Seasonal water storage and evapotranspiration partitioning controls on the relationship between continental moisture recycling and precipitation deuterium excess

Zhengyu Xia[1,1] and Matthew Winnick[1,1]

[1]University of Massachusetts Amherst

November 30, 2022

Abstract

Moisture recycling via evapotranspiration (ET) is often invoked as a mechanism for the high deuterium excess signals observed in continental precipitation (dP). However, a global-scale analysis of precipitation monitoring station isotope data shows that metrics of ET contributions to precipitation (van der Ent et al., 2014) explain little dp variability on seasonal timescales. This occurs despite the fact that ET contributions increase by ˜50% in continental locations such as the Eurasian interior from wet to dry seasons. To explain this apparent paradox, we hypothesize that the effects of ET on dP are dampened during dry seasons due to contributions from isotopically-evolved residual water storage that act to lower the d-excess of ET fluxes (dET), in combination with changes in transpiration fraction (T/ET). To test this hypothesis, we develop a parsimonious two-season (wet, dry) model for dET incorporating residual water storage and ET partitioning effects. We find that in environments with limited water storage, such as shallow-rooted grasslands, dry season dET is lower than wet season dET despite lower relative humidity. As global average ratios of annual water storage to precipitation are relatively low (Guntner et al., 2007), these dynamics may be widespread over continents. In environments where water storage is not limiting, such as groundwater-dependent ecosystems, dry season dET is still likely lower; however, this effect arises instead due to higher seasonal T/ET when energy-driven plant water use is enhanced and surface evaporation is relatively limited by water availability. Together, these analyses also indicate multiple mechanisms by which dET may be lower than dp during the same season, challenging the view that moisture recycling feedback increases the dp in continental interiors. This work demonstrates the potential complexity of seasonal dp dynamics and cautions against simple interpretations of dP as a process tracer for moisture recycling. References: Guntner et al., 2007. Water Resour. Res., 43, W05416. van der Ent et al., 2014. Earth Syst. Dynam., 5, 471–489.

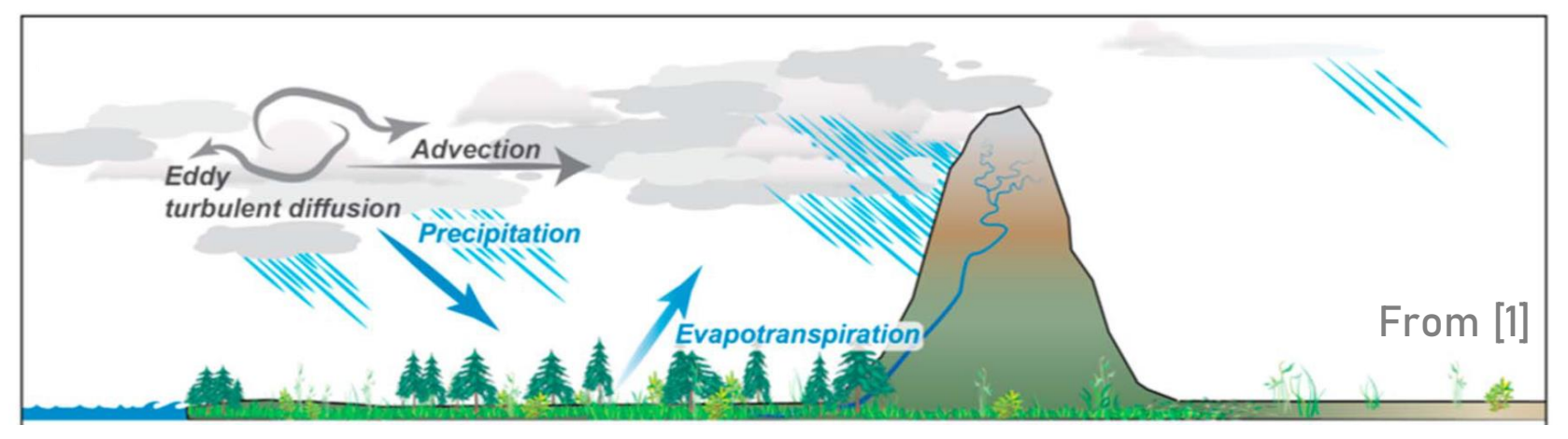
AGU FALL MEETING
New Orleans, LA & Online Everywhere
13–17 December 2021

Seasonal water storage and evapotranspiration partitioning controls on the relationship between continental moisture recycling and precipitation deuterium excess

