lehmann, 2019 WRR
Miralles et al. 2011 HESS
Zhang et al., 2016 Sci. Rep.

Surface evaporation in arid regions – *the SEC model*

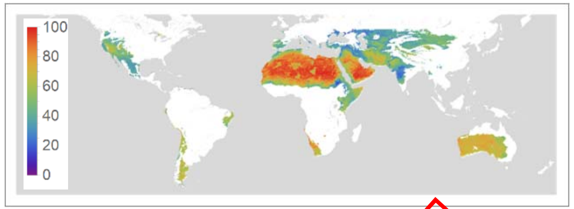
- One third of global land surface is arid supporting fragile and water-limited ecosystems
- Arid regions characterized by high ET_0 greatly exceeding annual rainfall P (P/ET_0 *aridity index* <0.2)
- In arid regions surface evaporation E often dominates soil water regime with infrequent rainfall
- The fraction of rain water that percolates into deeper layers F and become sheltered from surface evaporation is a complicated function of rainfall patterns, topography, vegetation and soil texture
- We seek to address the question – *how much of arid region rainwater is sheltered or protected from surface evaporation*? (hence could become available for plant uptake, storage or recharge)



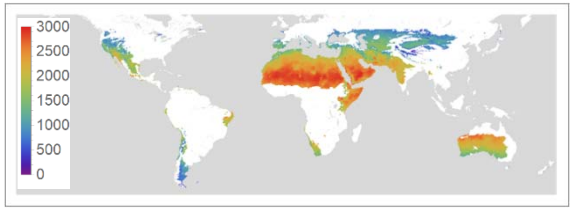
Estimates of surface evaporation *E* for global arid regions

- We applied the SEC model using soil properties and climatic data to estimate soil water dynamics for arid regions globally (*$P/ET_0<0.2$*) - 10 years climate and rainfall at ¼° resolution)

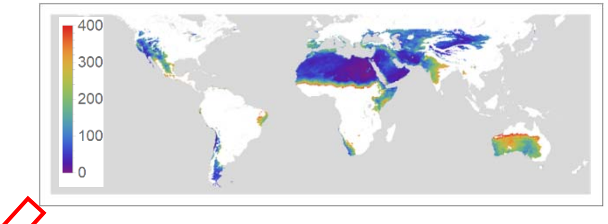
Soil texture (sand content %)



Potential evapotranspiration (mm/year)

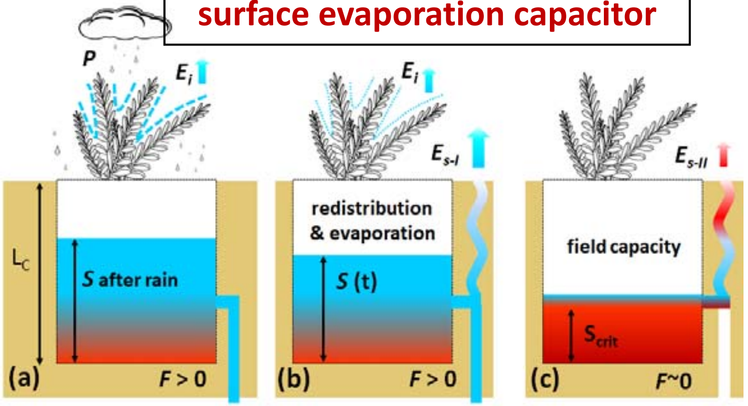


Precipitation (mm/year)



(Lehmann et al. 2019 GRL)

