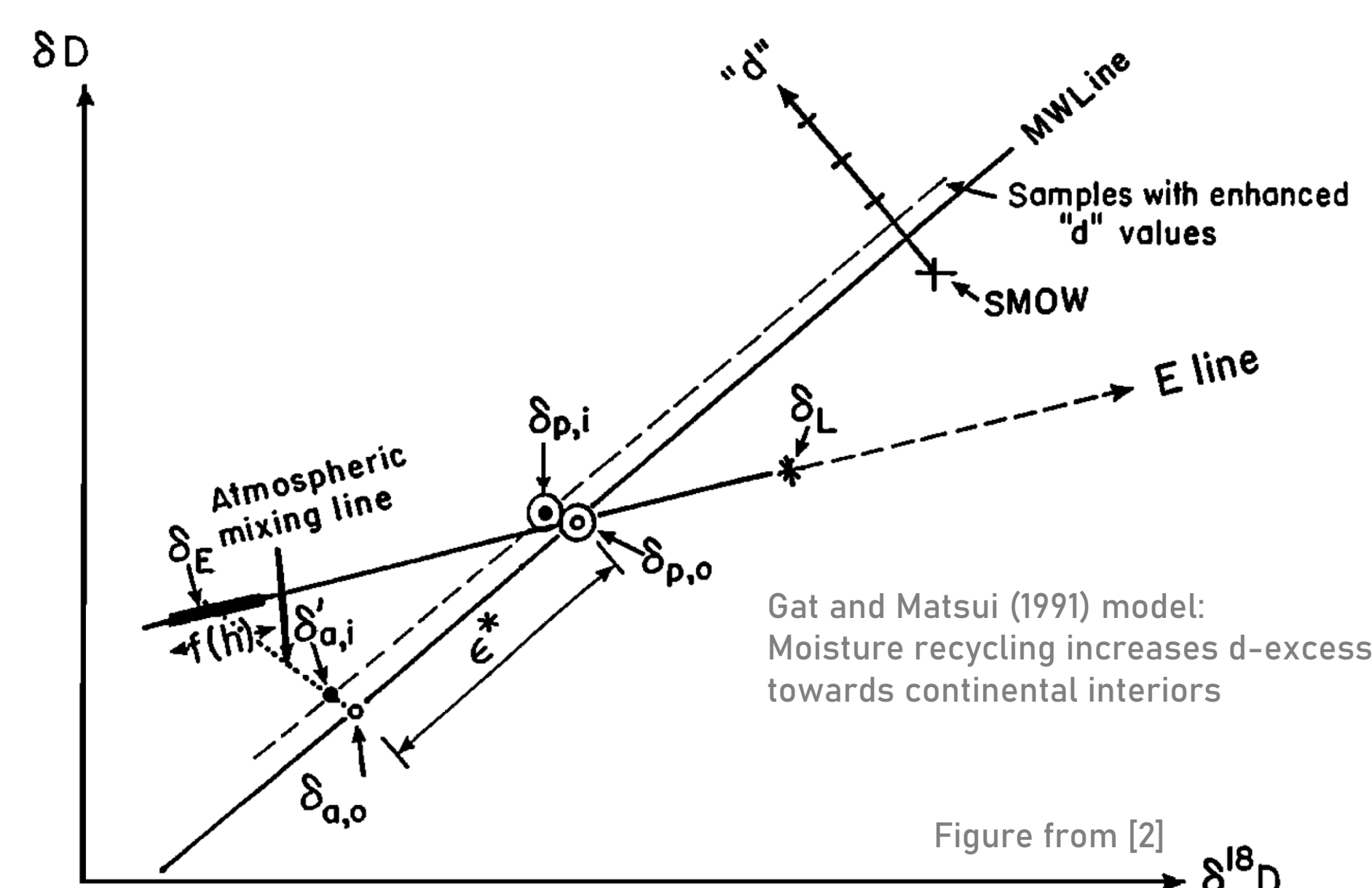
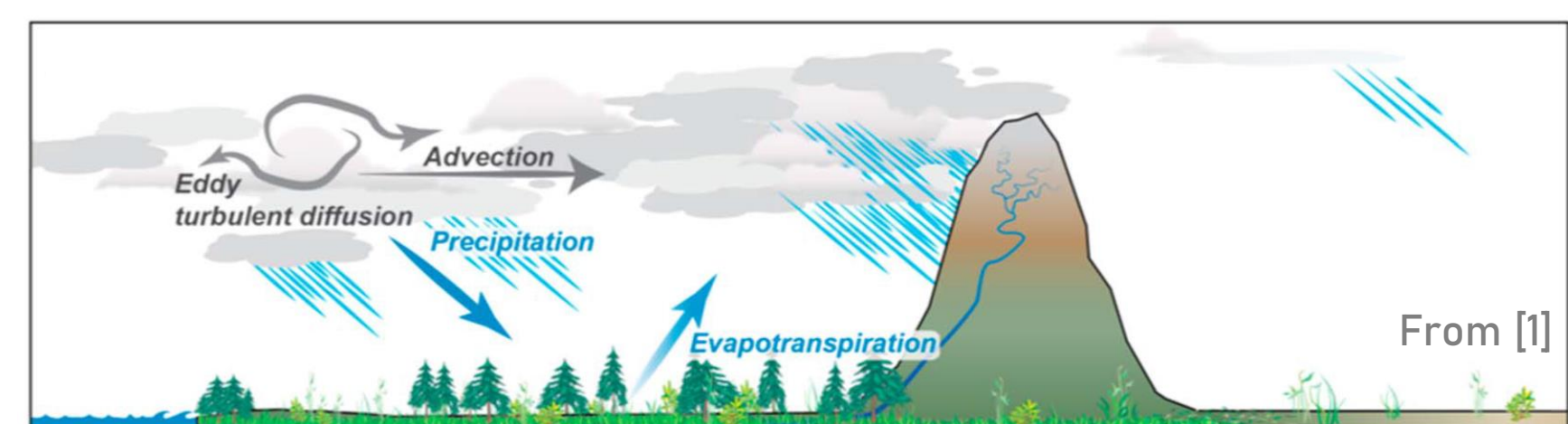