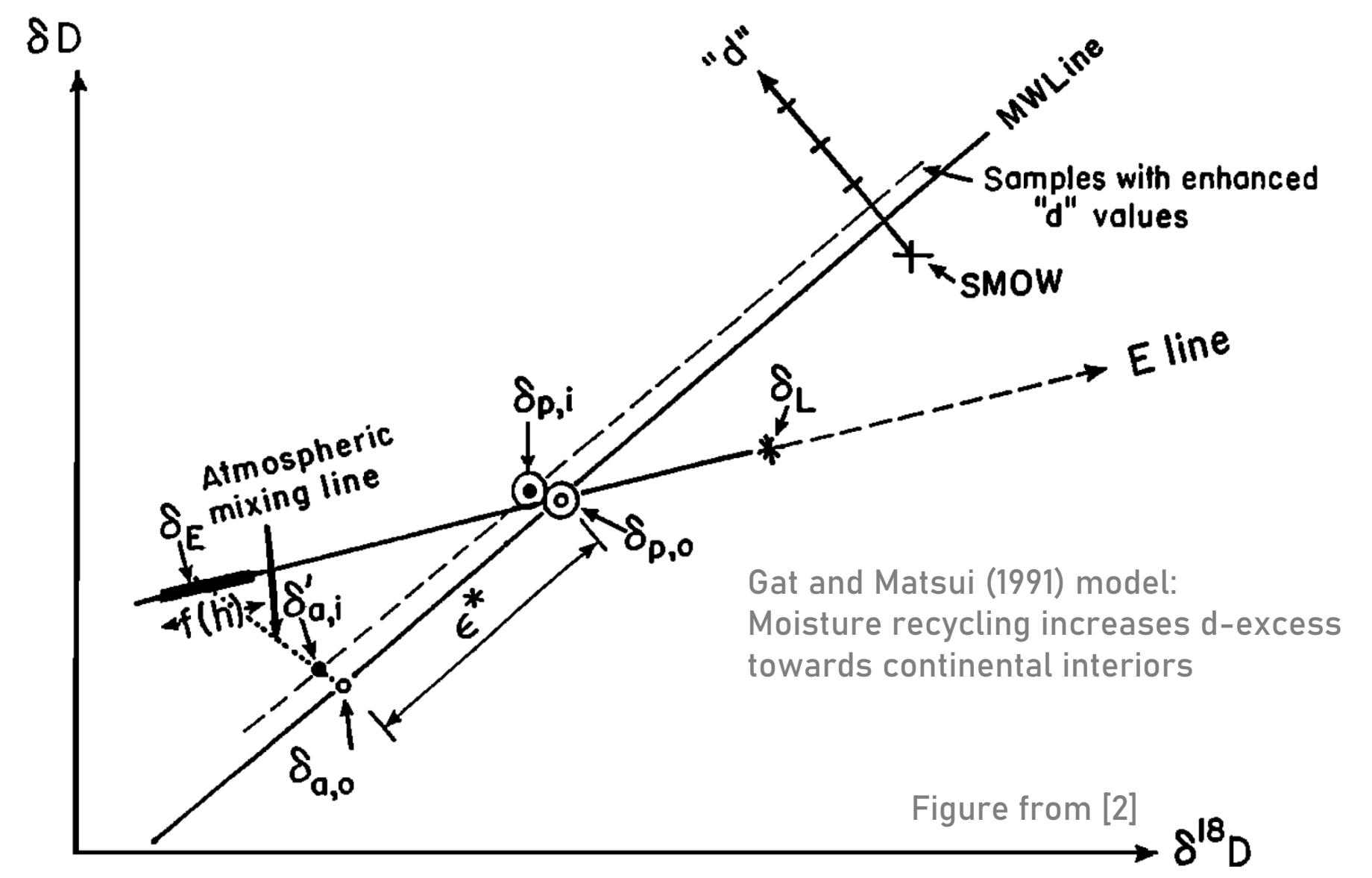
Zhengyu Xia[1*], Matthew J. Winnick[1]

[1] University of Massachusetts Amherst
[*] zhyxia@hotmail.com

1. Traditional paradigm



From [1]

