COLUMBIA UNIVERSITY
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Soil moisture-atmosphere feedbacks mitigate projected surface water availability declines in drylands

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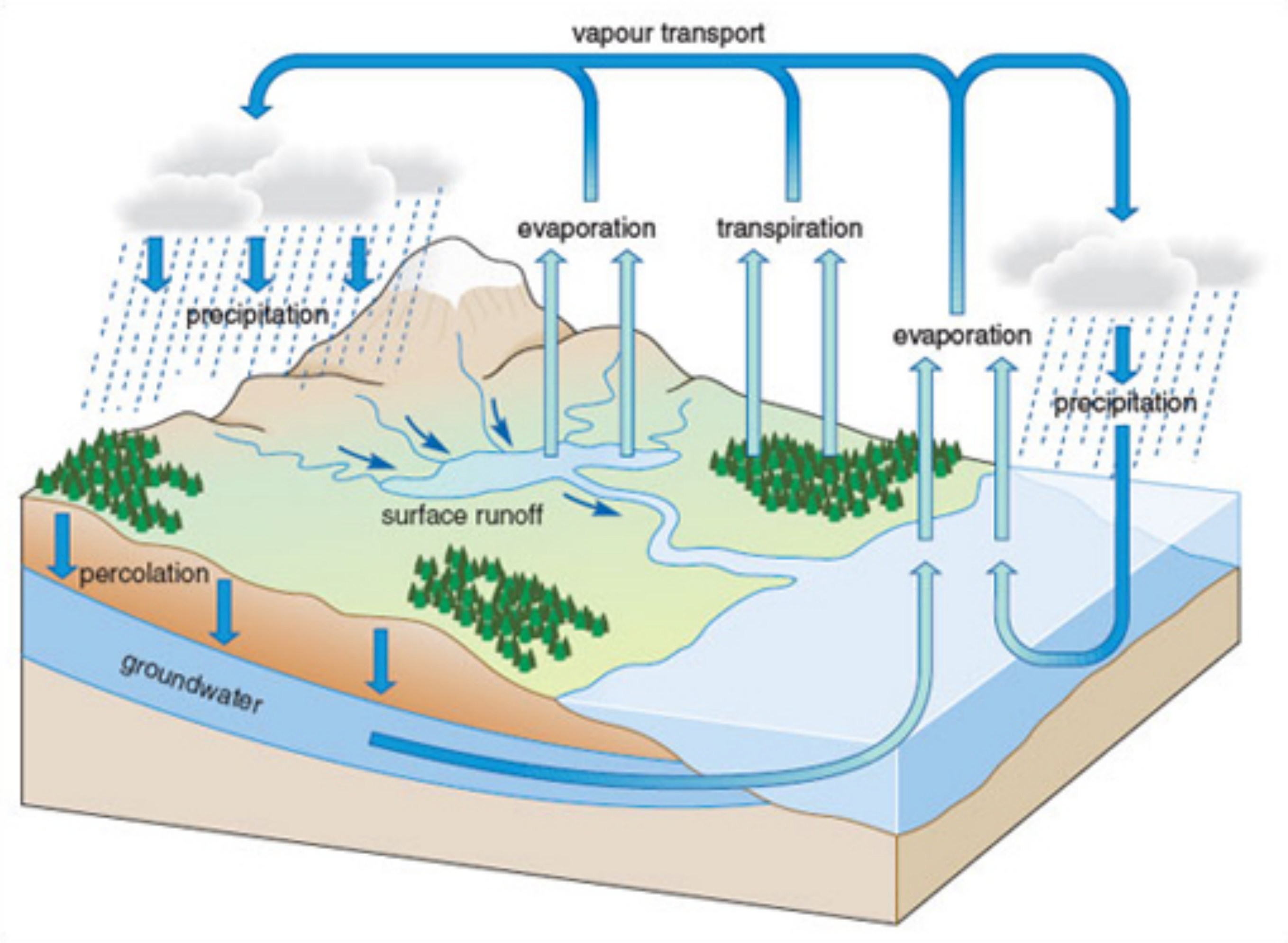
Global water cycle



Terrestrial water balance:

P-E = Runoff + ΔStorage$_{land}$

Atmospheric water balance:

