Integrating soil and subsurface processes in GEWEX:

The SoilWat Initiative

Dani Or[1] , Harry Vereecken[2], Michael Young[3] , and Gerrit de Rooij[4]

1 – *Environmental Systems Science, Swiss Federal Institute of Technology, ETH Zurich*
2 – *Institute of Bio-and Geosciences Agrosphere, Forschungszentrum Jülich*
3 – *Bureau of Economic Geology, University of Texas at Austin*
4 – *Helmholtz Centre for Environmental Research, UFZ Leipzig-Halle*

GEWEX SSG – ETH Zurich 2016

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

JÜLICH
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Bureau of Economic Geology
The University of Texas at Austin

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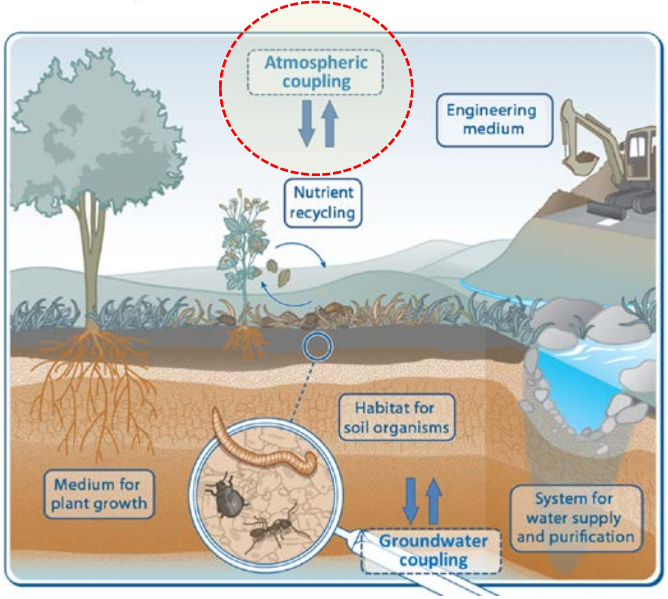
Soil – *Earth’s life support system*

- Soil is arguably the most biologically active compartment of the biosphere hosting largest pool of biodiversity
- Soil is a giant recycling system providing human needs for food and supports global biomass stocks
- Soil functions as Earths' life support body, a thin film of life covering terrestrial surfaces
- Nearly all contemporary societal challenges (from climate change to food security) involve a significant “***soil***” component
- In the past few years the soil and critical zone community is reaching out to other disciplines and to cross-disciplinary scientific platforms (e.g., GEWEX) to improve integration and provide better context for interdisciplinary consideration of key soil processes

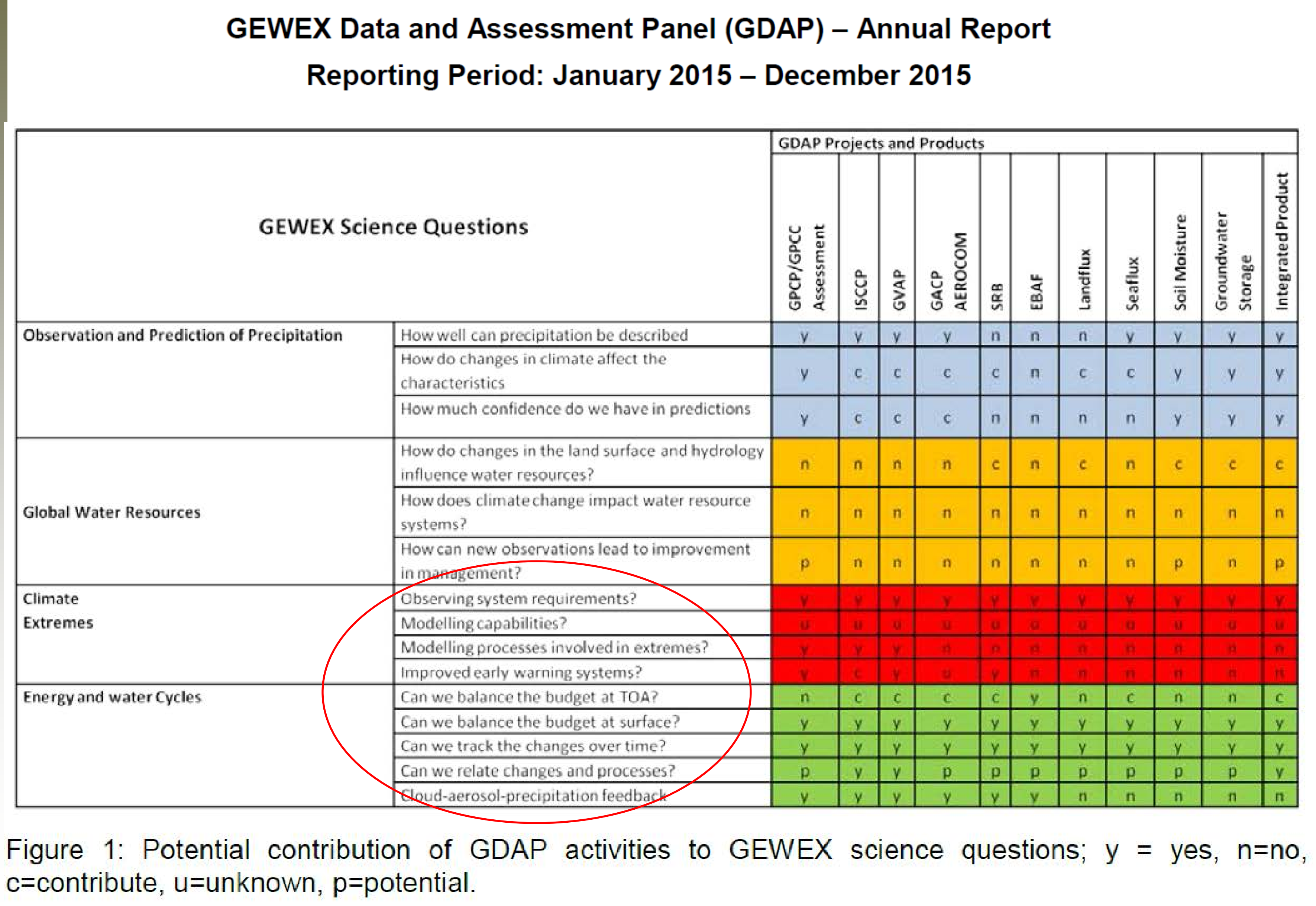
(NASA)



Potential *GEWEX-SoilWat* synergism - *examples*

- **Integration of *Critical Zone Observatories*** (CZO) and similar eco-hydrological observatories within GEWEX (eLTER-H2020 - European Long-Term Ecosystem Research Infrastructure; TERENO; ICOS; CUAHSI) – design; sensors; monitoring protocols; data repository [in coordination with GHP]
- **Formation of a global lysimeter network** – to inventory, standardize, and expand coverage of lysimeter observations; links with CZO's (lead – FZ Julich and Wageningen) [in coordination with GHP]
- **Integration of the *International Soil Modelling Consortium*** – coherence and better links between climate and soil modelers with respect to models, data sets for model testing, etc. (lead – FZ Julich) [in coordination with GLASS]
- **Development of linkages with the *Global Soil Map* initiative** [all panels]
- **Simple and low-cost soil moisture monitoring networks** (e.g., TxSON) for highly resolved soil moisture information [GHP and GDAP]
- **Integrating human interactions affecting soil-water processes** [GLASS, others]
- **Incorporation of near surface and small-scale soil processes** (evaporation physics; plants-soil interactions; biogeochemical processes) [GLASS]

Potential GEWEX-SoilWat synergism - *examples*



GEWEX Data and Assessment Panel (GDAP) – Annual Report

Reporting Period: January 2015 – December 2015

GEWEX Science Questions		GDAP Projects and Products GPCP/GPCC Assessment	ISCCP	GVAP	GACP AEROCOM	SRB	EBAF	Landflux	Seaflux	Soil Moisture	Groundwater Storage	Integrated Product
Observation and Prediction of Precipitation	How well can precipitation be described	y	y	y	y	n	n	n	y	y	y	y
	How do changes in climate affect the characteristics	y	c	c	c	c	n	c	c	y	y	y
	How much confidence do we have in predictions	y	c	c	c	n	n	n	n	y	y	y
Global Water Resources	How do changes in the land surface and hydrology influence water resources?	n	n	n	n	c	n	c	n	c	c	c
	How does climate change impact water resource systems?	n	n	n	n	n	n	n	n	n	n	n
	How can new observations lead to improvement in management?	p	n	n	n	n	n	n	n	p	n	p
Climate Extremes	Observing system requirements?	y	y	y	y	y	y	y	y	y	y	y
	Modelling capabilities?	u	u	u	u	u	u	u	u	u	u	u
	Modelling processes involved in extremes?	y	y	y	n	n	n	n	n	n	n	n
	Improved early warning systems?	y	c	y	u	y	n	n	n	n	n	n
Energy and water Cycles	Can we balance the budget at TOA?	n	c	c	c	c	y	n	c	n	n	c
	Can we balance the budget at surface?	y	y	y	y	y	y	y	y	y	y	y
	Can we track the changes over time?	y	y	y	y	y	y	y	y	y	y	y
	Can we relate changes and processes?	p	y	y	p	p	p	p	p	p	p	y
	Cloud-aerosol-precipitation feedback	y	y	y	y	y	y	n	n	n	n	n

Figure 1: Potential contribution of GDAP activities to GEWEX science questions; y = yes, n=no, c=contribute, u=unknown, p=potential.

Who is interested in *GEWEX-SoilWat* activities?

- ***Core group of highly motivated professionals:*** a wide range of people from all over the world were contacted and expressed keen interest and enthusiastic support
- ***Professional and scientific societies:*** the Soil Science Society of America (SSSA) – the primary dedicated professional society for soil science. Interest groups formed at AGU (Soil systems and critical zone processes Technical committee); The Geological Society of America - Soils and Soil Processes Interdisciplinary Interest Group); EGU-Soil Systems Section; others
- ***National agencies and projects:*** USDA/ARS; existing and future US-NSF, China and European CZO networks; eLTER H2020; Global soil map initiative
- ***Academic centers and industry:*** for example - *Water for Food* – NE; *World Food Centers* – ETH and UC Davis); Soil water sensor manufacturers (*Decagon*; *RainBird*; *Campbell Scientific; Delta-T*)

TERENO
TERRESTRIAL ENVIRONMENTAL OBSERVATORIES

LTER europe

World Food Center

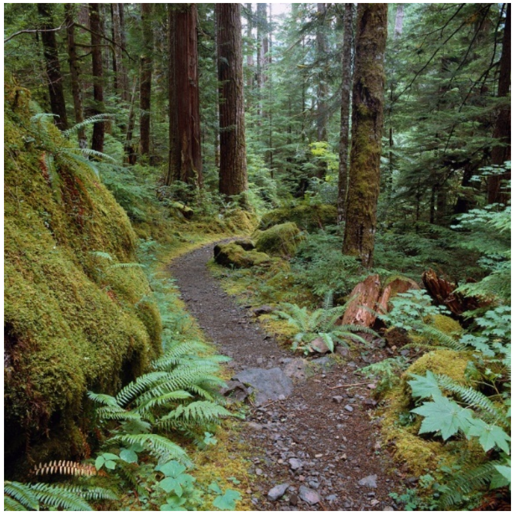
GlobalSoilMap.net

DECAGON DEVICES

Soil Science Society of America
Soils Sustain Life

How to move forward with *GEWEX-SoilWat* initiative?