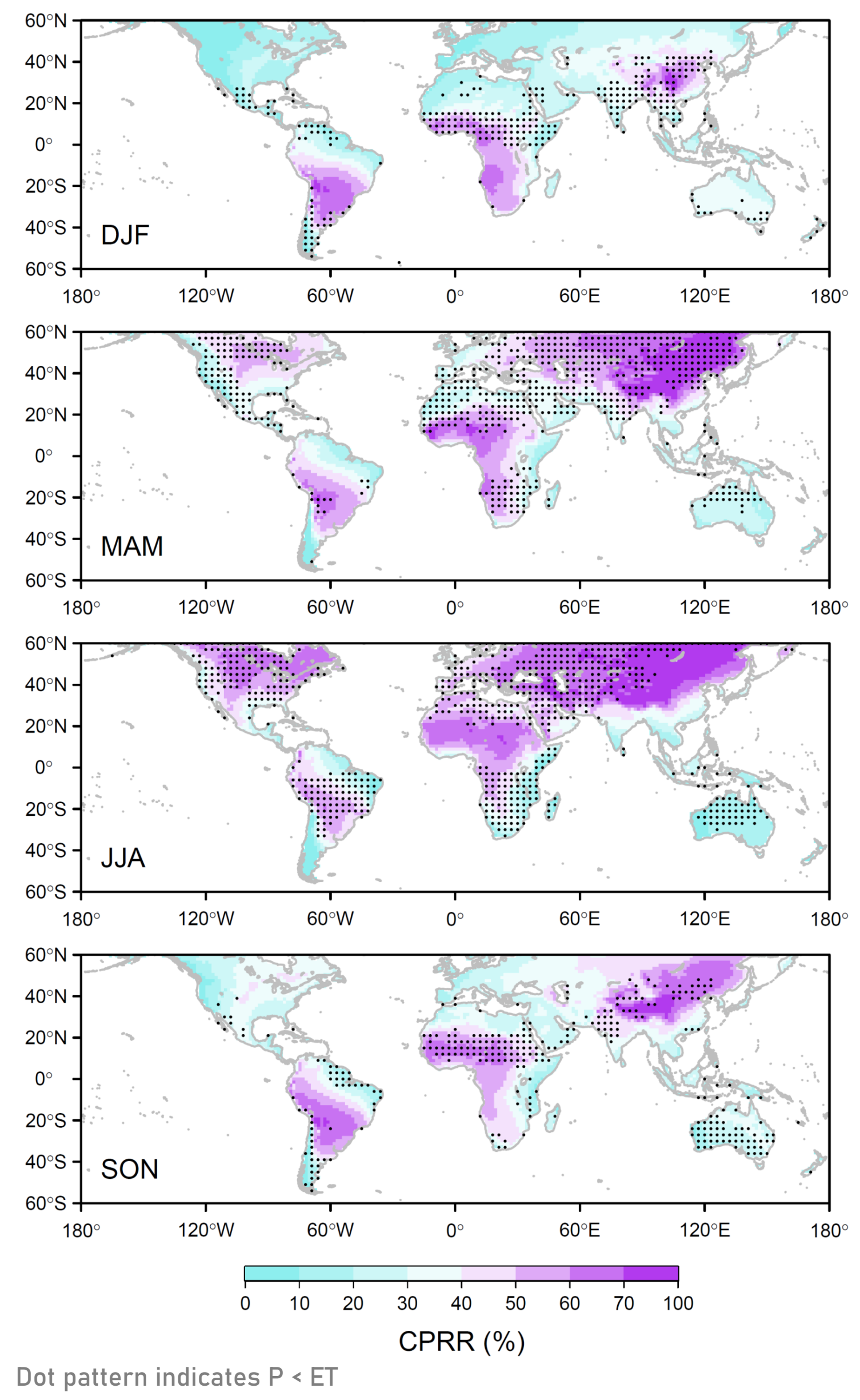


Gat and Matsui (1991) model:
Moisture recycling increases d-excess towards continental interiors

Figure from [2]

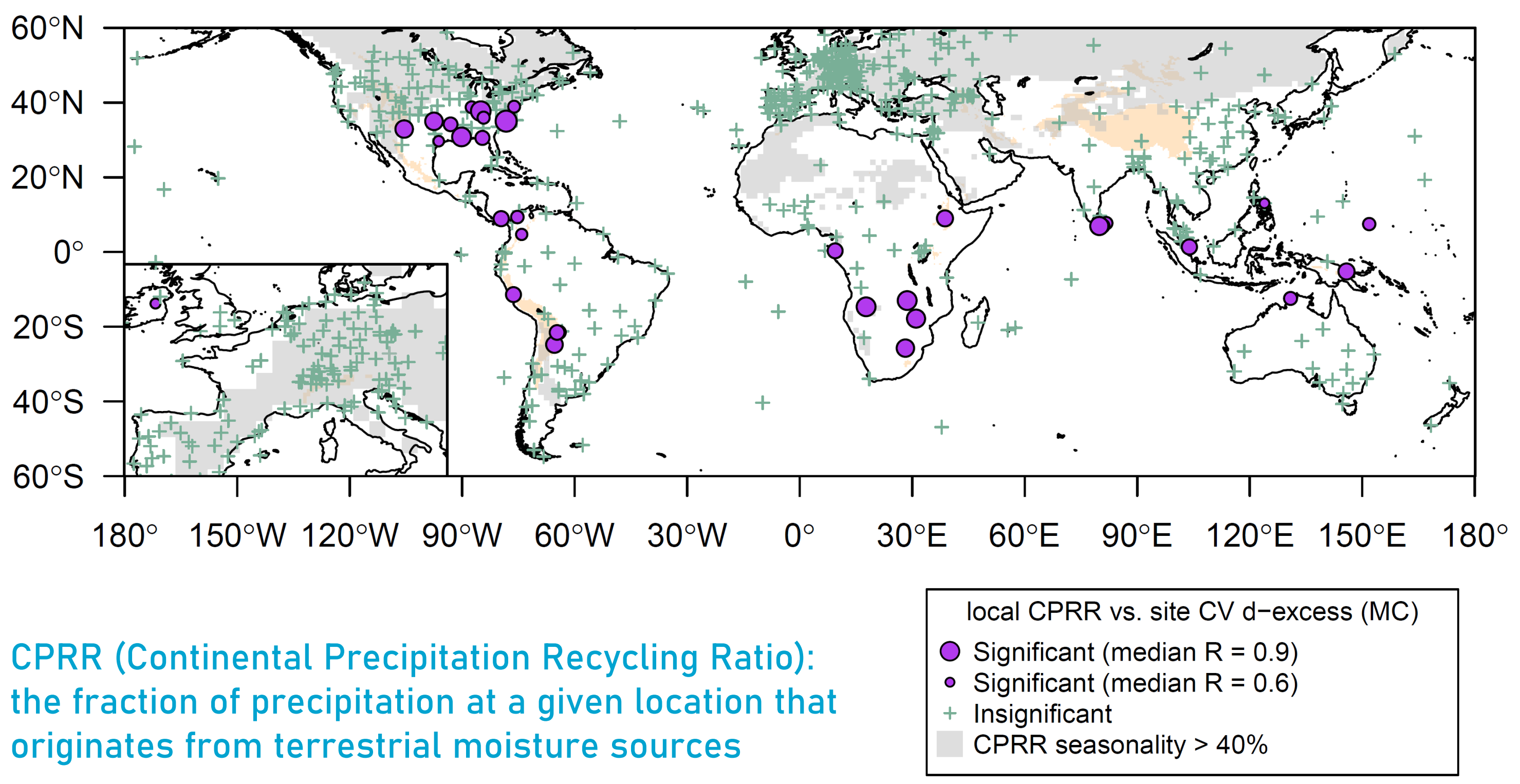
Limitations:

1) The model is based on steady-state mean annual conditions
2) May only apply to regions with high P/ET and weak seasonality



Dot pattern indicates P < ET

2. Seasonal swings in moisture recycling



CPRR (Continental Precipitation Recycling Ratio): the fraction of precipitation at a given location that originates from terrestrial moisture sources

Based on moisture tracking model WAM-2layers (from [3])

CV d-excess: "converted vapor" d-excess after correcting the fractionation in local condensation (data from GNIP and USNIP)

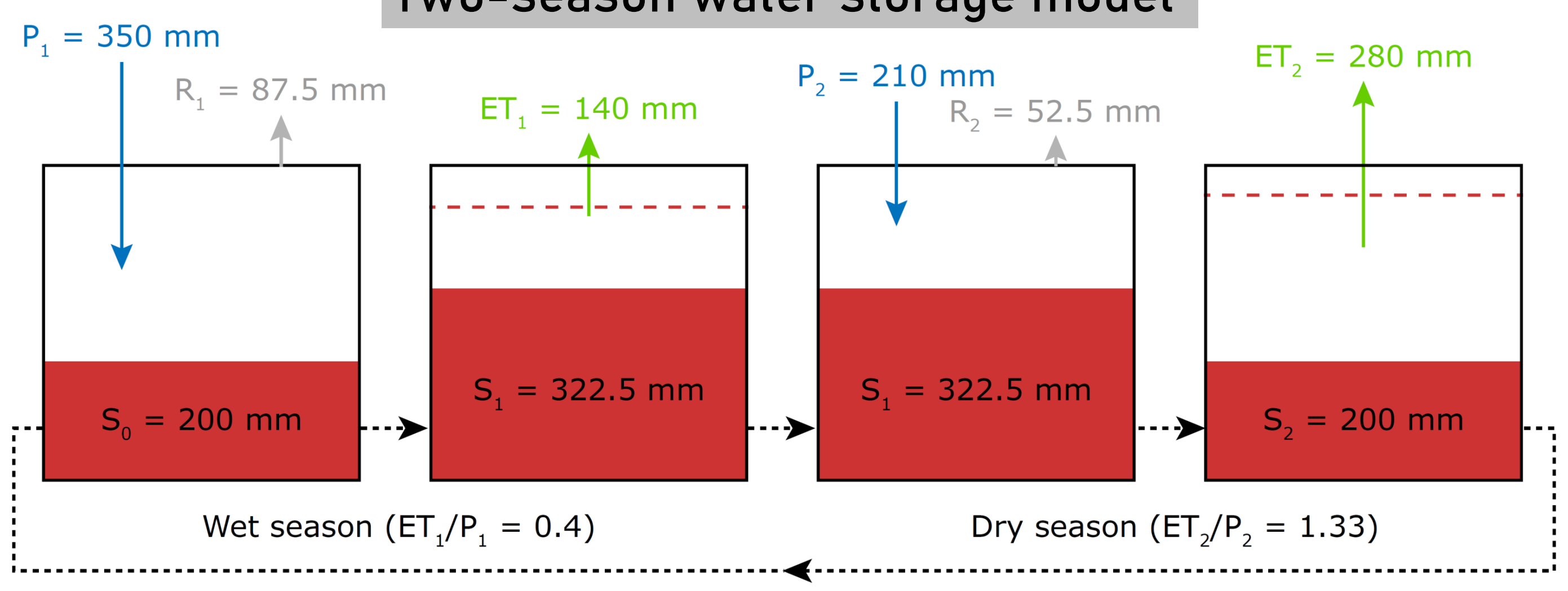
1) There are large seasonal changes in moisture recycling regime in North America and Eurasia, with CPRR increasing from 10% in winter to 60% in summer
2) However, precipitation d-excess does not increase in response to the seasonal swings in moisture recycling as shown by spatial correlation patterns
3) Widespread conditions of P < ET indicate that residual water storage is supplying ET flux