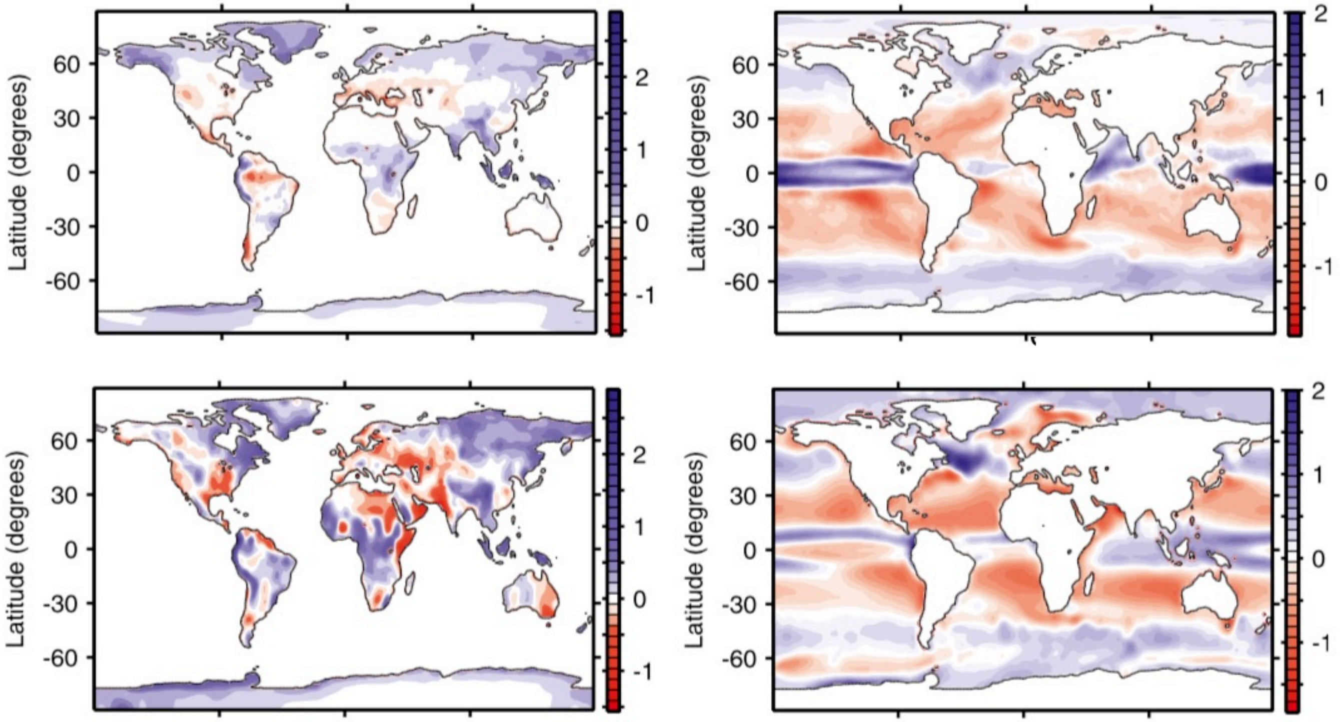
P-E = MC + ΔStorage$_{atmosphere}$

P-E (Surface water availability)

$\approx$MC (Moisture Convergence)

Wet-Get-Wetter, Dry-Get-Drier?

Land　　　　　　　　Ocean



Δ(P-E) in CMIP5 models:
Future (2070-2099, RCP8.5)-historical (1976-2005)

Thermodynamic scaling

$$\delta(P-E) \approx (\delta q_s/q_s)(P-E) - \mathbf{G} \cdot \nabla(\delta q_s/q_s)$$

Varying q
Constant u

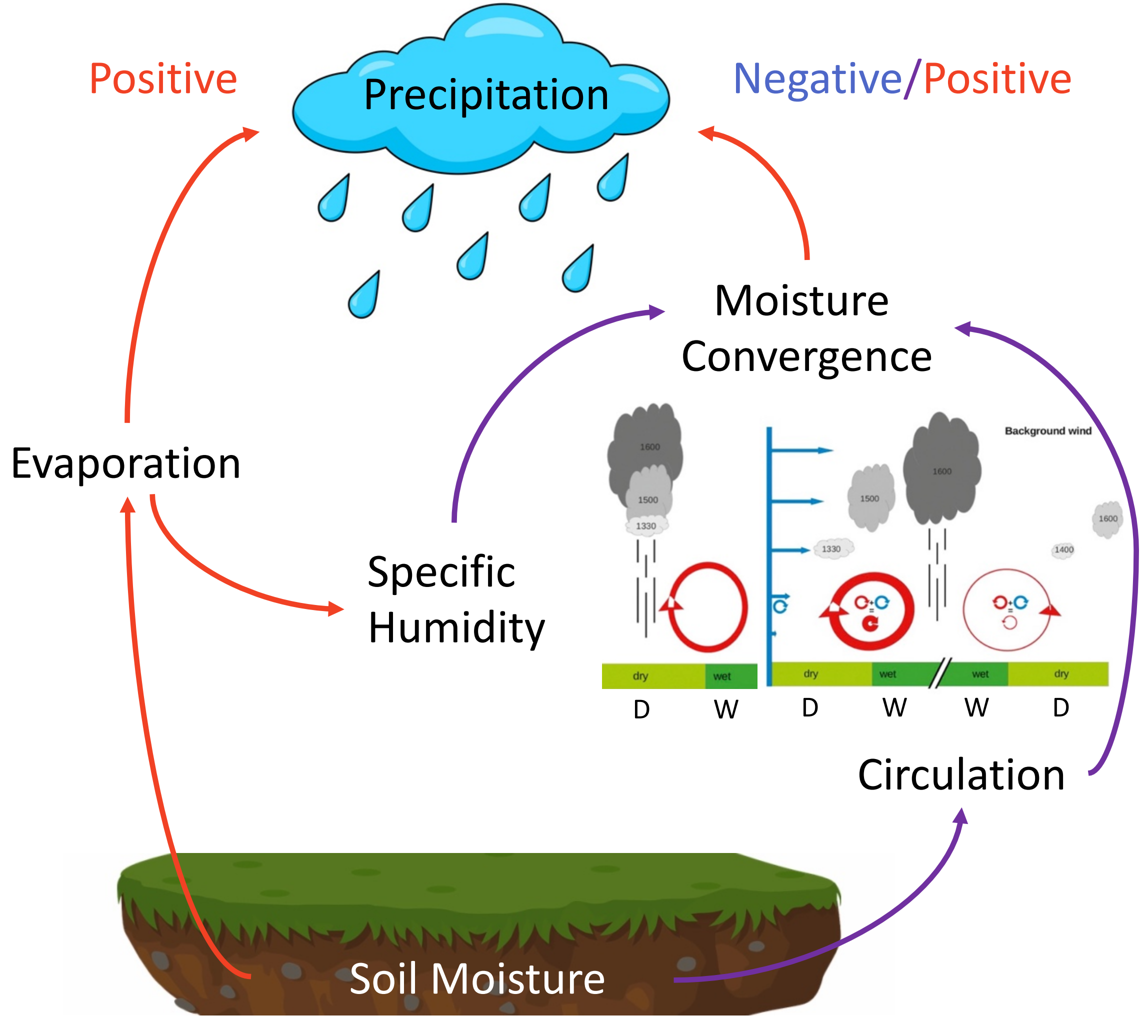
$$\delta(\text{P-E}) = \delta\text{MC} = -\frac{1}{\rho_w g}\nabla \cdot \int_0^{p_s} \delta(\boldsymbol{u} \cdot q)\,dp$$