- In early 2014 a document outlining potential synergism between the Soil/CZ and the Climate communities was circulated receiving enthusiastic feedback from the (evolving) core group expressing willingness to become engaged in GEWEX efforts
- We were invited as observers to the 7th GEWEX meeting in the Hauge (July 2014) to pitch the idea and identify potential synergies with existing Climate-Soil activities (in particular with the GLASS, GHP and GDAP panels)
- The recommendation was to identify most pressing gaps, formulate and prioritize areas of interactions via a dedicated planning workshop (Leipzig 2016 – *next slide*) and develop a "white paper" (published on GEWEX website)
- Establish joint sessions or discussions in future conferences (EGU, AGU, SSSA and other forums)
- Potential formation of integrated *GEWEX-SoilWat* activities by including core group and others



Planning workshop: *GEWEX-SoilWat UFZ Leipzig 28-30 June 2016*

- To provide a scientific basis, scope and integration of *SoilWat initiative* with existing GEWEX structures and activities, we plan a dedicated planning workshop hosted by UFZ in Leipzig-Halle (*June 28-30, 2016*) - the objective is to engage the GEWEX and Soil community members in the planning and in the workshop
- **Discussion areas/potential topics and core group** (tentative):
  1. Integrating (sub-) surface modeling in hydrological and climate models (*Conveners: **Dani Or, Harry Vereecken, Eleanor Blyth, Matthias Cuntz, Bill Kustas***)
  2. Model complexity and utility (simple vs complex models) (*Conveners: **Martin Best, Gab Abramovitz, Aaron Boone, Jan Vanderborght, Jasper Vrugt, Alex Mcbratney***)
  3. Groundwater-surface-atmosphere interactions (*Conveners: **Marc Bierkens, Remko Uijlenhoet, Gerrit de Rooij, Stephan Kollet***)
  4. Human interactions affecting soil-water processes (*Conveners: **Taikan Oki, Howard Wheater, Katja Frieler, Jacob Schewe, Shmuel Assouline, John Crawford, Michael Young***)
  5. Soil observations for hydro-climate research (*Conveners: **Jan Hopmans, Sonia Seneviratne, Steffen Zacharias , Hendricks-Franssen Harrie-Jan, Colin Campbell, Todd Caldwell***)
- **Potential outcomes:**
  1. to establish working groups for each of these to further develop the themes above
  2. to provide a scope and a first set of priority topics for the themes
  3. to develop modes of interactions and active collaborations on these topics
  4. to form a liaison group for exchange with related societies and communities – soil, GSA
  5. plan joint projects, white paper, interfacing with other initiatives (listed in the examples)

Workshops: ***ISMC*** *Austin April 2016;* ***GEWEX-SoilWat*** *UFZ Leipzig June 2016*

- The ***International Soil Modelling Consortium****:* inaugural conference in Austin (March 29 to April 1, 2016 - https://soil-modeling.org/austin-workshop/program); A white paper on challenges and perspectives in modelling soil processes (45 authors) submitted to VZJ (a basis for WGs discussions) – abstract submissions now open!
- *WG 1: ISMC Structure and Governance (Conveners: Dani Or, Sonia Seneviratne, Rainer Horn, Harry Vereecken)*
- *WG 2: Mission of ISMC and its links to other communities (Conveners: Michael Young, Jan Hopmans)*
- *WG 3: Model inter-comparison and modelling platforms (Conveners: Andrea Schnepf, Jan Vanderborght)*
- *WG 4: Linking data to modelling (Conveners: Yakov Pachepsky, Harry Vereecken)*
- *WG 5: Cross-cutting topics (Conveners: Lead Gerrit De Rooij, Kurt Roth, Peter van Oevelen, Mathieu Javaux)*

- To provide a scientific basis, scope and integration of ***SoilWat initiative*** with existing GEWEX structures and activities, we plan a dedicated **planning workshop** hosted by UFZ in Leipzig-Halle (*June 28-30, 2016*) - the objective is to engage GEWEX and soil community members in the planning and in the workshop
- The subjects below provide a basis (additional topics are welcome):

1. Integrating (sub-) surface modeling in hydrological and climate models
2. Model complexity and utility (simple vs complex models
3. Groundwater-surface-atmosphere interactions
4. Human interactions affecting soil-water processes
5. Soil observations for hydro-climate research

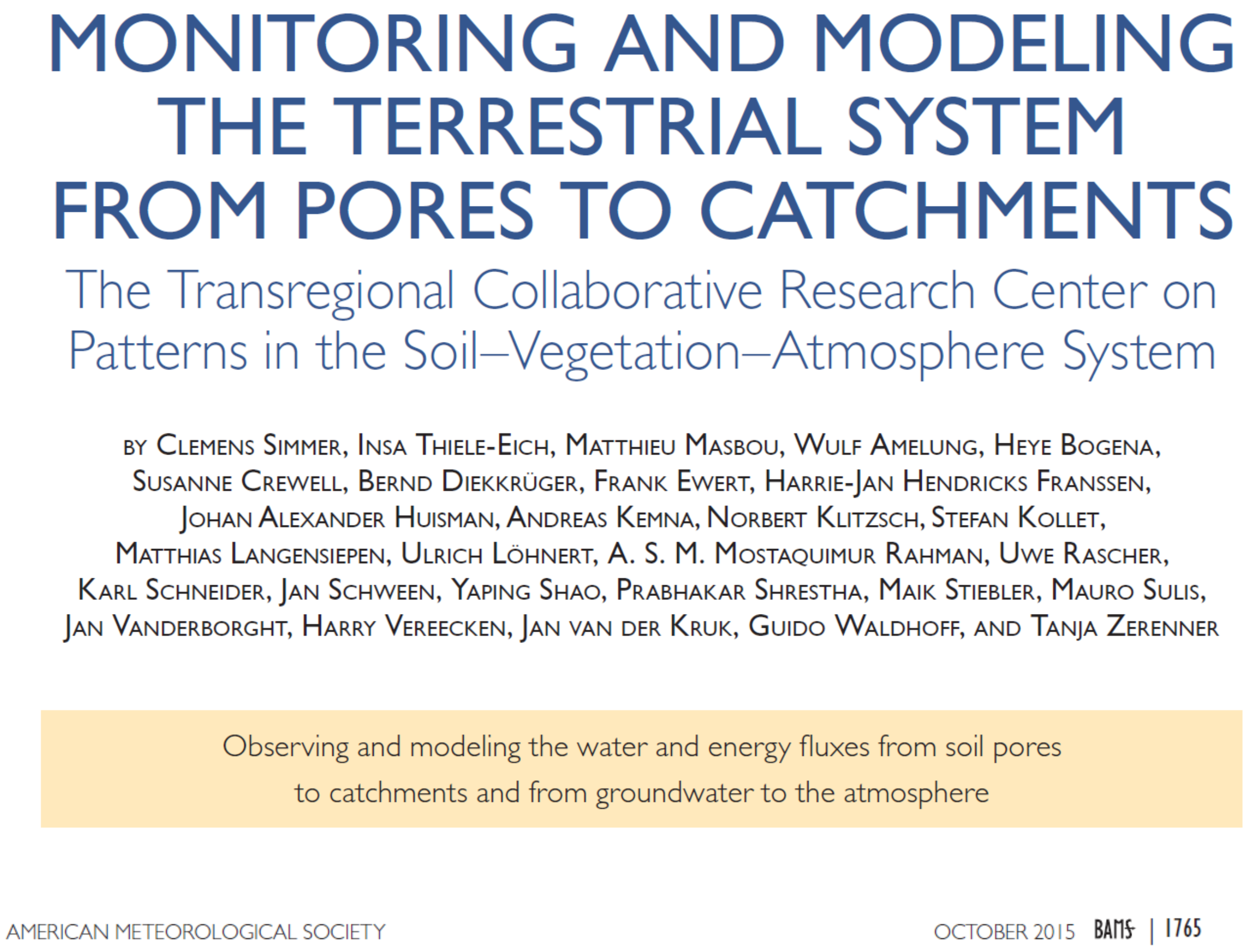
Interest group (*GEWEX*)

- Sonia Seneviratne (ETH Zurich) – GEWEX co-chair (extremes, land-atmosphere interactions
- Peter van Oevelen, IGPO – GEWEX, hydrology, subsurface processes
- Eleanor Blyth (CEH – Wallingford) – land surface modeling (GLASS)
- Aaron Boone (URA CNRS & Météo-France) - land-atmosphere feedbacks (GLASS co-chair)
- Gab Abramowitz (UNSW) – PALS, climate model structure and evaluation (GLASS)
- Taikan Oki (Univ. Tokyo) – global hydrology, sustainability
- Remko Uijlenhoet (Wageningen UR) – hydrology, water management
- Wolfgang Wagner, Wouter Dorigo (TU Wien) - soil moisture remote sensing, soil moisture network
- Eric Wood (Princeton) - land surface remote sensing, land hydrology
- Howard Wheater (Univ. Saskatchewan) Global institute for water security, Sask. River Basin Project

Interest group (*SoilWat*)

- Harry Vereecken – *Julich, Germany (CZO activities, sensors)*
- Jan Hopmans – *UC Davis, USA (SSSA links, food security)*
- Michael Young – *UT Austin, USA (GSA and water resources-climate)*
- David Robinson – *Bangor, UK (Ecosystem services & climate)*
- Binayak Mohanty – *Texas A&M, USA (Remote sensing – soil)*
- Steve Evett – *ARS Bushland, USA (Irrigation, energy balance, sensor development, lysimetry)*
- Josh Heitman – *NC State University, USA (evaporation/instruments methods)*
- Dani Or – *ETH Zurich, Switzerland (Surface processes/sensor development)*
- Jasper Vrugt – *UC Irvine, USA (Upscaling strategies – linking soil processes)*
- Nurit Agam – *Sede Boker, Israel (Remote sensing and processes in arid regions)*
- Isabelle Braud – *Cemagref Lyon, France (soil ET partitioning hydro-isotopes)*
- Jérôme Ogée/Lisa Wingate – *INRA Bordaux, France (plant-soil interactions, stable isotopes)*
- Shmuel Assouline/Shabtai Cohen – *Volcani Ctr., Israel (soil & micrometeoroloy)*
- Bill Kustas - *USDA, USA (Thermal and other remote sensing methods)*
- John Baker - *USDA/Univ. Minnesota, USA (Soil fluxes and instrumentation)*
- Colin Campbell – *Decagon, USA (soil moisture and other sensors)*
- John Crawford – *Rothamsted Research, UK (Sustainable soil systems)*
- Gerrit de Rooij – *UFZ, Germany (Soil and hydrological processes)*
- Todd Caldwell – *UT Austin, USA (soil water fluxes and land data assimilation)*
- Dominique Arrouays – *ISRIC-INRA, France (Global soil map)*
- Alex McBratney – *Univ. of Sydney, Australia (Global soil map)*