3. Hypothesis and model design

The d-excess in ET flux is likely not increased during the dry season in highly seasonal climate areas due to:

1) contributions from isotopically-evolved residual water storage (lower d-excess) to supply ET flux
2) higher transpiration fractions (T/ET)

Two-season water storage model



The isotopic composition of ET flux

assuming ET removal as a Rayleigh-type process with "closure assumption", from [4]

$$\delta_{ET} = \left(\frac{E}{ET}\right)\frac{\int_1^F[\alpha_{ET}(\delta_I+1000)F^{\alpha_{ET}-1}-1000]dF}{F-1} + \left(\frac{T}{ET}\right)\delta_I \quad \text{with} \quad \alpha_{ET} = \left(\frac{E}{ET}\right)\left[k\frac{\alpha_{eq}^{v-l}}{(1-h)\left(1+k\frac{E}{ET}\frac{h}{1-h}\right)}\right] + \left(\frac{T}{ET}\right)\left(\frac{1}{1+k\frac{E}{ET}\frac{h}{1-h}}\right)$$

Water flux relationship

The residual water storage size:

$$S_1 = S_0 + P_1 - R_1 - ET_1 \text{ and } S_2 = S_1 + P_2 - R_2 - ET_2$$

The fraction of residual liquid water remaining after ET loss:

$$F_1 = \frac{S_1}{S_1+ET_1} \text{ and } F_2 = \frac{S_2}{S_2+ET_2}$$

The fraction of residual water storage in the source water pool for ET:

$$X_1 = \frac{S_0}{S_0+P_1-R_1} \text{ and } X_2 = \frac{S_1}{S_1+P_2-R_2}$$

Isotopic flux relationship

The isotopic composition of "modified source water" mixing the new precipitation input (after runoff loss) with the old residual water storage:

$$\delta_{I_1} = X_1\delta_{S_0} + (1-X_1)\delta_{P_1} \text{ and } \delta_{I_2} = X_2\delta_{S_1} + (1-X_2)\delta_{P_2}$$

The isotopic composition of residual water storage after ET loss using isotope mass balance:

$$\delta_{S_1} = \frac{\delta_{I_1}-(1-F_1)\delta_{ET_1}}{F_1} \text{ and } \delta_{S_2} = \frac{\delta_{I_2}-(1-F_2)\delta_{ET_2}}{F_2}$$

The boundary condition constraint

$$S_2 = S_0 \text{ and } \delta_{S_2} = \delta_{S_0}$$

4. Simple model test

Kinetic fractionation factor of evaporation
$k = (D'/D)^m$

Determine the relative importance of seasonal residual water storage

	Wet season	Dry season
Model inputs		
Water flux		
Precipitation (mm)	350 (P_1)	210 (P_2)
Runoff (mm)	87.5 (R_1)	52.5 (R_2)
ET (mm)	140 (ET_1)	280 (ET_2)
Physical climate		
Temperature (°C)	5	15
RH (%)	80	65
Aerodynamic exponent	0.8	0.8
Ecosystem condition		
T/ET	0.6	0.6
Relative water storage size (S_0/P_1)	0.57	-
Isotope flux		
Precipitation δ¹⁸O (‰)	–10	–6
Precipitation d-excess (‰)	10	10
Model results		
"Modified" source water δ¹⁸O (‰)	–6.0 (δ_{I_1})	–4.9 (δ_{I_2})
ET δ¹⁸O (‰)	–9.9 (δ_{ET_1})	–7.8 (δ_{ET_2})
Residual water storage δ¹⁸O (‰)	–4.3 (δ_{S_1})	–0.8 (δ_{S_0} or δ_{S_2})
"Modified" source water d-excess (‰)	1.1	1.9
ET d-excess (‰)	8.4	10.8
Residual water storage d-excess (‰)	–2.1	–10.6

How large is the available subsurface water storage?