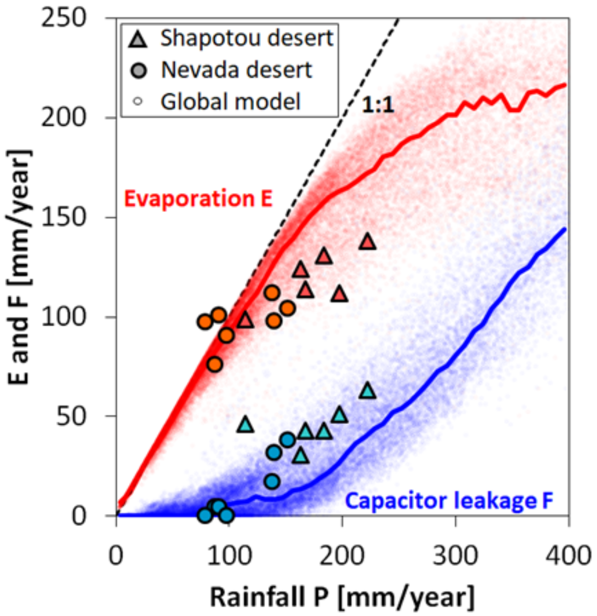
Define a local and dynamic surface evaporation capacitor

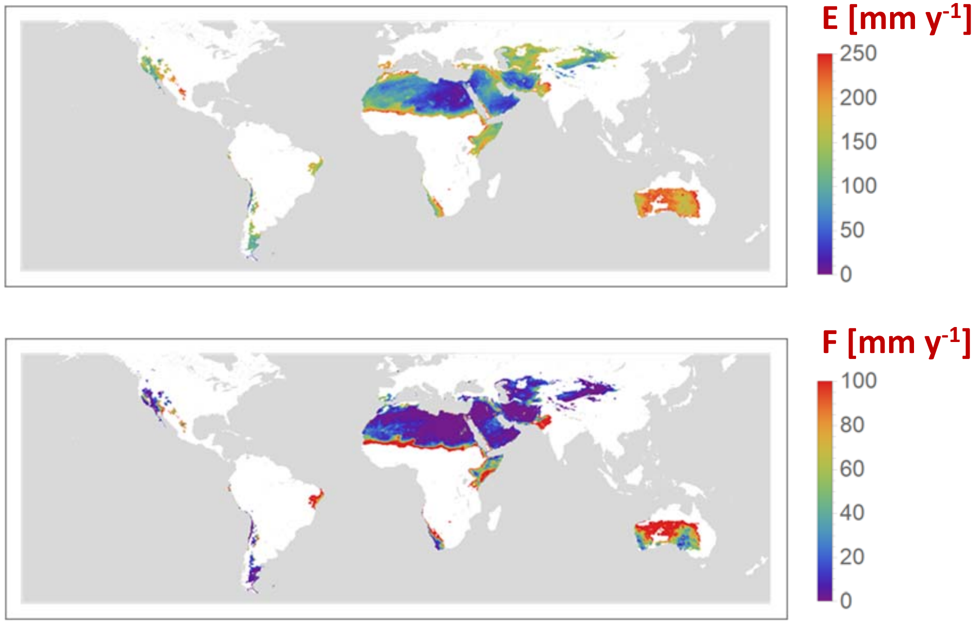


- Interception losses *negligible* in arid regions
- *Stage-2* evaporation - *very important*
- Rainfall characteristics – *very important*

Rainfall partitioning in arid regions – *bare soil (no vegetation)*

- Both lysimeter data and SEC estimates confirm existence of a rainfall threshold (~*85 mm*) for “triggering” water leakage *F* into deeper soil layers (protected from surface evaporation *but not from plant water uptake*)
- The spread in SEC estimates is due to soil type and rainfall characteristics