Hypothesis: thermodynamic processes reduce P-E in subtropical drylands, which may be largely mitigated by dynamic processes.

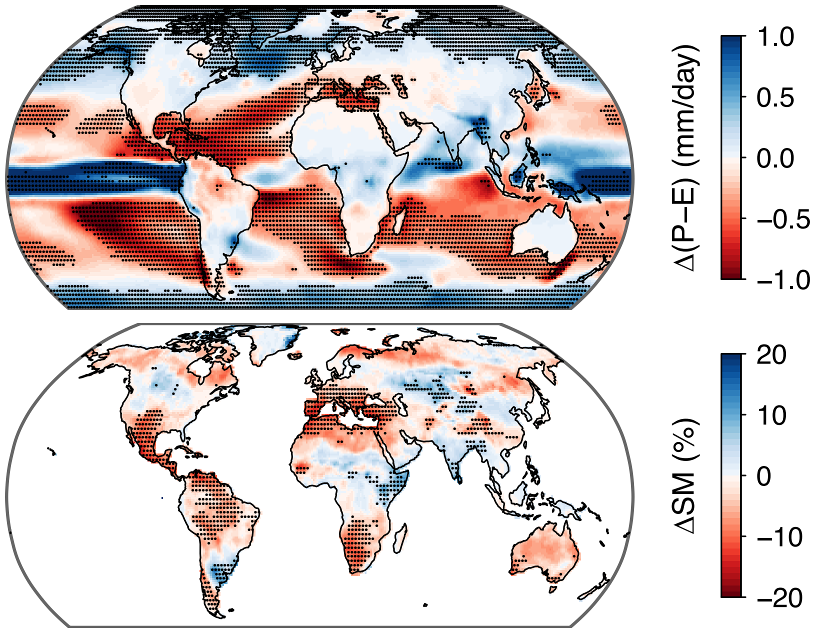
$\boldsymbol{u}$: wind vector; q: specific humidity

Byrne and O' Gorman (2015)

What is the long-term SM effect on P-E?



Δ(P-E) in CMIP5 models:
Future (2071-2100, RCP8.5)-historical(1971-2000)



Research Question:
How does long-term SM changes impact future projected P-E changes?

Isolate the SM effect on future P-E changes

Global Land-Atmosphere Coupling Experiment (GLACE)-CMIP5 (1950-2100)