Linking processes – *groundwater-soil-atmosphere*



MONITORING AND MODELING THE TERRESTRIAL SYSTEM FROM PORES TO CATCHMENTS

The Transregional Collaborative Research Center on Patterns in the Soil–Vegetation–Atmosphere System

BY CLEMENS SIMMER, INSA THIELE-EICH, MATTHIEU MASBOU, WULF AMELUNG, HEYE BOGENA,
SUSANNE CREWELL, BERND DIEKKRÜGER, FRANK EWERT, HARRIE-JAN HENDRICKS FRANSSEN,
JOHAN ALEXANDER HUISMAN, ANDREAS KEMNA, NORBERT KLITZSCH, STEFAN KOLLET,
MATTHIAS LANGENSIEPEN, ULRICH LÖHNERT, A. S. M. MOSTAQUIMUR RAHMAN, UWE RASCHER,
KARL SCHNEIDER, JAN SCHWEEN, YAPING SHAO, PRABHAKAR SHRESTHA, MAIK STIEBLER, MAURO SULIS,
JAN VANDERBORGHT, HARRY VEREECKEN, JAN VAN DER KRUK, GUIDO WALDHOFF, AND TANJA ZERENNER

Observing and modeling the water and energy fluxes from soil pores to catchments and from groundwater to the atmosphere

AMERICAN METEOROLOGICAL SOCIETY

OCTOBER 2015 BAMS | 1765

Linking processes – *modeling groundwater to atmosphere*

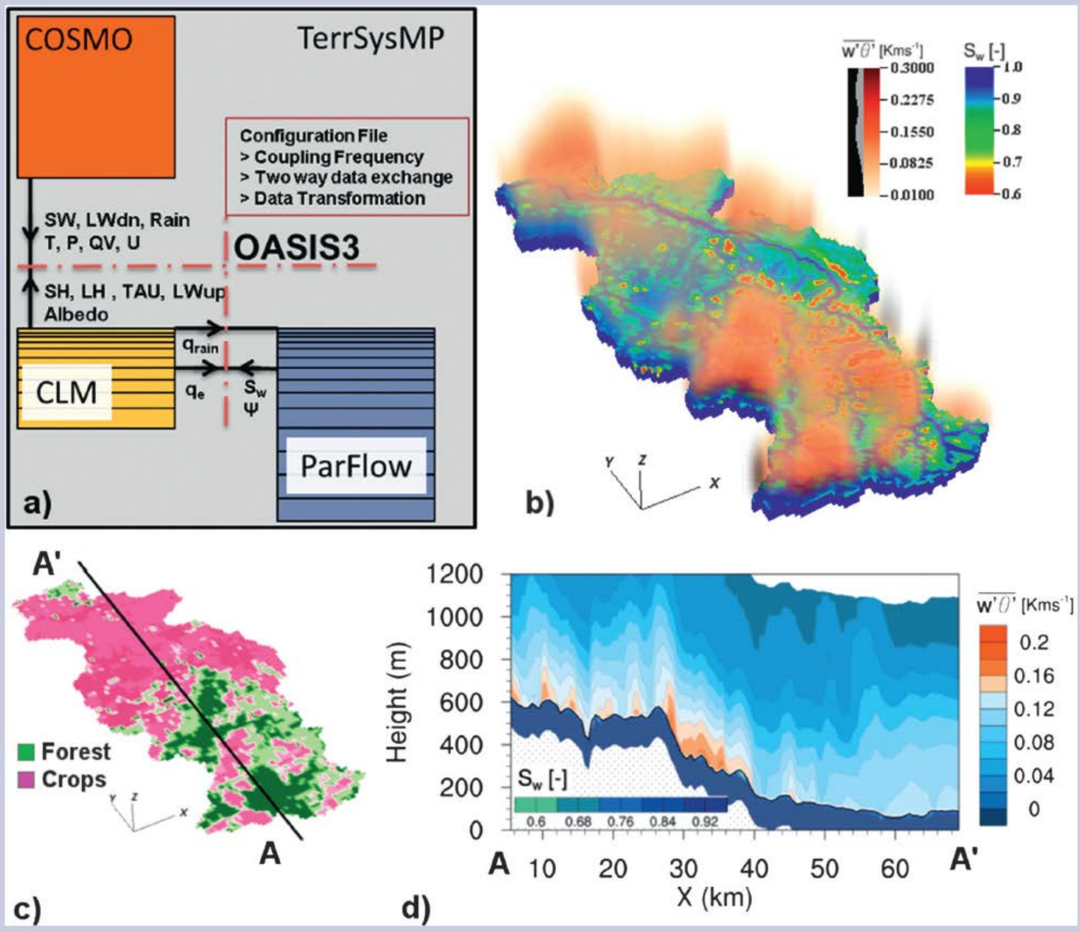


FIG. SB1. (a) Schematic of TerrSysMP [modified after Shrestha et al. (2014)] showing the fluxes and state variables exchanged between the three model components: **COSMO** (atmosphere), **CLM** (land surface and subsurface), and ParFlow (subsurface hydrology) via the **OASIS** coupler. SW, LWdn, Rain, *T*, *P*, QV, and *U* are passed from **COSMO** to **CLM**, while **CLM** passes back SH, LH, TAU, LWup, and albedo. **CLM** shares the upper soil layers with ParFlow within which q_{rain} and q_e are passed from **CLM** to ParFlow, which transmits back S_w and Ψ. (b) Turbulent eddy heat flux and relative soil saturation (nondimensional) along the Rur catchment. (c) Main land-use classes in the catchment. (d) Meridional cross section of turbulent eddy heat flux and relative soil saturation.

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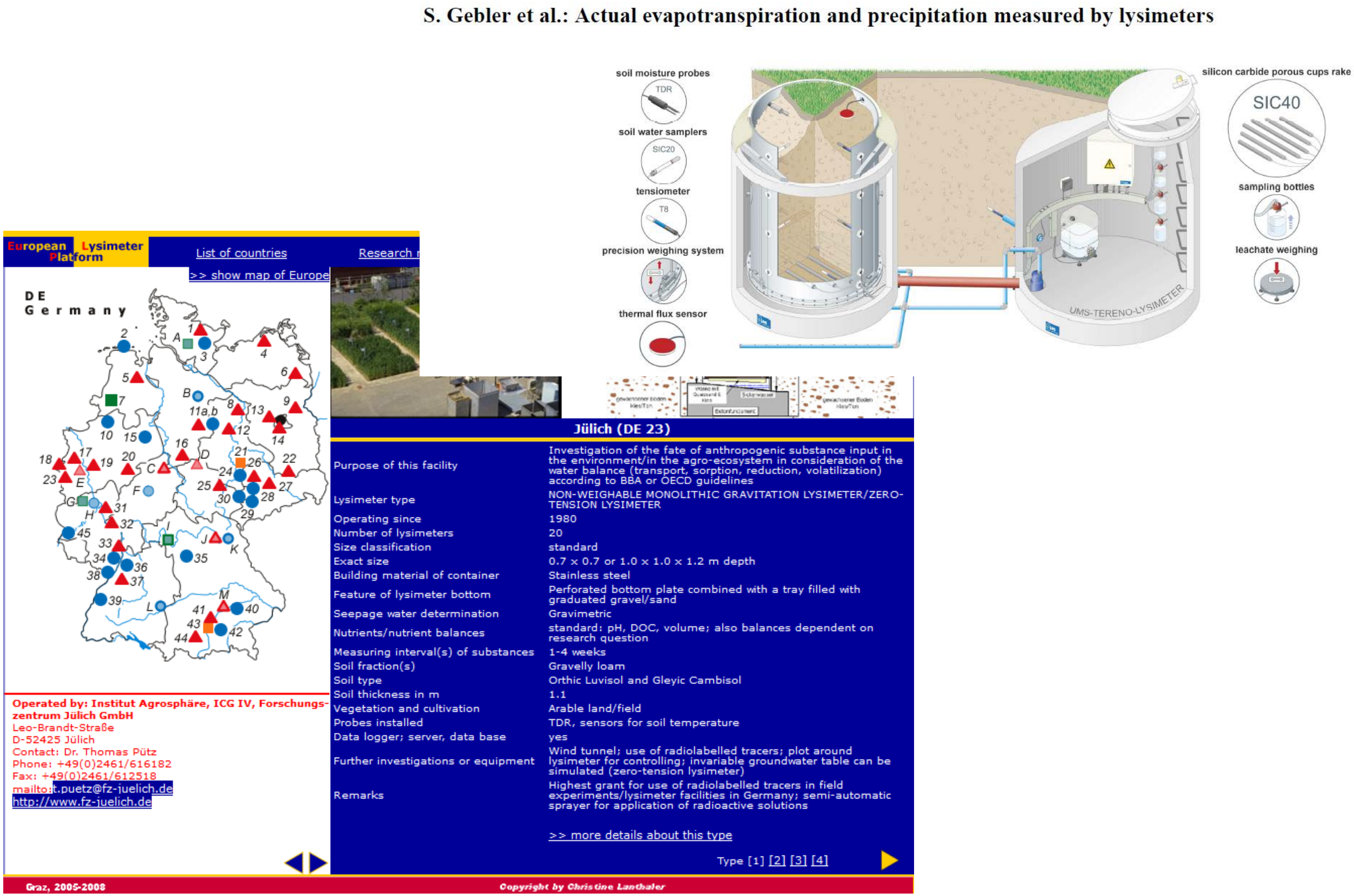
Soil observations - *Lysimeter network (actual evap., infiltration)*



S. Gebler et al.: Actual evapotranspiration and precipitation measured by lysimeters

Jülich (DE 23)

Purpose of this facility	Investigation of the fate of anthropogenic substance input in the environment/in the agro-ecosystem in consideration of the water balance (transport, sorption, reduction, volatilization) according to BBA or OECD guidelines
Lysimeter type	NON-WEIGHABLE MONOLITHIC GRAVITATION LYSIMETER/ZERO-TENSION LYSIMETER
Operating since	1980
Number of lysimeters	20
Size classification	standard
Exact size	0.7 x 0.7 or 1.0 x 1.0 x 1.2 m depth
Building material of container	Stainless steel
Feature of lysimeter bottom	Perforated bottom plate combined with a tray filled with graduated gravel/sand
Seepage water determination	Gravimetric
Nutrients/nutrient balances	standard: pH, DOC, volume; also balances dependent on research question
Measuring interval(s) of substances	1-4 weeks
Soil fraction(s)	Gravelly loam
Soil type	Orthic Luvisol and Gleyic Cambisol
Soil thickness in m	1.1
Vegetation and cultivation	Arable land/field
Probes installed	TDR, sensors for soil temperature
Data logger; server, data base	yes
Further investigations or equipment	Wind tunnel; use of radiolabelled tracers; plot around lysimeter for controlling; invariable groundwater table can be simulated (zero-tension lysimeter)
Remarks	Highest grant for use of radiolabelled tracers in field experiments/lysimeter facilities in Germany; semi-automatic sprayer for application of radioactive solutions