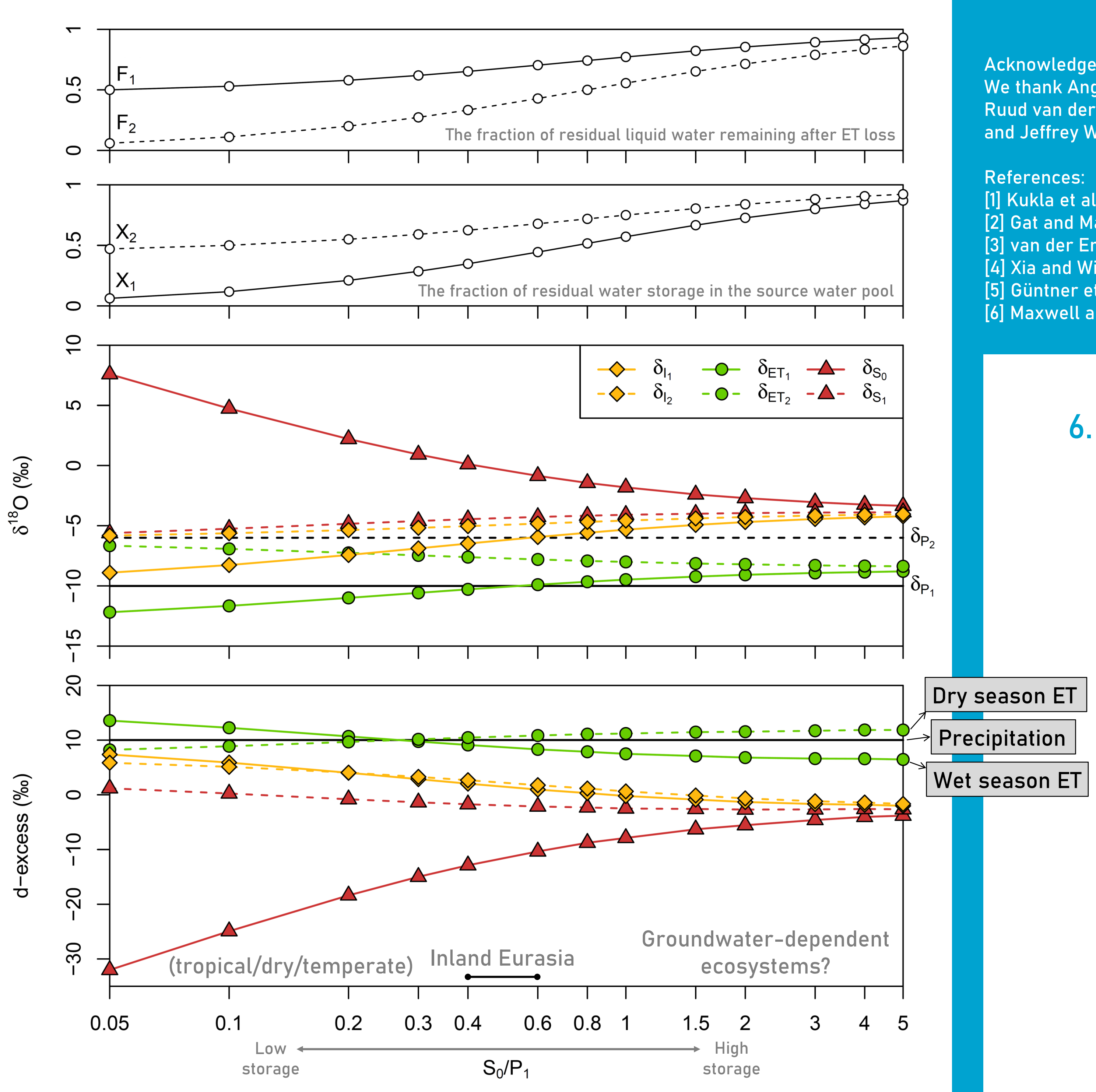
Koeppen Climate Zone	Mean annual precipitation (MAP) (mm)	Total water storage (TWS) (mm)	TWS/MAP
A, tropical	1859	337	0.18
Af, no dry season	2806	607	0.22
Am, short dry season	2294	426	0.19
Aw, distinct dry season	1408	217	0.15
B, dry	270	30	0.11
BS, steppe	441	51	0.12
BW, desert	144	14	0.10
C, temperate	1146	180	0.16
Cf, no dry season	1364	266	0.20
Cw, dry winter	1203	143	0.12
Cs, dry summer	616	77	0.13
D, cold	561	258	0.46
Df, no dry season	948	478	0.50
Dw, dry winter	478	125	0.26
E, polar	452	160	0.35
ET, tundra	460	148	0.32
EF, arctic	375	278	0.74
Global	818	179	0.22

Güntner et al. (2007) model-based estimates on the continental total water storage in different climate zones (from [5])

Inland Eurasia

1) Water storage size is climate-dependent, but highly heterogeneous locally due to many biotic and abiotic factors
2) Overall, the total water storage is less than half of the mean annual precipitation

5. The effects of water storage size



Assuming T/ET = 60% for both wet and dry seasons:

1) The dry season ET d-excess is lower than the wet season ET d-excess when the relative water storage size is small (low S_0/P_1), driven by high contributions of residual water storage to dry season ET fluxes, and vice versa
2) The ET d-excess is likely lower than precipitation d-excess, challenging the simple view that admixture of recycled moisture increases d-excess towards continental interiors

Get the poster PDF!