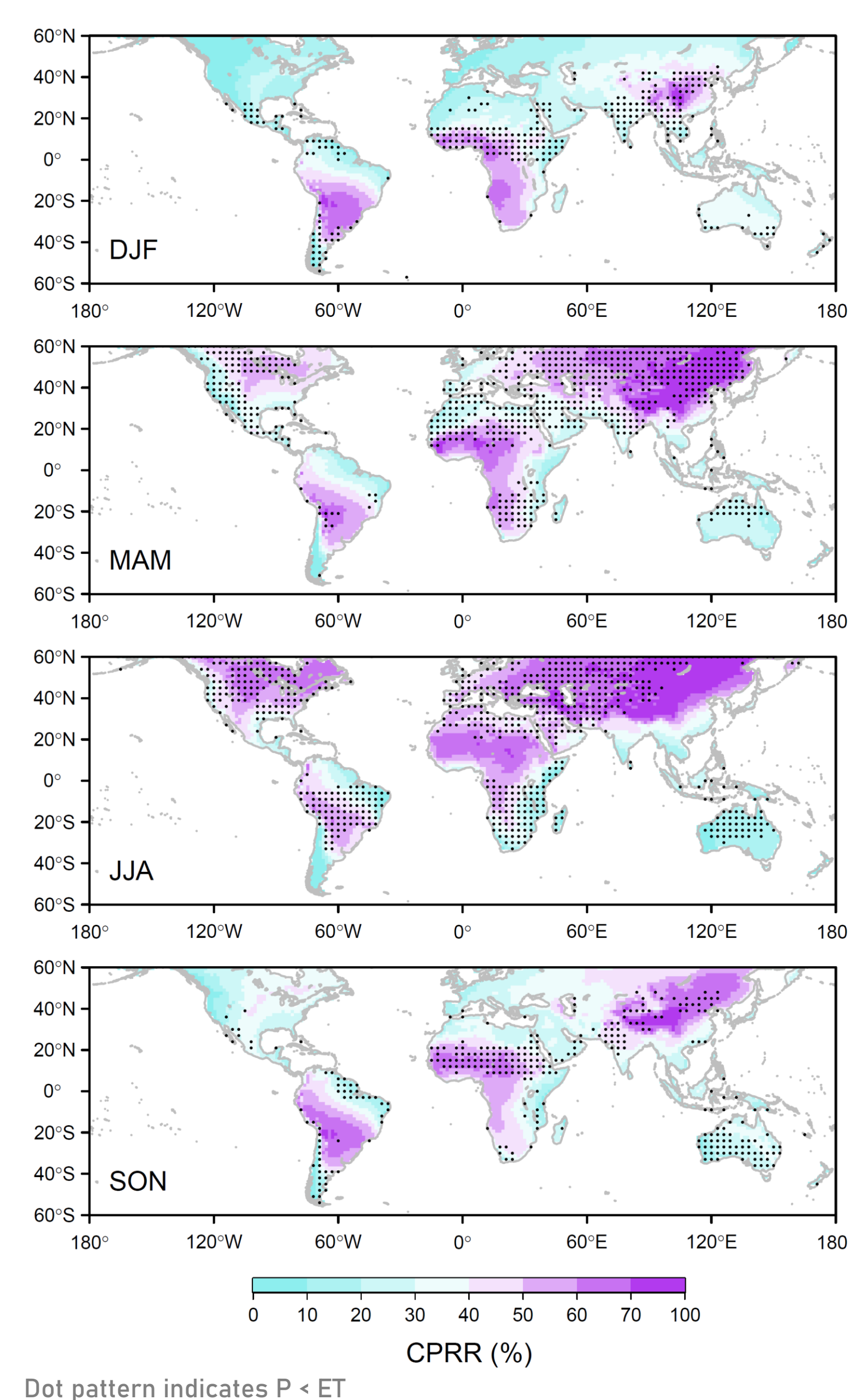
1. Traditional paradigm



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

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])

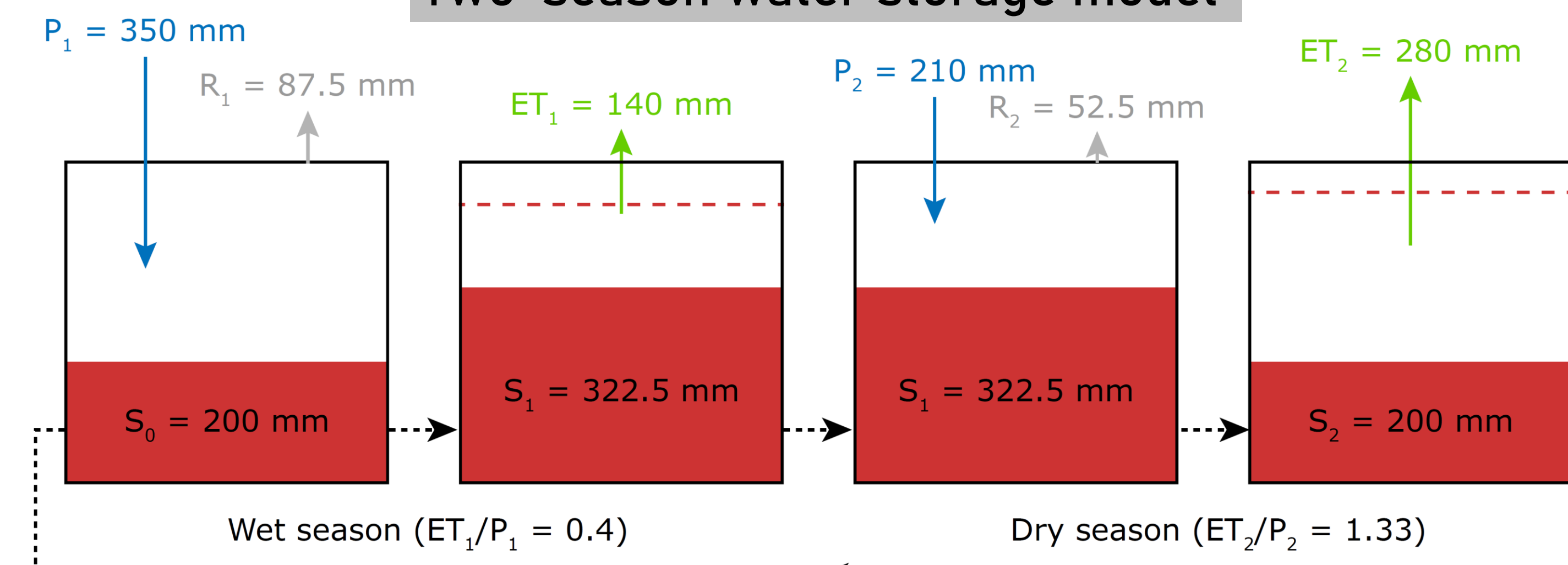
- 1) There are large seasonal changes in moisture recycling regime in North America and Eurasia, with CPRR increasing from 10% in winter to 60% in summer
- 2) However, precipitation d-excess does not increase in response to the seasonal swings in moisture recycling as shown by spatial correlation patterns
- 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]

$$\delta_{ET} = \left(\frac{E}{ET} \right) \frac{\int_0^1 [\alpha_{ET}(\delta_1 + 1000) F^{\alpha_{ET}-1} - 1000] dF}{F-1} + \left(\frac{T}{ET} \right) \delta_1 \quad \text{with} \quad \alpha_{ET} = \left(\frac{E}{ET} \right) \left[k \frac{\alpha_{ET}^{-1}}{(1-k)(1+\frac{\alpha_{ET}-1}{ET})} \right] + \left(\frac{T}{ET} \right) \left(\frac{1}{1+k \frac{E}{ET} - k} \right)$$