>> more details about this type

Type [1] [2] [3] [4]

Operated by: Institut Agrosphäre, ICG IV, Forschungszentrum Jülich GmbH
Leo-Brandt-Straße
D-52425 Jülich
Contact: Dr. Thomas Pütz
Phone: +49(0)2461/616182
Fax: +49(0)2461/612518
mailto:t.puetz@fz-juelich.de
http://www.fz-juelich.de

Graz, 2005-2008

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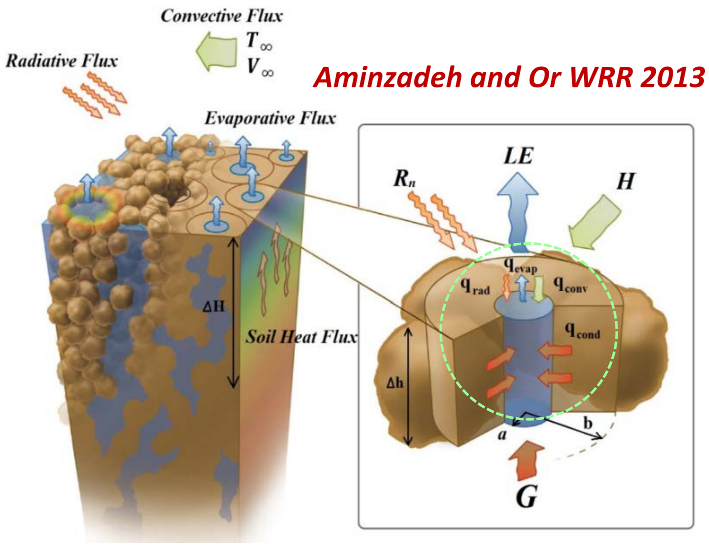
Pore scale model for surface temperature dynamics

- During stage-1, evaporation occurs from hydraulically connected discrete pores at the soil surface (<u>vaporization plane at the surface</u>)
- Spacing between active pores (“dry” surface) increase with reduced surface water content
- The pore-scale analytical model couples surface temperature dynamics with pore evaporative flux (as BC) considering feedbacks between surface temperature and vapor pressure



Aminzadeh and Or WRR 2013

$$q_{cond} \times 2\pi a \Delta h = (q_{evap} - [q_{conv} + q_{rad} + G]) \times \pi a^2$$

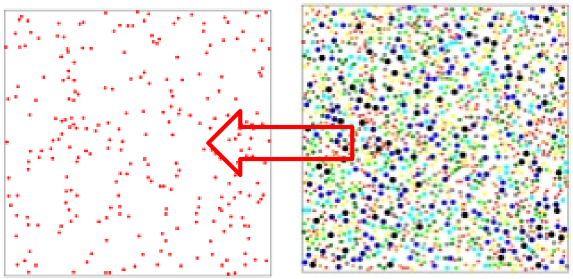
$$q_{evap} = \frac{1}{1 + \frac{2}{\pi}\frac{a}{\delta_m}\sqrt{\frac{\pi}{4\theta}}\left[\sqrt{\frac{\pi}{4\theta}} - 1\right]} \frac{D[C_s(T|_{r=a}) - C_a]}{\delta_m}\left(\frac{L}{\theta}\right)$$

$$\underbrace{\frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)}_{\text{Conduction}} + \frac{1}{\Delta h}\left[\underbrace{\sigma\varepsilon(T_\infty^4 - T^4) + R_s}_{\text{Radiation}} + \underbrace{h_a(T_\infty - T)}_{\text{Convection}} + \underbrace{\frac{k}{\Delta H}(T_\infty - T)}_{\text{Soil Heat Flux}}\right] = 0$$

$$a \le r \le b$$

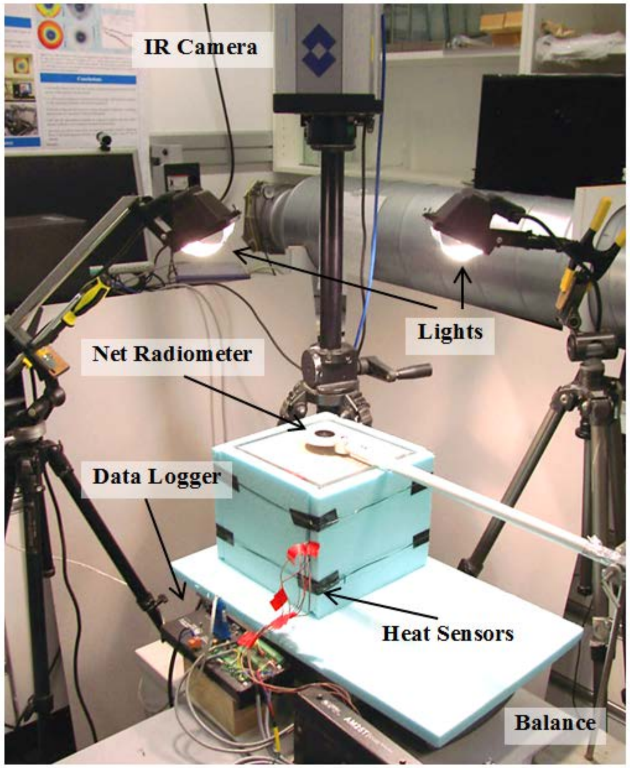
$$\left.\frac{\partial T}{\partial r}\right|_{r=b} = 0$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=a} = \frac{q_{cond}}{k}$$

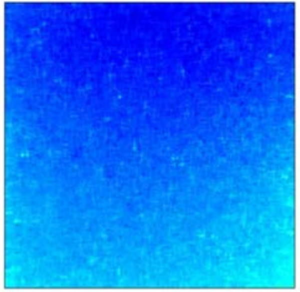


Gradual drying of evaporating surface (red – small pores)

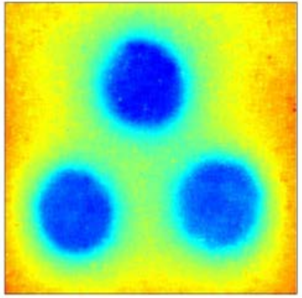
Results – *drying of sand surfaces (shortwave radiation)*

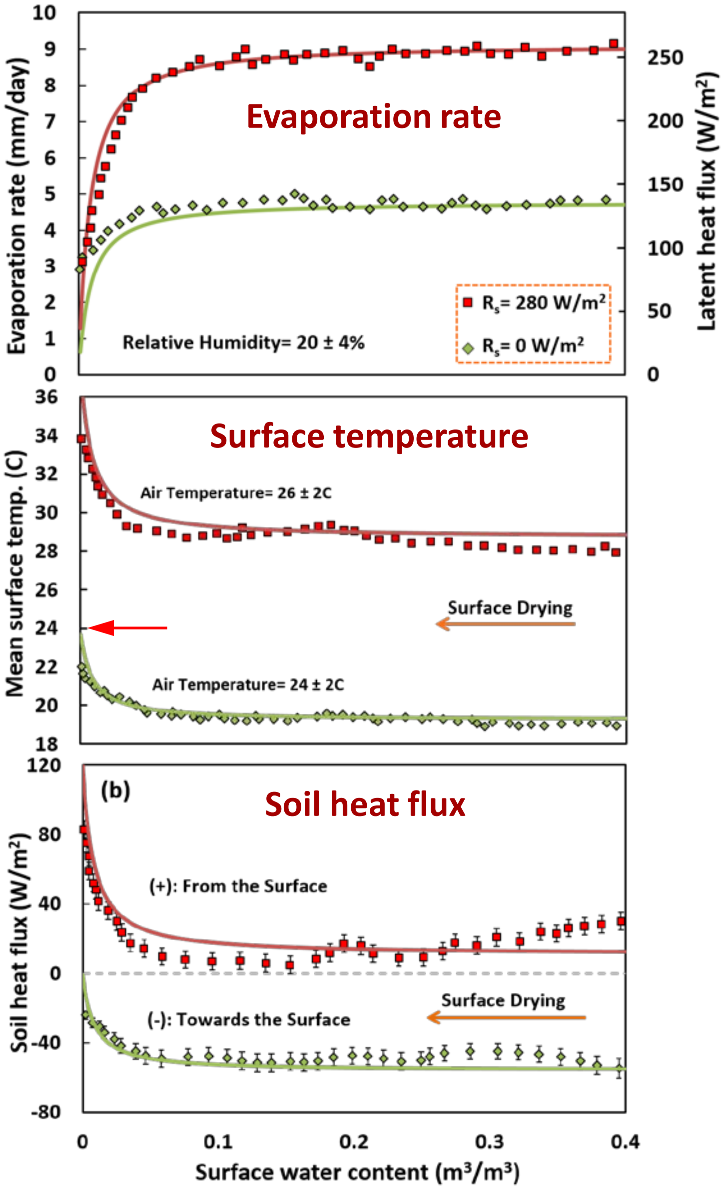


Homogeneous Surface



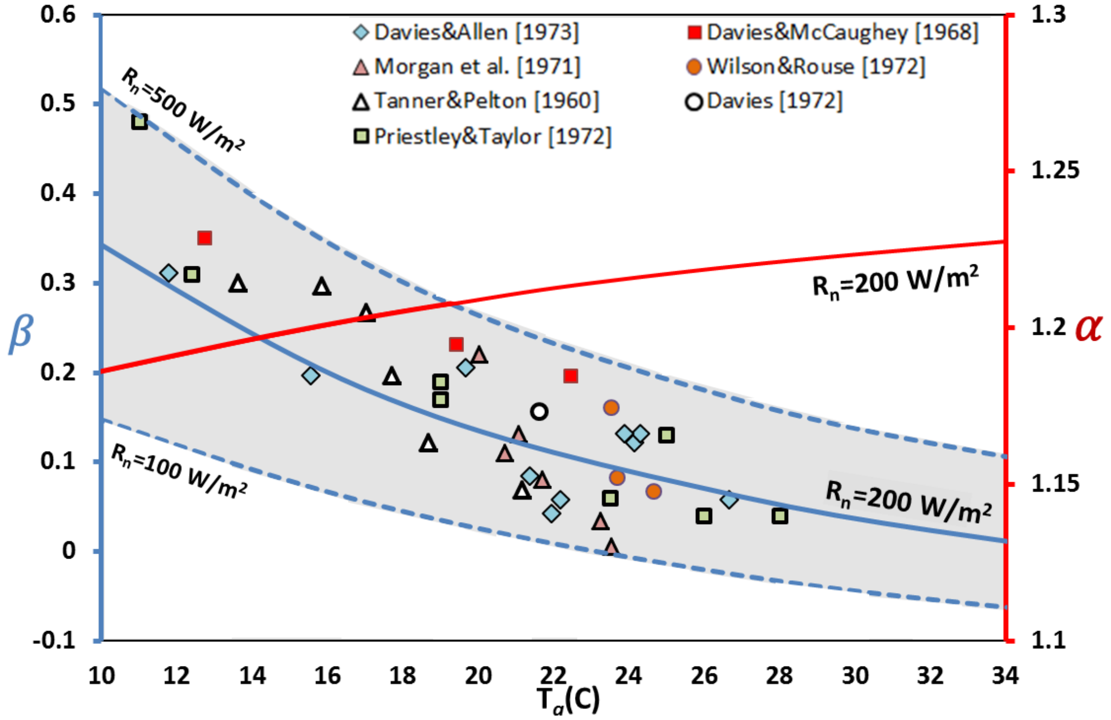
Heterogeneous Surface





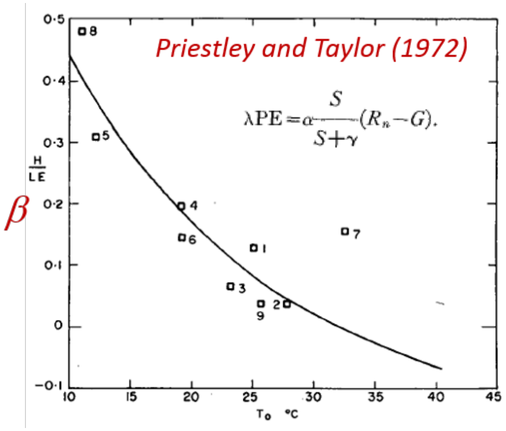
- Evaporation experiments from initially-saturated sand under different BC (wind speed and shortwave radiation) - monitoring surface temperatures, mass loss rates, and heat fluxes