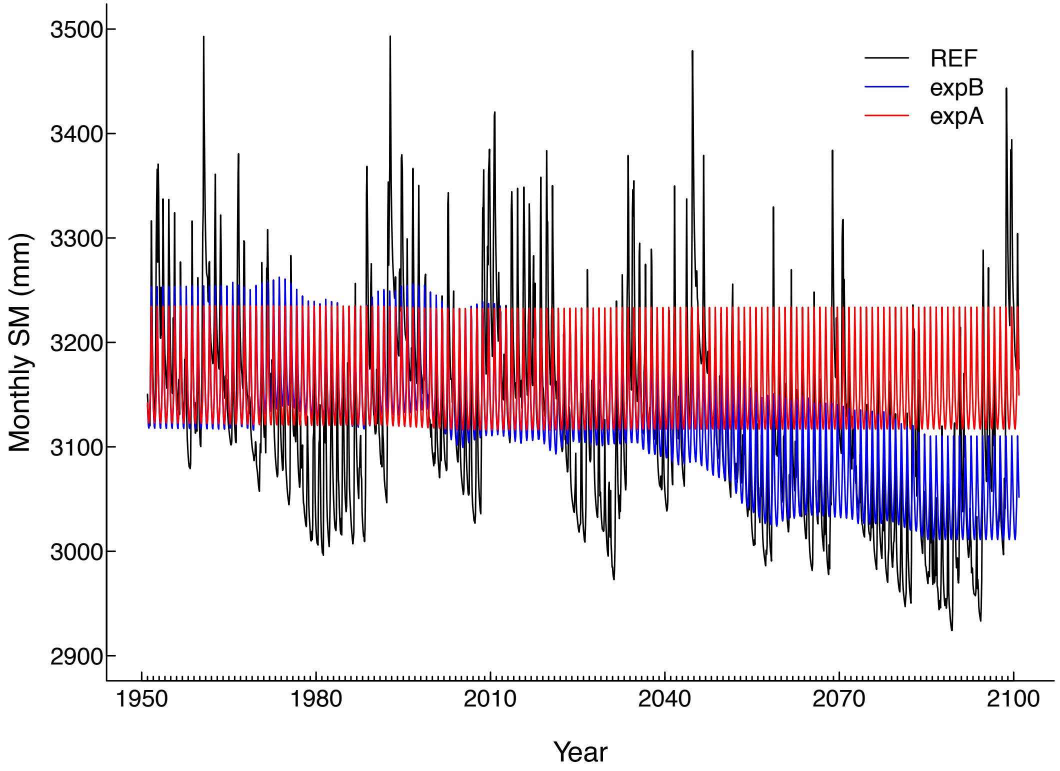
Four models: EC-Earth, ECHAM6, GFDL, IPSL

Three simulations:

- **REF**: SM fully interactive with the atmosphere (CMIP5 historical + future _RCP8.5)
- **expB**: prescribed SM as a centered, 30-year running mean climatology from REF
- **expA**: prescribed SM as 1971-2000 climatology from REF

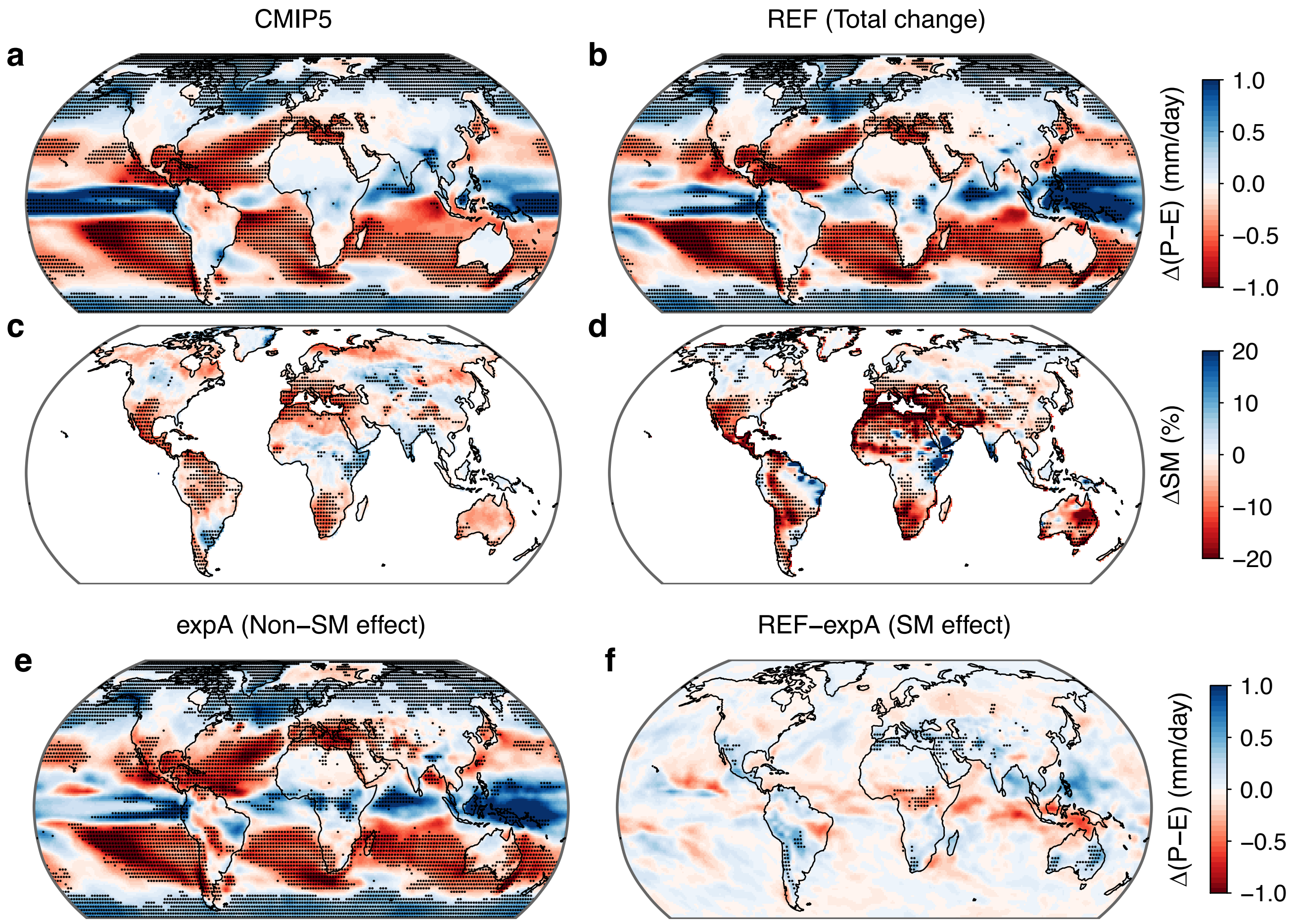
SM effect on P-E	Simulations
Total SM effect	REF-expA
SM trends	expB-expA
SM variability	REF-expB