Water flux relationship

The residual water storage size:

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

The fraction of residual liquid water remaining after ET loss:

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

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

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

Isotopic flux relationship

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

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

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

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

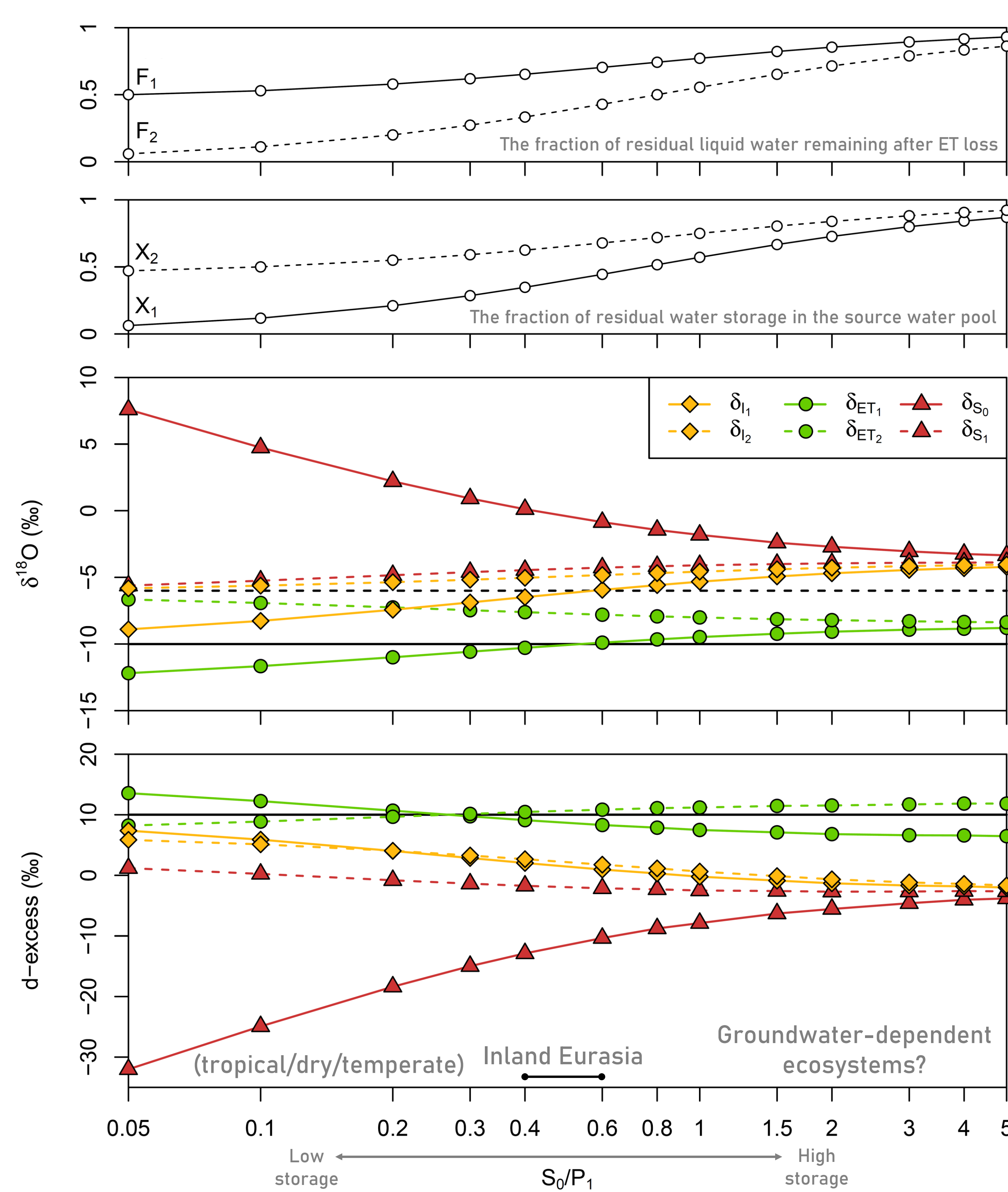
$$S_2 = S_0 \quad \text{and} \quad \delta_{S_2} = \delta_{S_0}$$