Results – *predicting the Bowen Ratio for evaporating surfaces*



$$\beta = \frac{h_a(\bar{T} - T_\infty)}{\theta\, q_{evap}}$$

$$\beta = \frac{1 - \alpha\frac{s}{s+\gamma}}{\alpha\frac{s}{s+\gamma}}$$

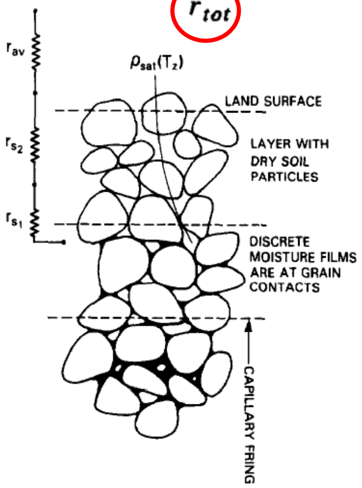


- The prediction of surface evaporation rate and temperature simultaneously enables estimates of surface energy partitioning, thus the Bowen ratio (β) and Priestley-Taylor "constant" (α)
- Unclear "surface temperature" even in the original P-T data (Tair as surrogate)
- Experimental data constrained by model predictions across a wide range of R_n values

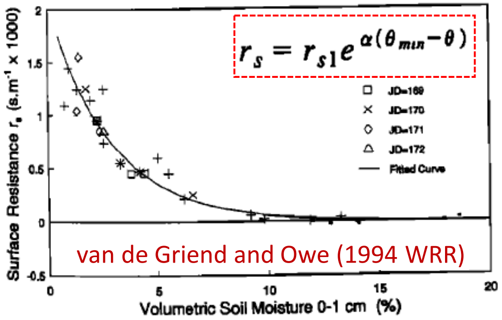
From pore scale evaporation to surface resistance model

- Haghighi et al. [2013] have used a pore diffusion model to estimate surface evaporative resistance as a function of surface water content (θ_{surf}) and mean pore size $<R_p>$ (from pore scale □ surface representation)

$$E = \frac{\rho_a - \rho_{sat}(T_s)}{\boxed{r_{tot}}}$$



$$r_s = r_{s1} e^{\alpha(\theta_{min} - \theta)}$$

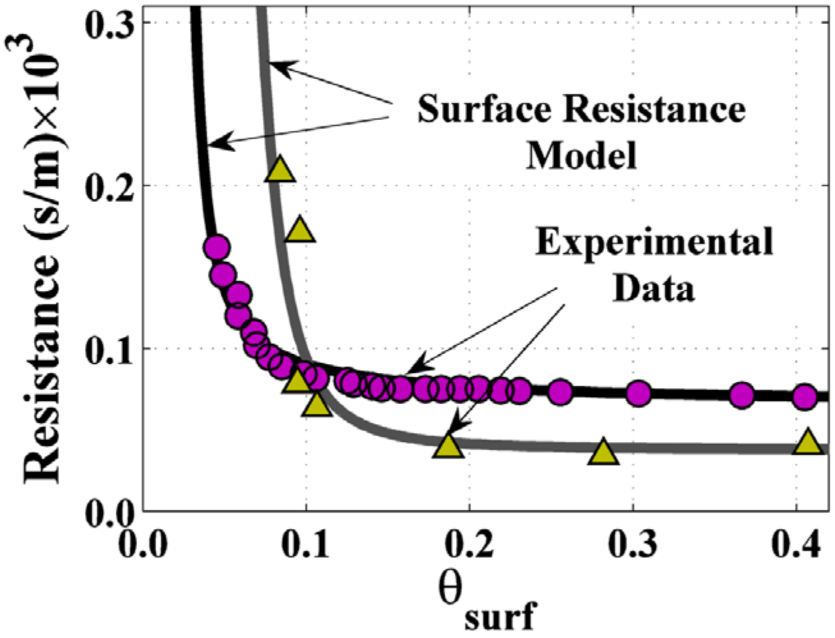


van de Griend and Owe (1994 WRR)

$$r_{S+BL} = \frac{\delta_m + < R_P > f(\theta_{surf})}{D}$$

$$f(\theta) = \frac{2}{\pi}\sqrt{\frac{\pi}{4\theta}}\left(\sqrt{\frac{\pi}{4\theta}} - 1\right)$$

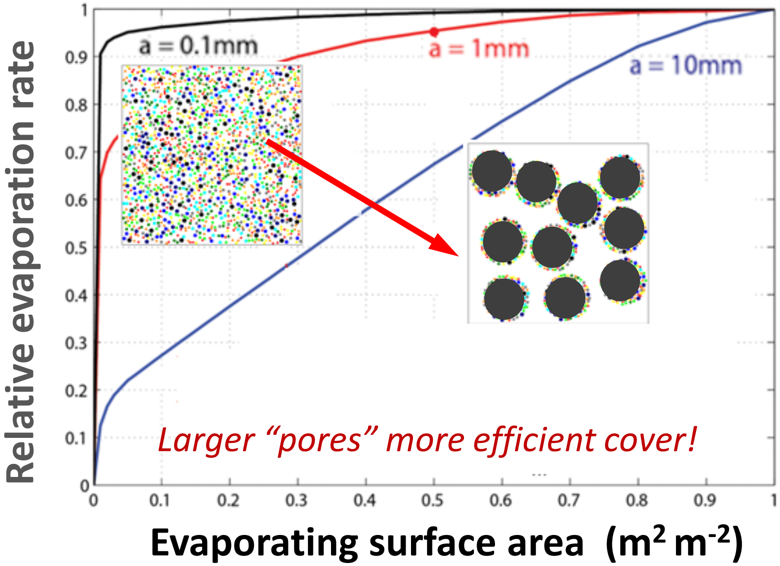
Haghighi et al. WRR 2013



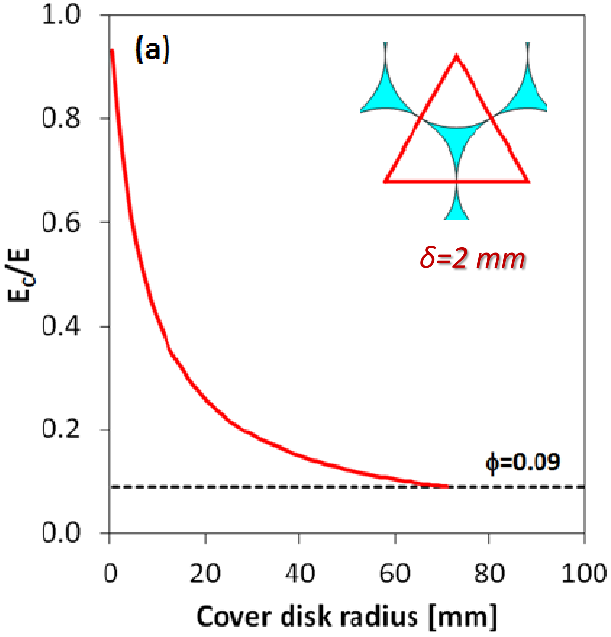
Water losses from partially covered reservoirs

- Evaporative losses from reservoirs and other water bodies may exceed 20% of water used in irrigated agriculture (in some regions >40%)
- One option for reducing evaporative losses from reservoirs is to use of partial floating covers – do we want large or small "pores" for the floating cover?

Assouline, Narkis & Or (WRR 2010; 2011)

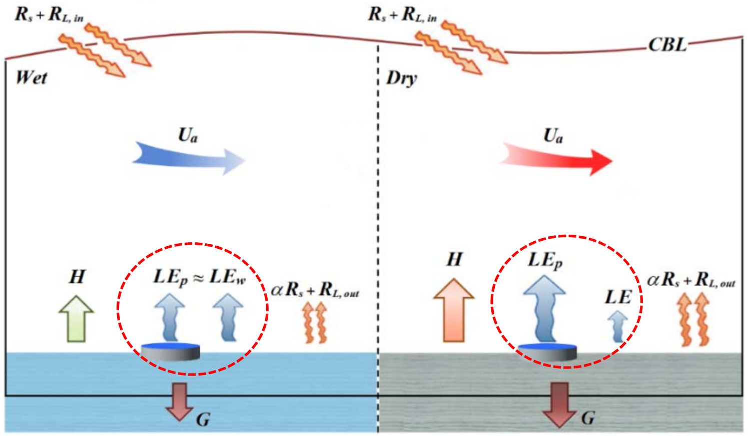


Larger "pores" more efficient cover!



A new look at E_p and complementary relationship (CR)

- Potential evaporation (E_p) is used as a reference state for non-limiting evaporative conditions
- E_p is key to the complementary relationship (CR) *Bouchet (1963)* linking E_p with actual evaporation E
- Schematic of **CR** feedbacks between drying land surface (low E) and air properties affecting E_p



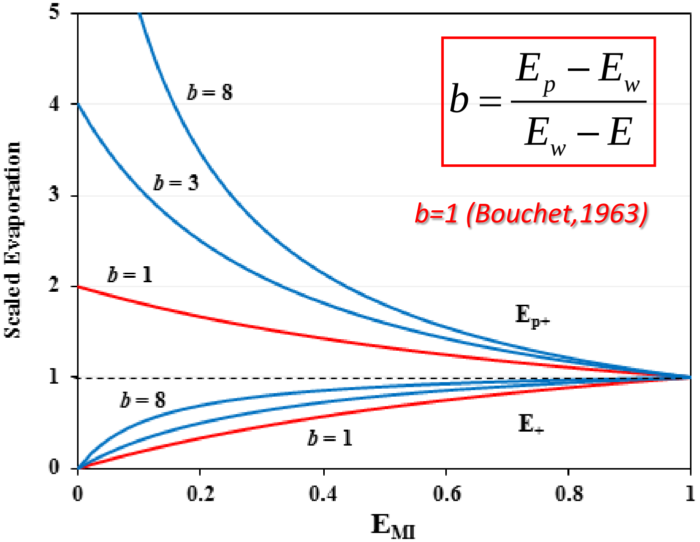


Figure 1. $E_+ = E / E_w$ and $E_{p+} = E_p / E_w$, as functions of the evaporative moisture index $E_{MI} = E / E_p$. The curves were obtained with Eqs. (4a) and (4b), respectively, for different values of the effectiveness parameter, b [Kahler and Brutsaert, 2006].