SM time series at one grid

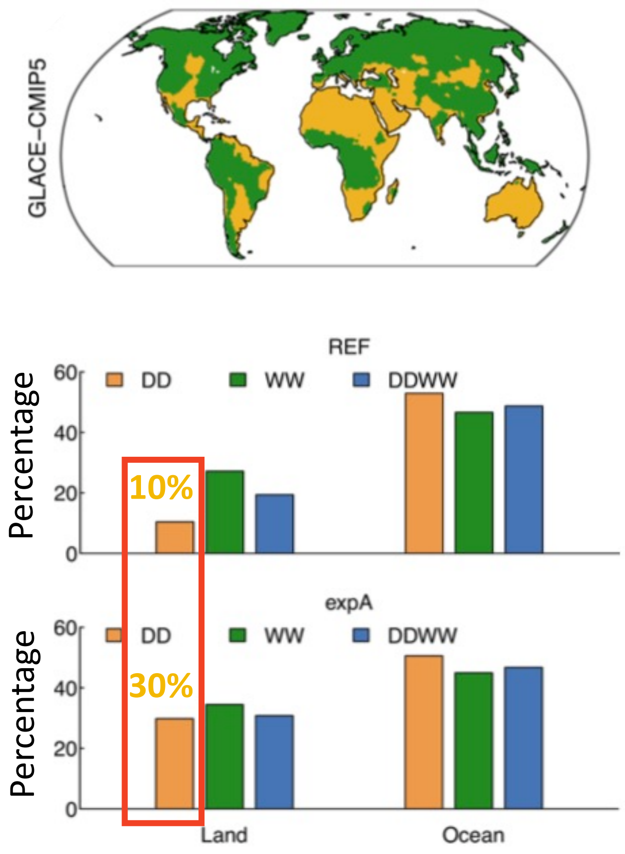


Negative SM effect on dryland P-E changes

Future (2071-2100, RCP8.5)-historical (1971-2000)



Drylands and Non-drylands



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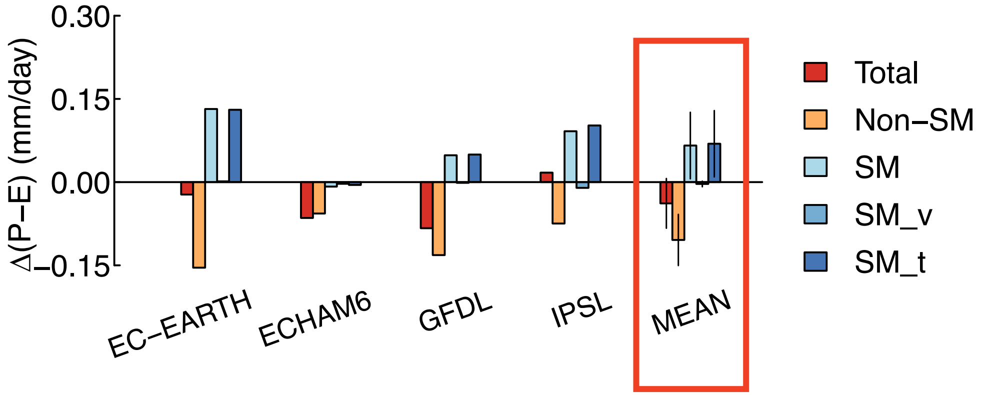
Negative SM effect on dryland P-E changes