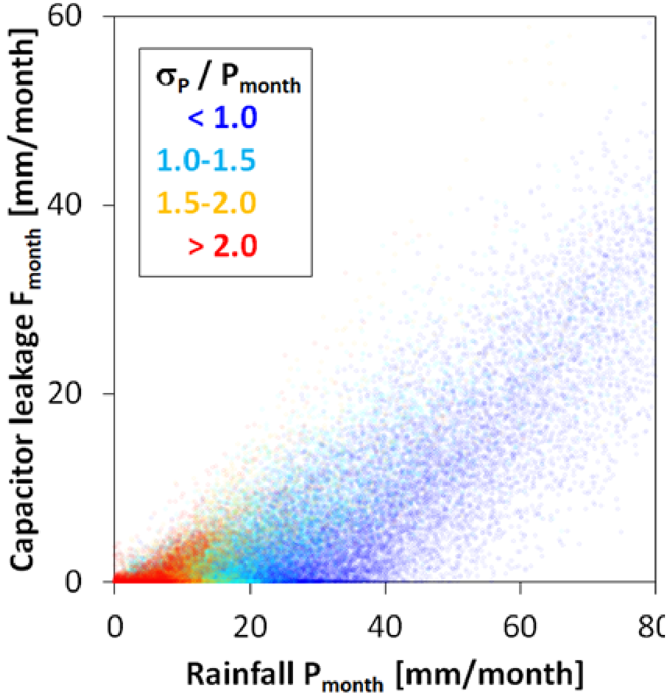


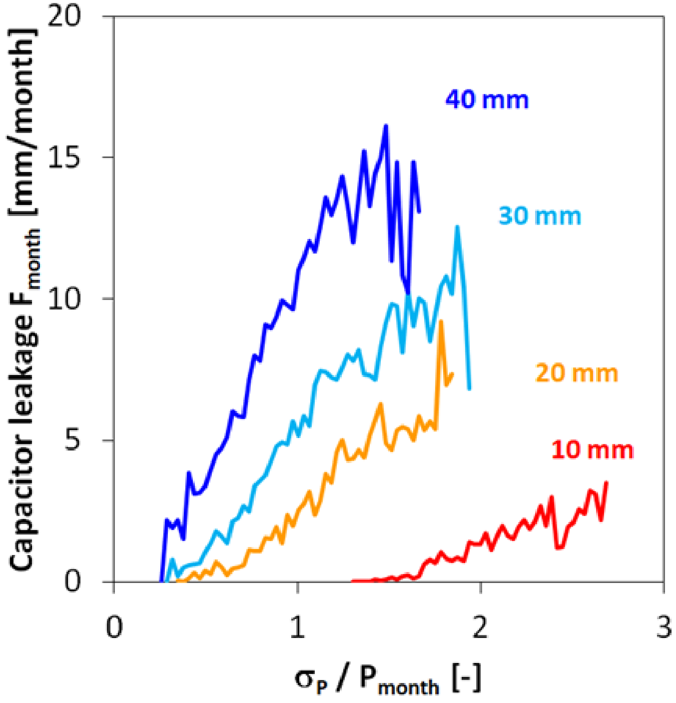


(Lehmann et al. 2019 GRL)

Role of rainfall variability - *SEC estimates of **F** (leakage)*

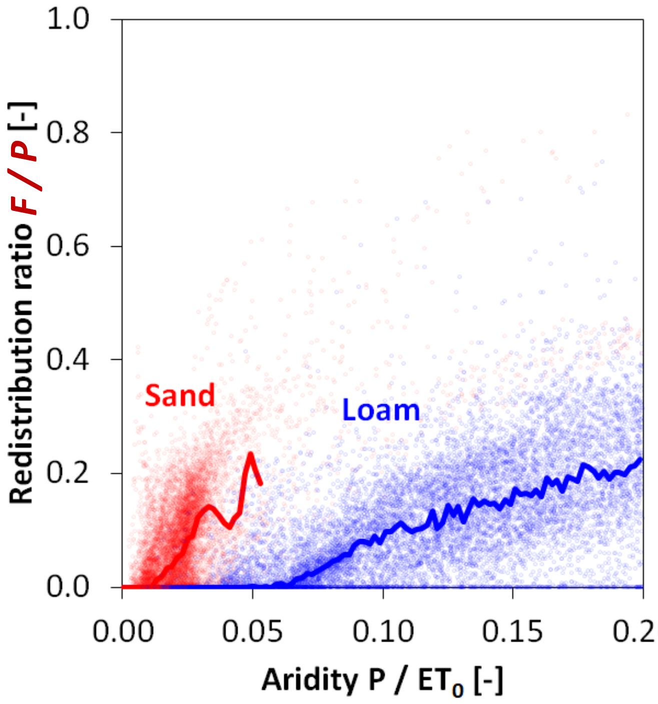
- The DRI lysimeter study have shown that rainfall variability affects *F*, the leakage below the capacitor layer (i.e., only 3 rainfall events in a decade contributed to *F*)
- Global SEC application and rainfall record show that (estimated) leakage *F* or water protected from surface evaporation, increases with rainfall STD σ_P and mean monthly amount P_{month}