- A generalized form of the CR employs an empirical parameter (***b***≥1) to account for different rates of potential evaporation increase with declining actual evaporation from drying surfaces (*Kahler and Brutsaert 2006*)

$$\boxed{(1+b)E_w = bE + E_p}$$

E_w = "Wet" surface evaporation

(often P-T with fixed α!)

E_p = Potential evaporation

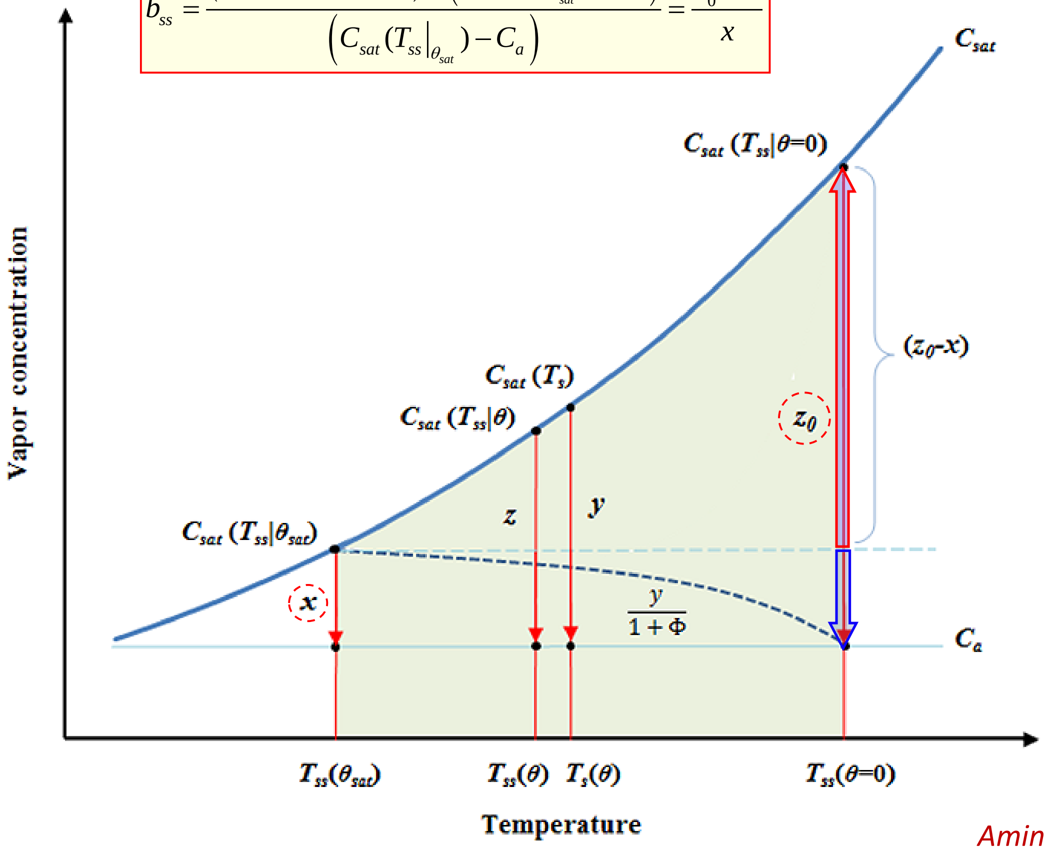
(often Class A pan)

E = Actual (surface) evaporation

Representing the CR on the vapor-temperature plane

- Schematic representation of actual (**E**), potential (**E_p**) and wet surface evaporation (**E_W**) in terms of temperature and vapor pressure given as: $\frac{y}{1+\Phi}$ (*dashed-line*), **z** and **x**, respectively, for a drying surface
- The parameter **b** is estimated from "dry" surface condition (where **$E=0$**) ⇨ $b = \frac{E_p - E_w}{E_w - \cancel{E}}$

$$b_{ss} = \frac{\left(C_{sat}(T_{ss}|_{\theta=0}) - C_a\right) - \left(C_{sat}(T_{ss}|_{\theta_{sat}}) - C_a\right)}{\left(C_{sat}(T_{ss}|_{\theta_{sat}}) - C_a\right)} = \frac{z_0 - x}{x}$$



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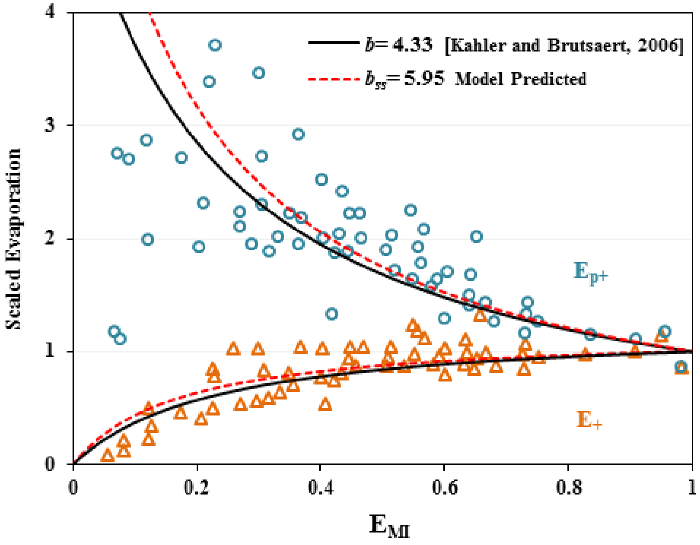
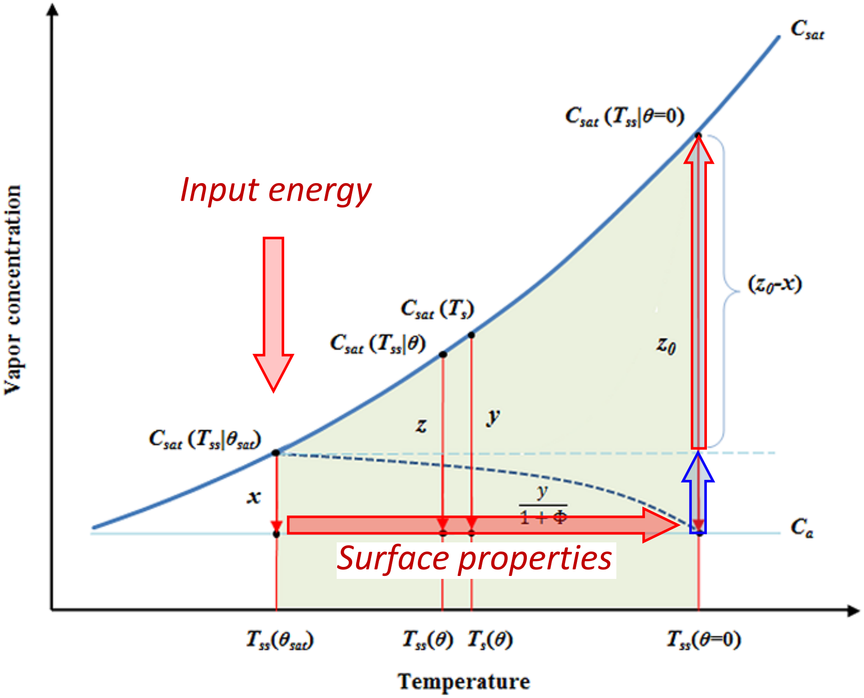
The origins of the CR asymmetry





- The surface temperature range on the horizontal axis is defined by surface properties and climatic variables determine the origins of the CR asymmetry (thus different values of the parameter ***b***) where surface properties define the *temperature range* and the energy input the *location (position) of hatched area*

Aminzadeh, Roderick & Or (2015, WRR)

The revised CR framework - *predicting actual evaporation*

- Key steps for estimating ***b*** and actual evaporation, ***E***:

parameter	calculation
$T_{ss}\|_{\theta_{sat}}$ =24.75 ºC	Eq. (14)
$T_{ss}\|_{\theta=0.28}$ =24.9 ºC	Eq. (14)
$E_R(T_{ss}\|_{\theta_{sat}})$ =8.5 mm/day	Eq. (15) (E_w in Eq. 20)
$E_R(T_{ss}\|_{\theta=0.28})$ =8.8 mm/day	Eq. (15) (E_p in Eq. 20)
b^*_{ss} =4.9	Eq. (19) (b in Eq. 20)
E =8.45 mm/day	Eq. (20)

$A=(3U_a+2)\times 10^{-3}$

$B=(24.3U_a-1.44)(C_a+22\times 10^{-3})+0.3$

$$(1-\alpha)R_s+\sigma T_{ss}^4(\varepsilon_a-\varepsilon_s)-\frac{k}{\Delta Z}(T_{ss}-T_z)=\frac{D_aL\left[C_{sat}(T_{ss})-C_a\right]}{\delta(1+\Phi)}$$

$$\Downarrow$$

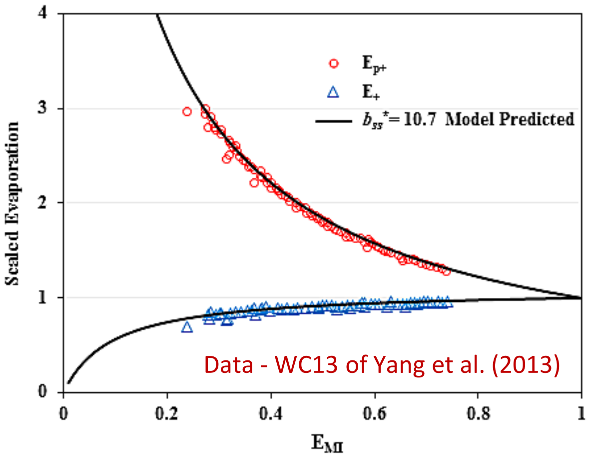
$$LE_R(T_{ss})=\frac{D_aL}{\delta}\left[C_{sat}(T_{ss})-C_a\right]$$

$$\Downarrow$$

$$b^*_{ss}=A\,R_{S,net}+B$$

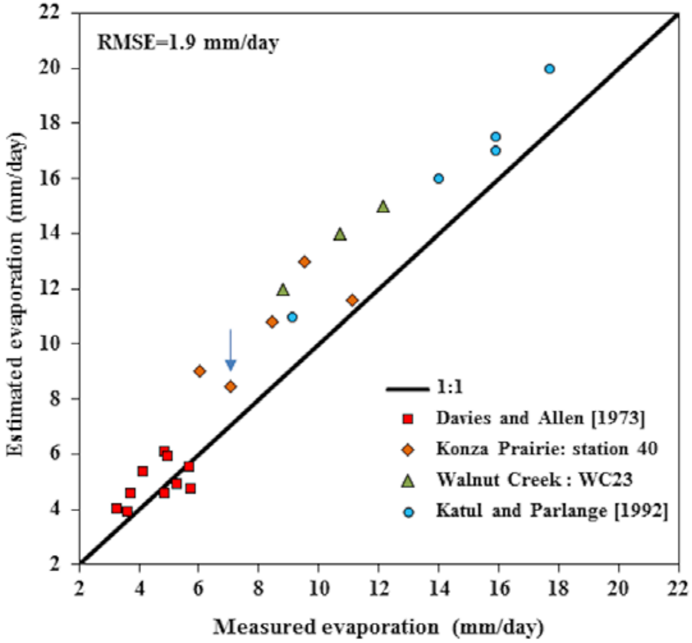
$$\Downarrow$$

$$\boxed{E=\frac{(1+b)E_w-E_p}{b}}$$



Data - WC13 of Yang et al. (2013)