Drylands

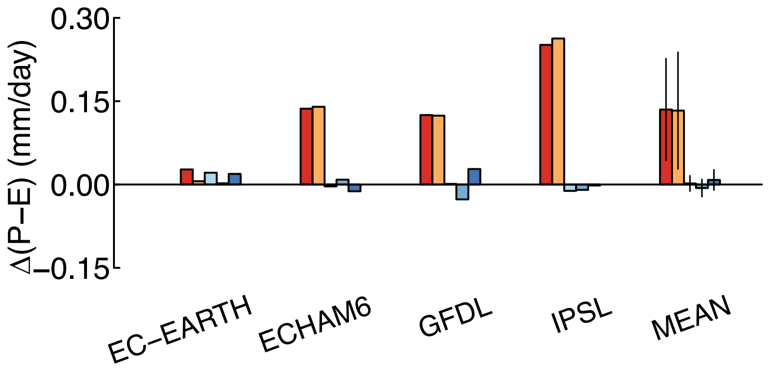


63% of P-E declines in drylands is mitigated by negative SM-(P-E) feedbacks

SM (trends) effect: 0.066±0.060mm/day

Non-SM effect: -0.104±0.046mm/day

Non-drylands



P-E increases in non-drylands are caused by non-SM effects

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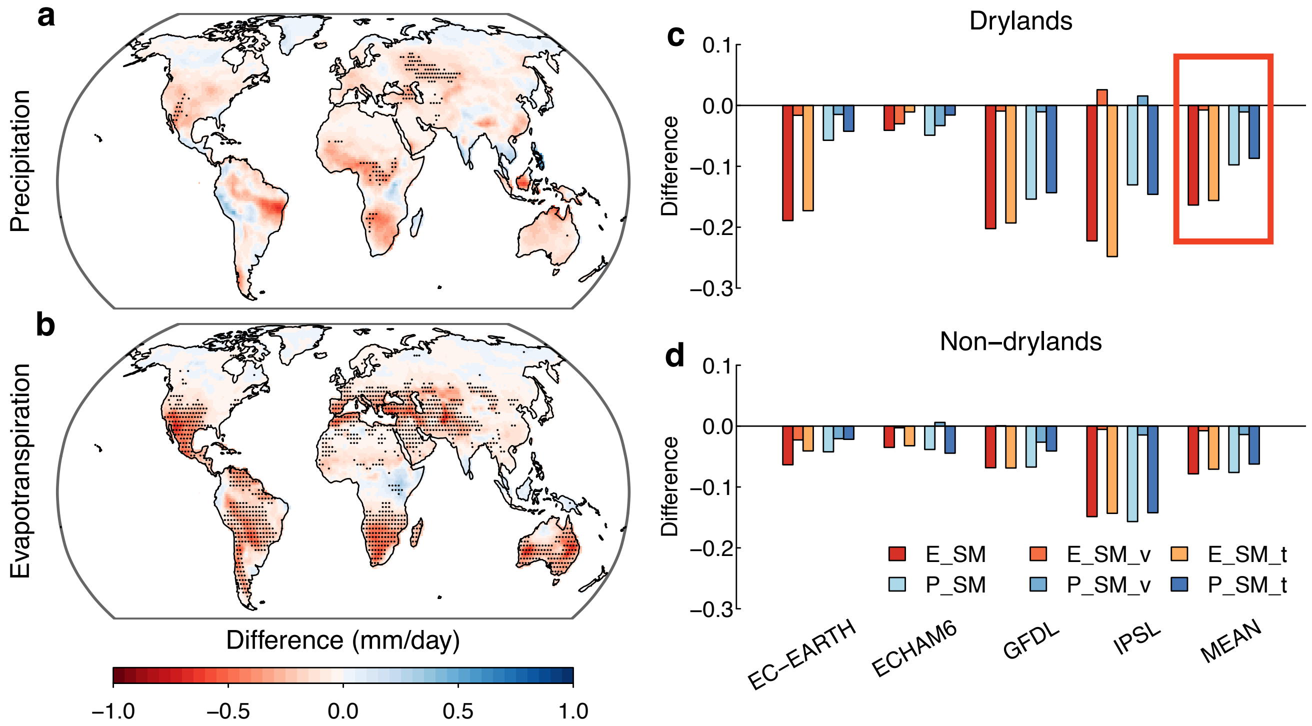
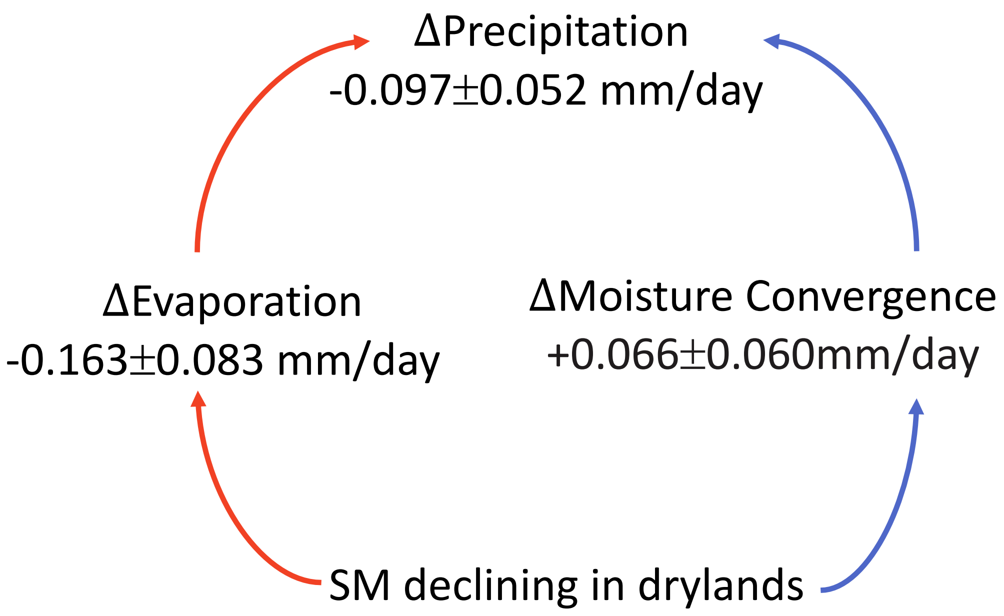
Stronger SM limitation on E than on P