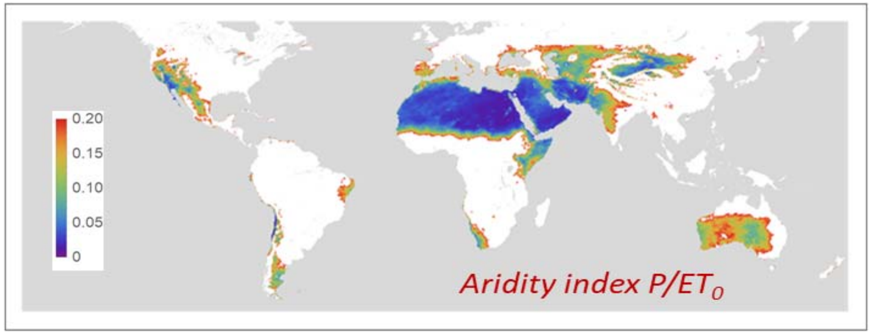


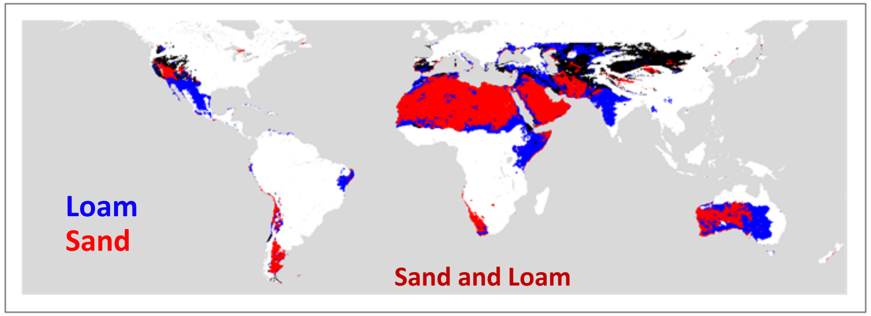


Effects of soil texture on *F*

- In addition to climatic effects, rainfall partitioning is sensitive to soil texture (affecting *drainage rates, water retention, surface resistance and characteristic length*)
- Sand is the dominant soil texture in many hyper-arid regions
- Loamy soils have higher storage capacity and require larger rainfall events to trigger “leakage”
- Global mean F/P ratio in arid regions is 0.14 (similar to F/P=0.11 found in the lysimeter study)