- Predicted actual evaporation in good agreement with measurements (*arrow for the calculation in the table above*)



- Limitations: complex surfaces (containing non-drying regions – forests, lakes) require special upscaling considerations (e.g., to estimate *b*)

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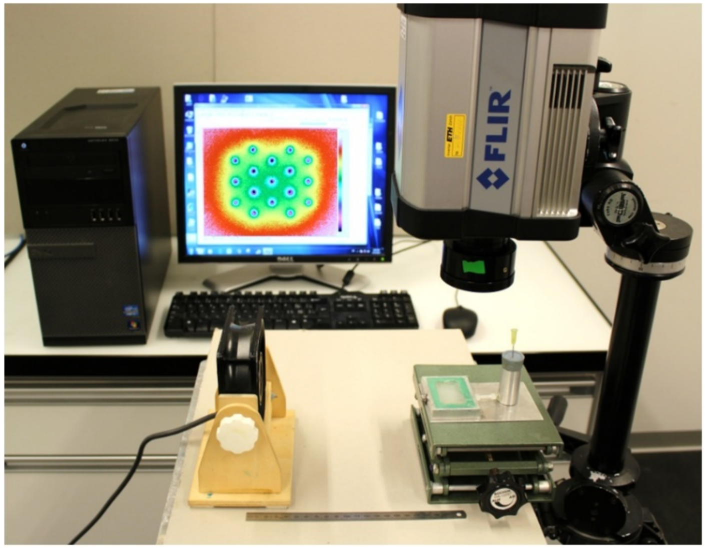
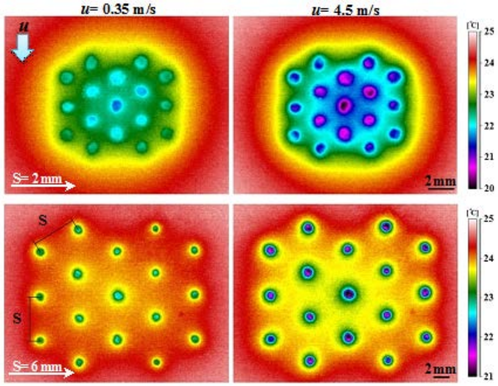
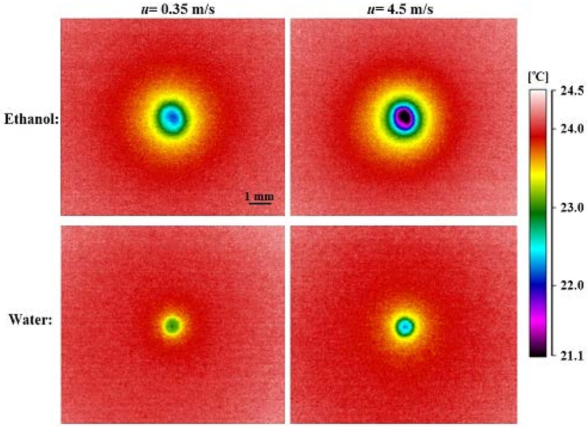
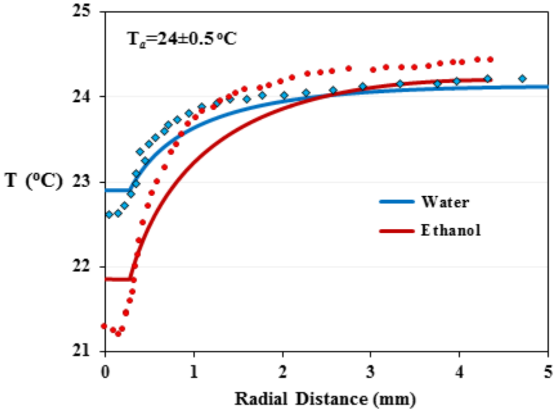
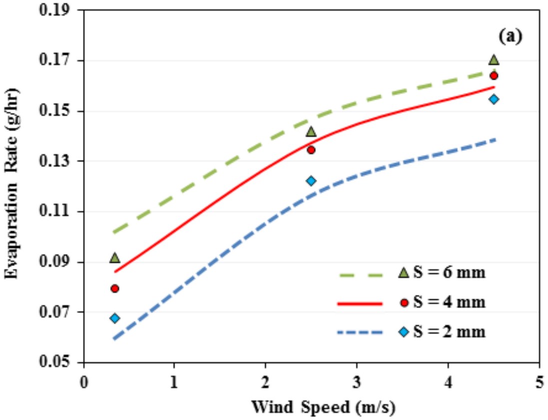
Evaluation of the PCEB model – *thermal fields around pores*











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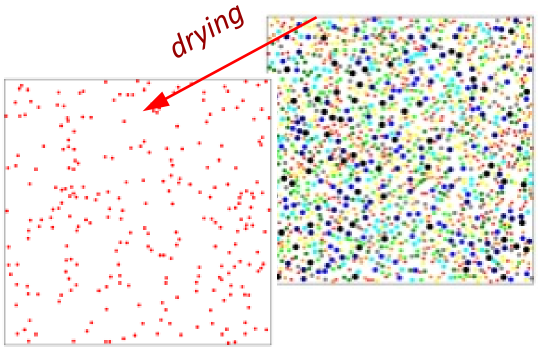
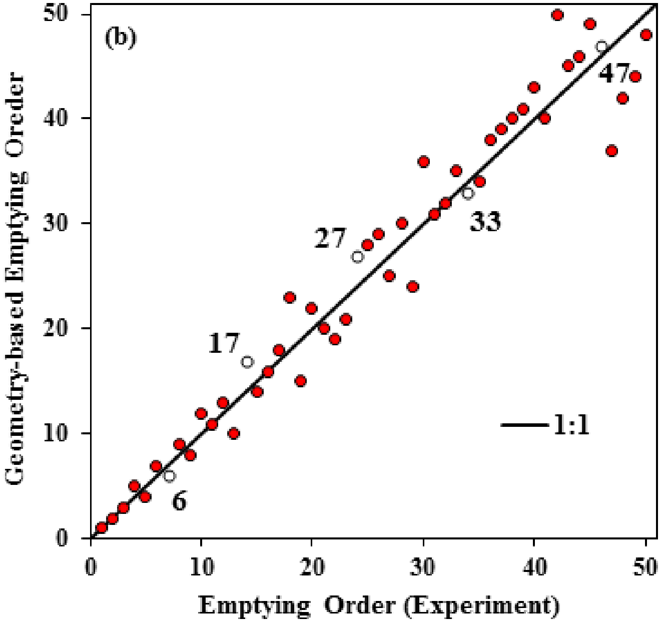
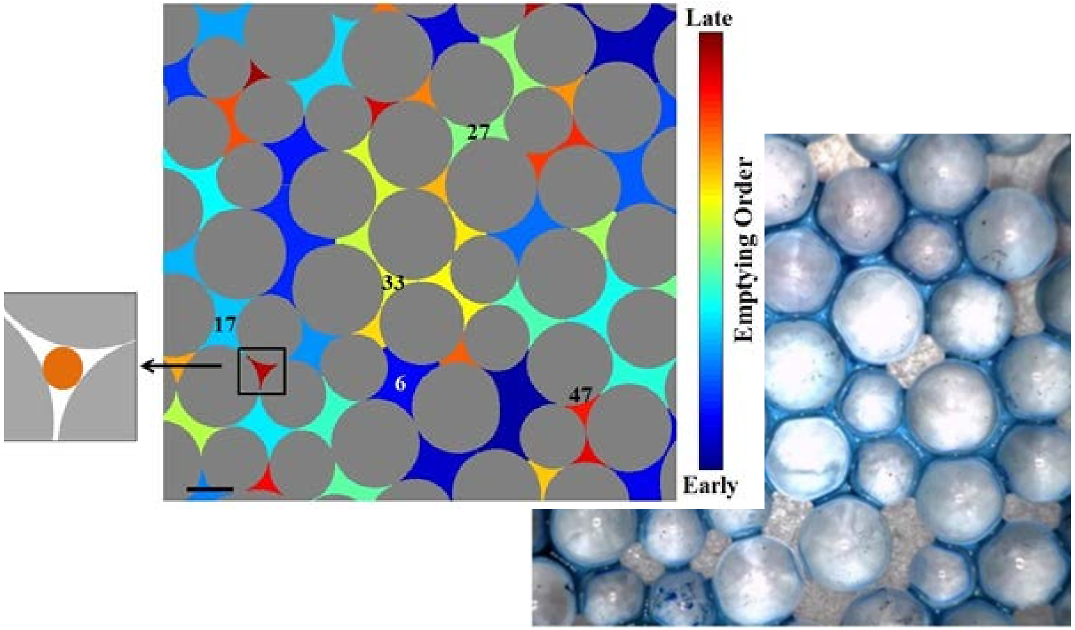
Pore-scale details of drying evaporating surfaces

- The gradual drying of a porous surface resembles a drainage process - pore drying sequence is entirely predictable from capillary considerations
- We assume a spatially uniform distribution of pore sizes (pore clustering could also be considered)



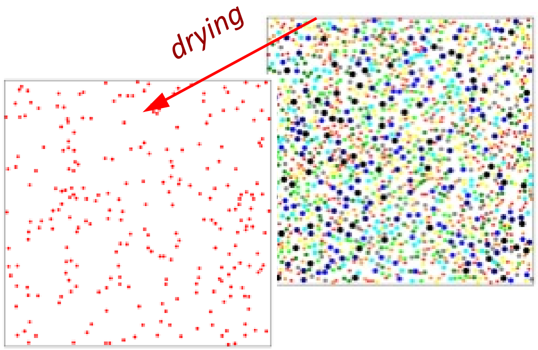
Gradual drying of a surface
(red – smallest pores)