$\Delta(P\text{-}E)_{SM} = \Delta P_{SM} - \Delta E_{SM} = \Delta MC_{SM}$





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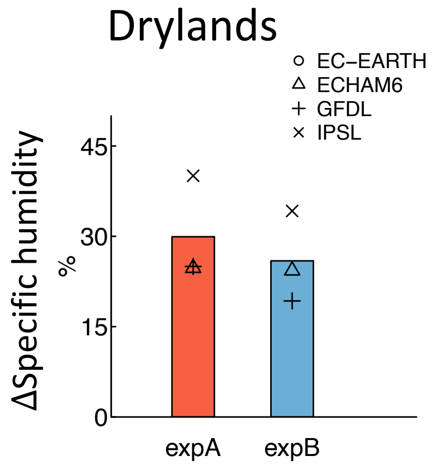
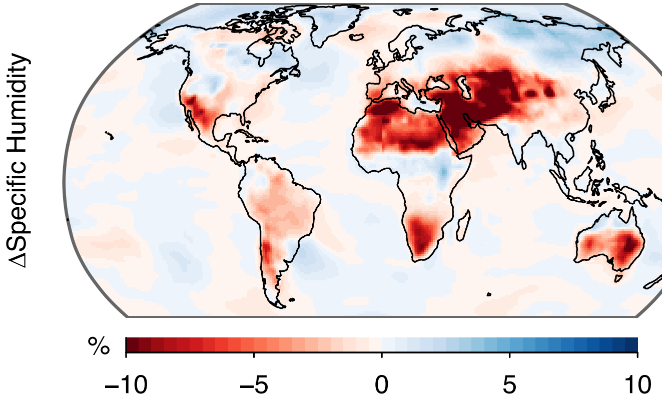
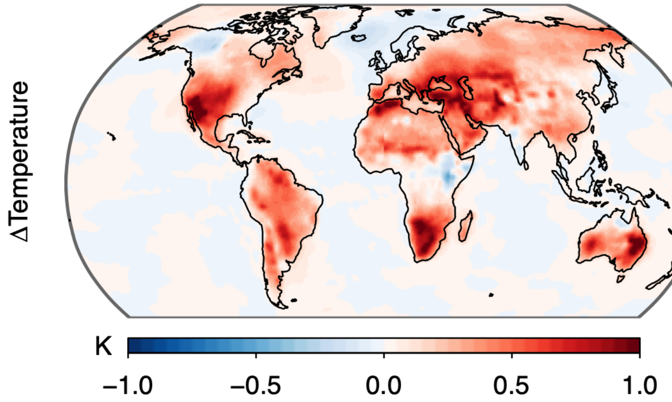
Thermodynamic mechanisms



expB (SM trends)- expA





Thermodynamic scaling

$$\delta(P-E) \approx (\delta q_s/q_s)(P-E) - \mathbf{G} \cdot \nabla(\delta q_s/q_s)$$

Local humidity reductions
Negative

Horizontal moisture advection
Positive

Thermodynamic effects associated with SM trends

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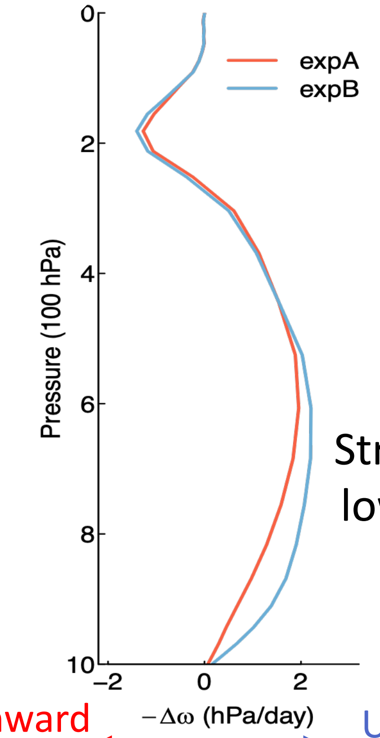
Declining SM promotes upward motion