SCAN ME

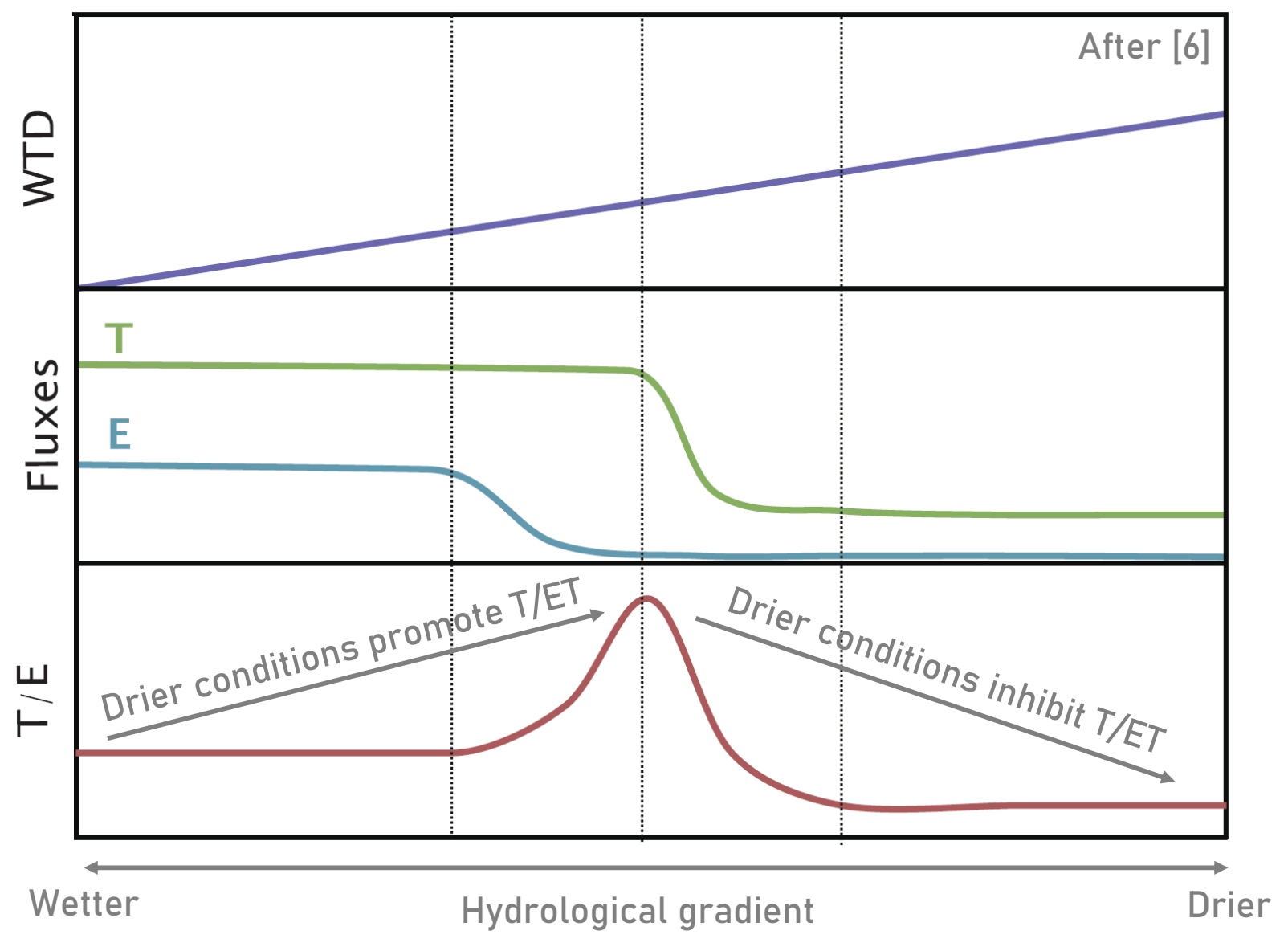
Acknowledgements:
We thank Angela Ampuero Grández, Andreas Link, and Ruud van der Ent for help on running the WAM-2layers, and Jeffrey Welker for providing USNIP data.