The boundary condition constraint

4. Simple model test

Model inputs	Wet season	Dry season
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 $\delta^{18}O$ (‰)	-10	-6
Precipitation d-excess (‰)	10	10
Model results		
"Modified" source water $\delta^{18}O$ (‰)	-6.0 (δ_{I_1})	-4.9 (δ_{I_2})
ET $\delta^{18}O$ (‰)	-9.9 (δ_{ET_1})	-7.8 (δ_{ET_2})
Residual water storage $\delta^{18}O$ (‰)	-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

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

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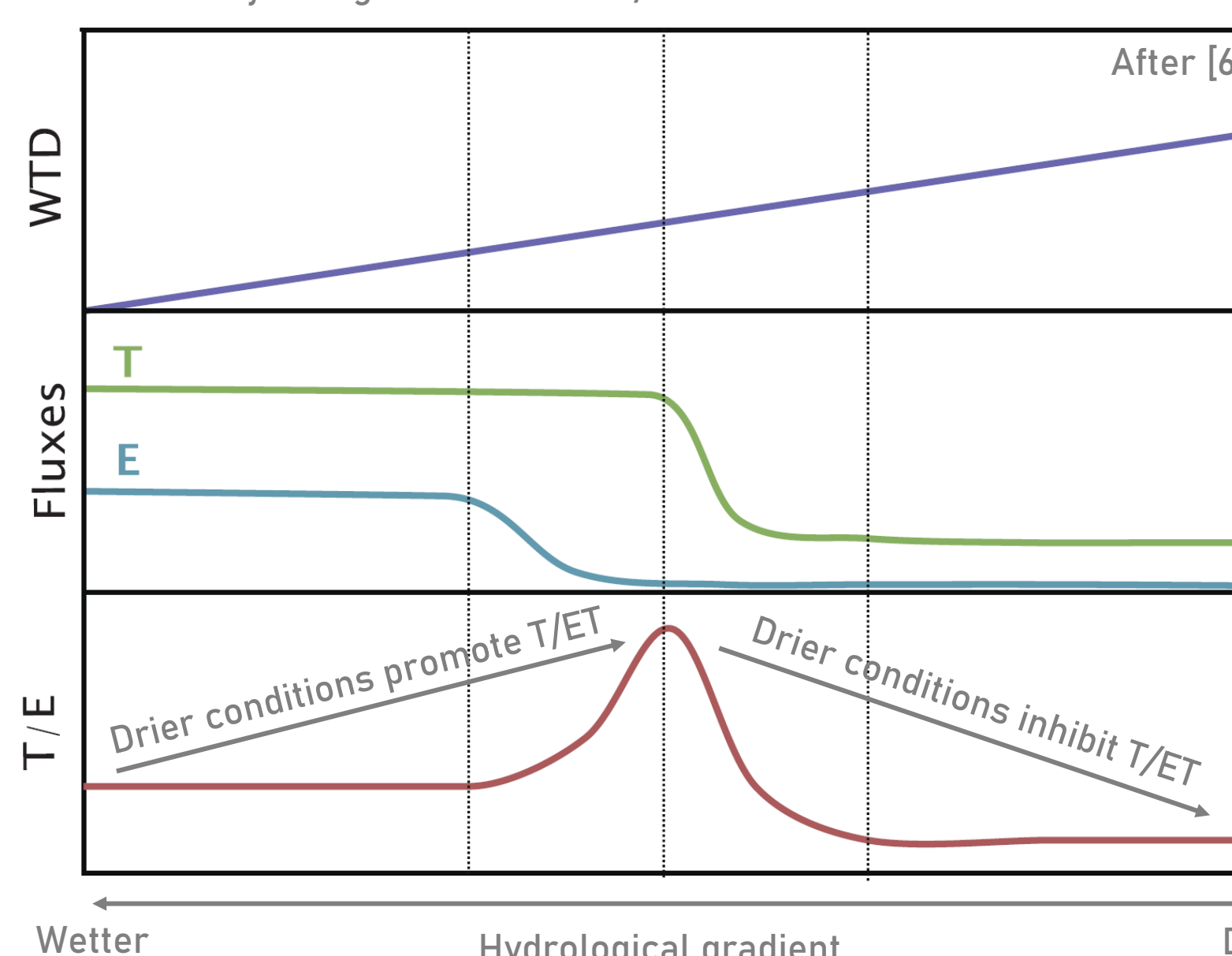
References:

- [1] Kukla et al., 2019, J. Geophys. Res. Atmos., 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.
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- [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

$$ET \Delta d\text{-excess} = \text{wet season } ET \text{ d-excess} - \text{dry season } ET \text{ d-excess}$$

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



- 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

How large is the available subsurface water storage?

Koepfen 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

- 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

Inland Eurasia

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