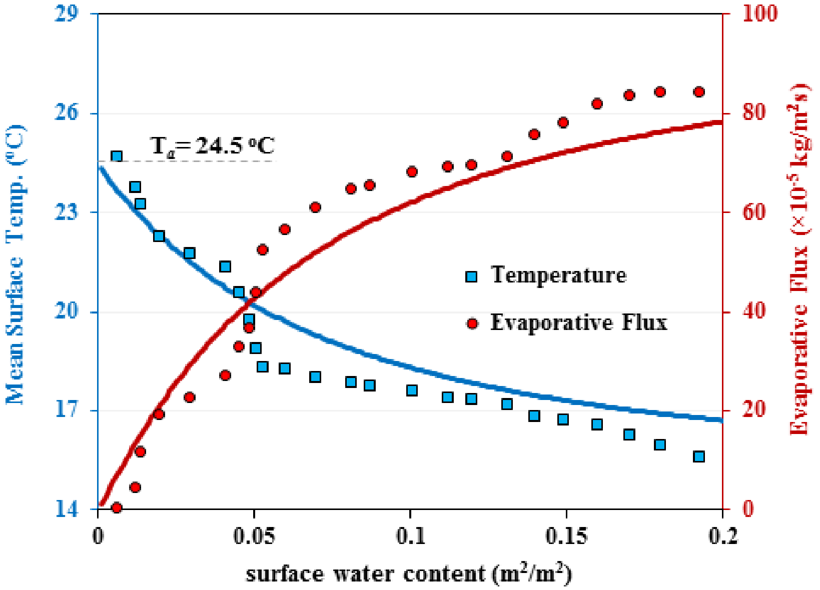


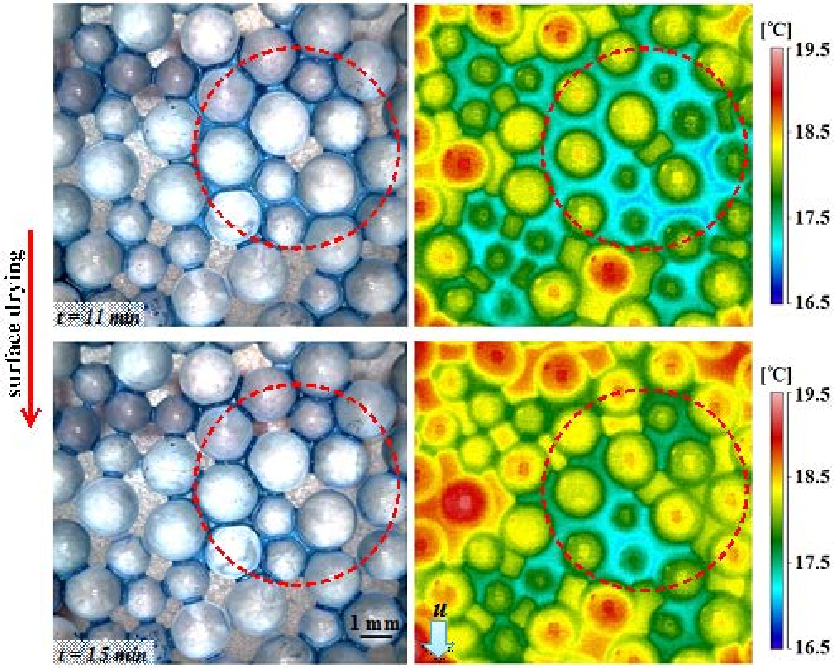
Pore-scale surface drying and temperature adjustment

- The gradual drying of a porous surface resembles a drainage process (capillarity determines the order)
- Surface pore emptying (instantaneously) affects details of surface temperature and energy partitioning (local and average)



Gradual drying of a surface
(red – smallest pores)





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Potential evaporation at steady surface temperature

- A new definition for potential evaporation - considers radiative and advective conditions

$$(1-\alpha)R_S+\sigma\varepsilon_a T_a^4-\sigma\varepsilon_s T_s^4-\frac{k}{\Delta Z}(T_s-T_Z)=\cancel{h_a(T_s-T_a)}+\frac{D_a L\left[C_{sat}(T_s)-C_a\right]}{\delta(1+\Phi)}$$

- The steady surface temperature (***T_{SS}***) at which "most" input energy is converted to evaporation (***$H=0$***) with associated "non-limited" evaporation (yellow box) define a potential evaporation at steady surface temperature: ***$E_R(T_{SS})$***

$$\underbrace{(1-\alpha)R_S+\sigma T_{ss}^4(\varepsilon_a-\varepsilon_s)-\frac{k}{\Delta Z}(T_{ss}-T_Z)}_{\text{LHS}}=\frac{D_a L\left[C_{sat}(T_{ss})-C_a\right]}{\delta(1+\Phi)}$$

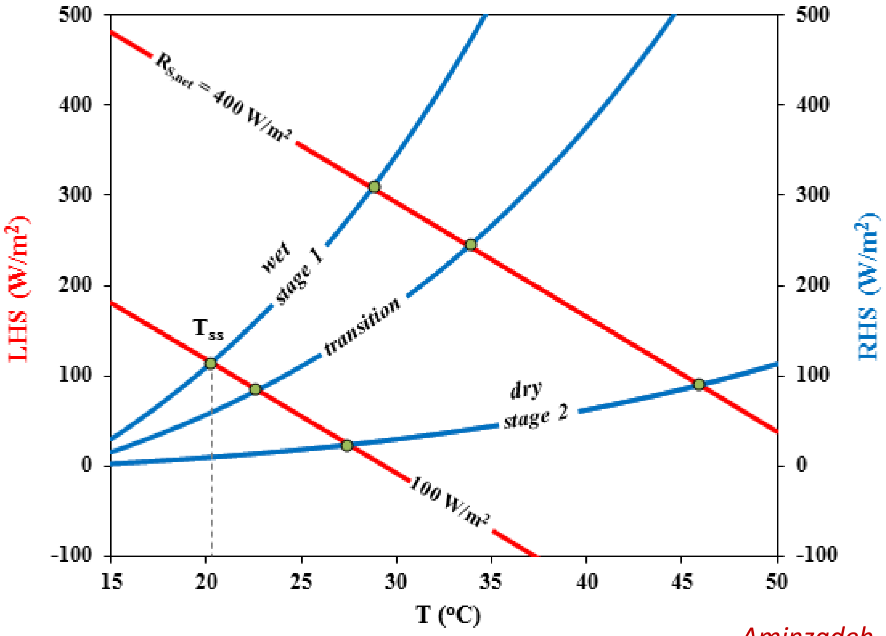
RHS

$$\boxed{LE_R(T_{ss})=\frac{D_a L}{\delta}\left[C_{sat}(T_{ss})-C_a\right]}$$

- Steady state surface temperature (***T_{SS}***) adjusts for different energy inputs & surface wetness

$$\Phi=\frac{2a}{\pi\delta}\sqrt{\frac{\pi}{4\theta}}\left[\sqrt{\frac{\pi}{4\theta}}-1\right]$$

Surface resistance



Aminzadeh, Roderick & Or (2015, WRR)

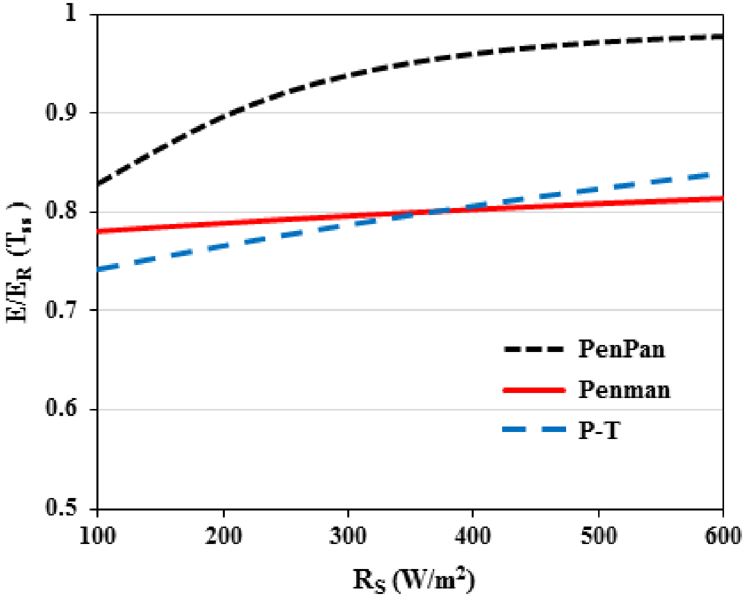
Surface temperature-based potential evaporation

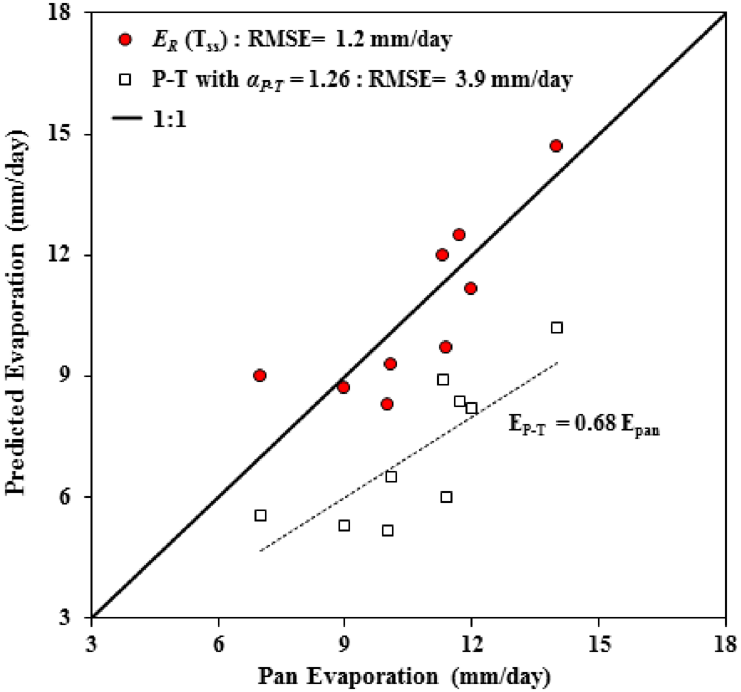
- Interestingly, data show that *class A pan* evaporates at rates predicted ***$E_R(T_{ss})$*** implying (typically) ***H*=0** for (summer) pan evaporation
- The new ***$E_R(T_{ss})$*** was used in the CR framework to analytically predict ***b*** and actual evaporation ***E*** based on standard meteorological data

$$(1-\alpha)R_S+\sigma T_{ss}^4(\varepsilon_a-\varepsilon_s)-\frac{k}{\Delta Z}(T_{ss}-T_Z)=\frac{D_a L\left[C_{sat}\left(T_{ss}\right)-C_a\right]}{\delta(1+\Phi)}$$

$$\Downarrow$$

$$\boxed{LE_R(T_{ss})=\frac{D_a L}{\delta}\left[C_{sat}\left(T_{ss}\right)-C_a\right]}$$





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