References:
[1] Kukla et al., 2019. J. Geophys. Res. Atmo., 124, 563–582.
[2] Gat and Matsui, 1991. J. Geophys. Res., 96, 13179–13188.
[3] van der Ent et al., 2014. Earth Syst. Dynam., 5, 471–489.
[4] Xia and Winnick, 2021. Earth Planet. Sci. Lett., 572, 117120
[5] Güntner et al., 2007. Water Resour. Res., 43, W05416.
[6] Maxwell and Condon, 2016. Science, 353, 377–380.

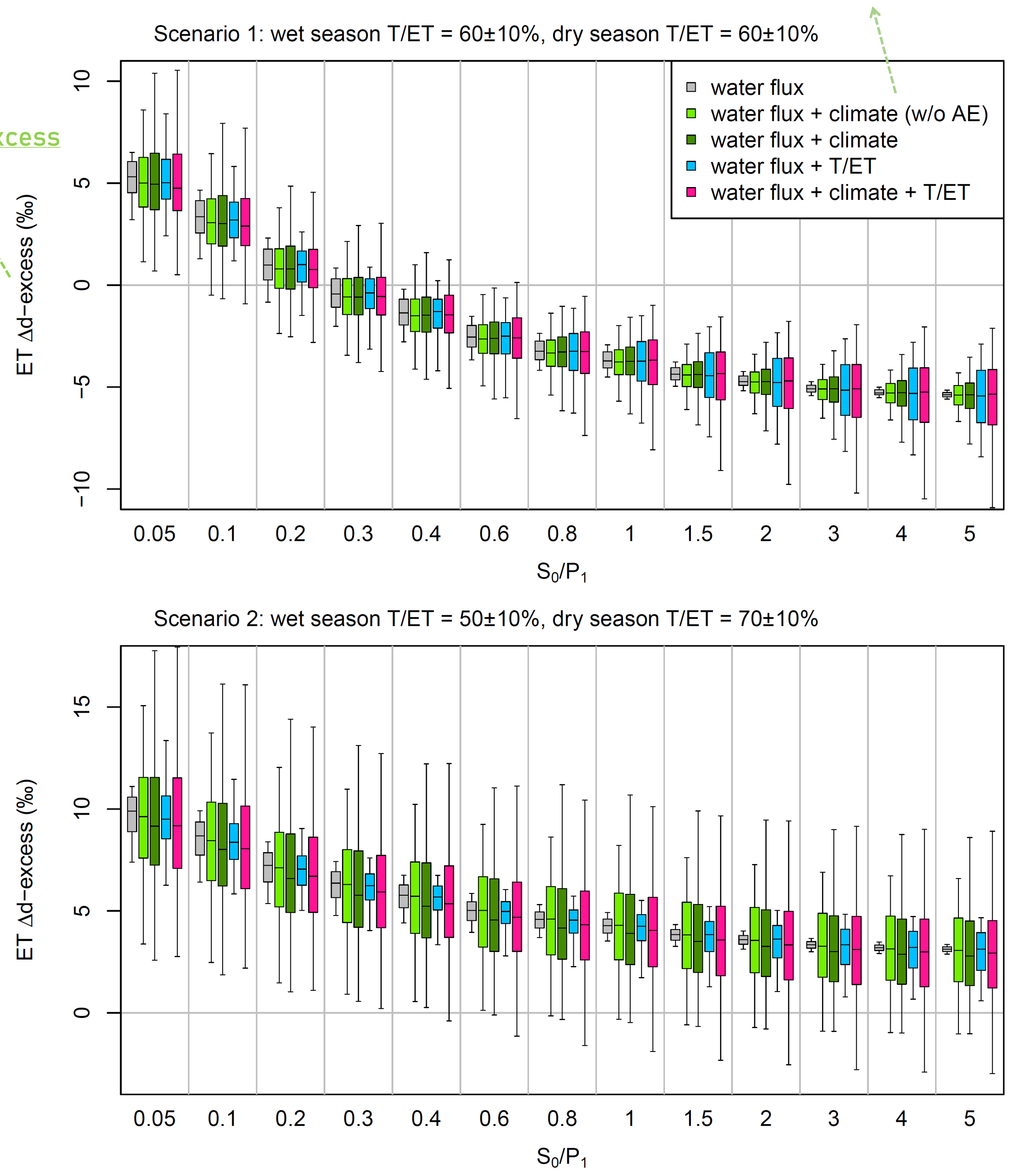
6. The effects of ET partitioning and sensitivity to model parameters

ET Δd-excess = wet season ET d-excess – dry season ET d-excess

Maxwell and Condon (2016) conceptual diagram on the hydrological control of T/ET



Monte Carlo simulations using randomized model parameters



1) Seasonal ET partitioning is dependent on macroclimates and ecosystem types that are in part related to the water storage size
2) If T/ET is higher in the dry season, the dry season ET d-excess remains lower than the wet season ET d-excess even at high water storage
3) Randomized water fluxes and other model parameters (within certain ranges) do not affect the results