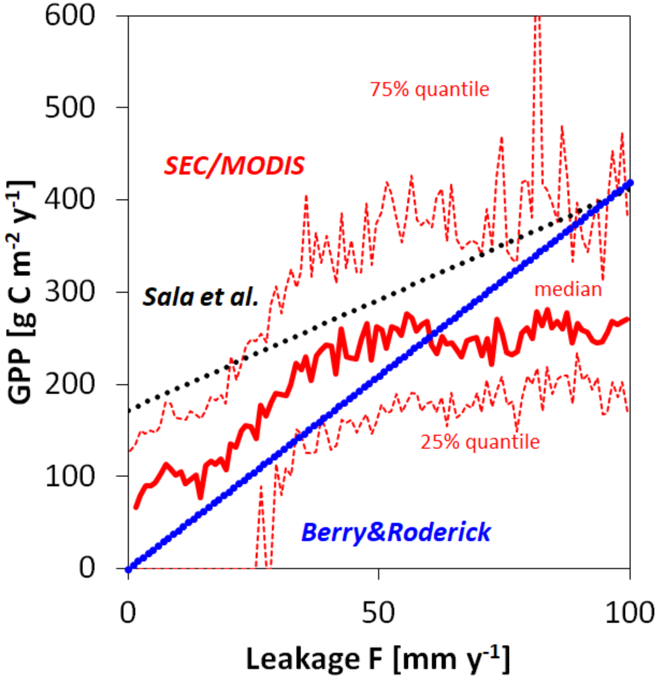




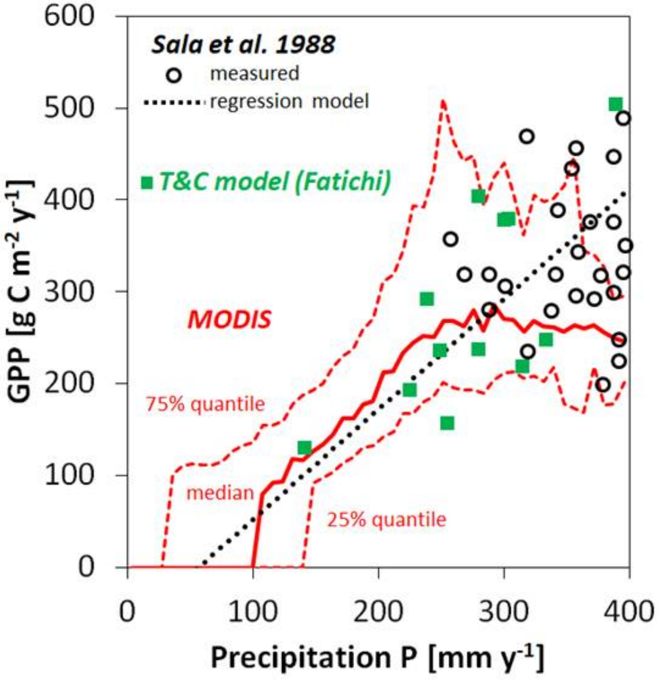


Can "protected" storage *F* predict arid land vegetation capacity?

- Considering SEC leakage *F* available for plant water uptake, it may offer a simple estimate for transpiration *T* and vegetation carrying capacity for arid landscapes (i.e., *GPP*)
- To test the idea, we converted SEC *F* estimates using *WUE* (*Berry and Roderick, 2004*) to arid regions *GPP* (*comparing MODIS, model and Sala et al. 1988*) – *tests of WUE and surface runoff effects are needed*



SEC - F



Gross primary productivity and transpiration flux of the Australian vegetation from 1788 to 1988 AD: effects of CO_2 and land use change

SANDRA L. BERRY and MICHAEL L. RODERICK

Summary and conclusions

- Pore scale evaporation physics are used to address the challenge of separating *ET* to *E* and *T* components to better constrain evaporative pathways independently (beyond *PM closure*)
- A soil-specific *evaporative characteristic length* is used to define a near-surface evaporation zone with consideration of internal drainage dynamics – both are soil type dependent
- The model was tested in the lab and was generalized to the *soil evaporation capacitor* (*SEC*)
- The *SEC* provides an estimate (upper bound) for surface evaporation combining an analytical model with precipitation, potential ET and soil type (+ LAI vegetation cover)
- Tests of the *SEC* using literature and lysimeter data support the feasibility of the method
- Soil texture affects surface evaporation via (1) resistance, (2) capillary length (3) dynamics
- Globally, E/ET_0 ratio exhibits remarkably narrow range irrespective of rainfall or soil type
- Application of SEC to arid region evaporation – *improved understanding rainfall partitioning and potential prediction of landscape vegetation carrying capacity from "leakage"*

Acknowledgments

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Thank you!