ΔNegative pressure velocity ($-\Delta\omega$) over drylands

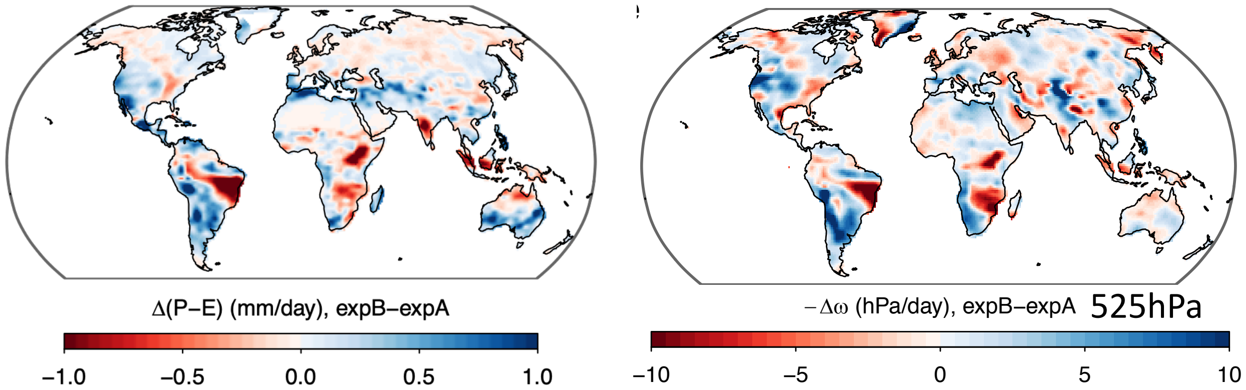


Downward (Moisture Divergence)

Upward (Moisture Convergence)

Stronger enhancement of low-level upward motion in expB than in expA

Strong correlation (r=0.59) between Δ(P-E) and $-\Delta\omega$ over drylands



Downward (Moisture Divergence)

Upward (Moisture Convergence)

Reduced SM may promote atmospheric upward motion, potentially contributing to the negative SM effect on P–E.

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Negative SM→(P-E) in drylands

Multiple linear regression model

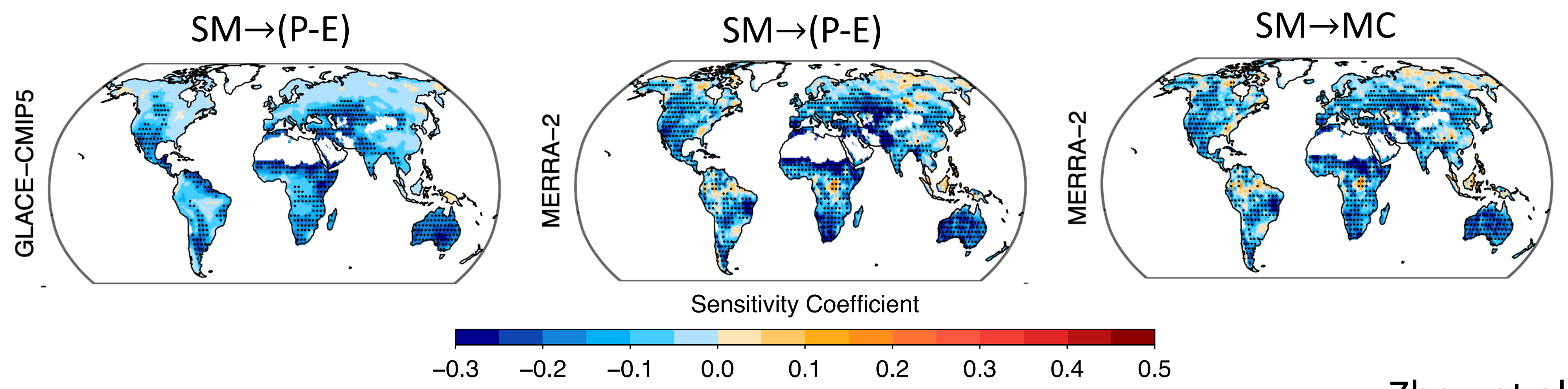
$$(P-E)_d(t+1) = n_0 + n_1 \cdot SM_d(t) + n_2 \cdot (P-E)_d(t)$$

- $(P-E)_d$: Remove seasonal cycle and trend
- n_1: SM→(P-E) Sensitivity Coefficient
- $n_2 \cdot (P-E)_d(t)$: Remove autocorrelation

$$n_1 = \frac{\partial (P-E)_d(t+1)}{\partial SM_d(t)}$$

Data: monthly SM, P-E, MC

- GLACE-CMIP5: 1971-2100
- MERRA-2: 1980-2018



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Dynamic effect dominates negative SM→(P-E)

Moisture convergence decomposition

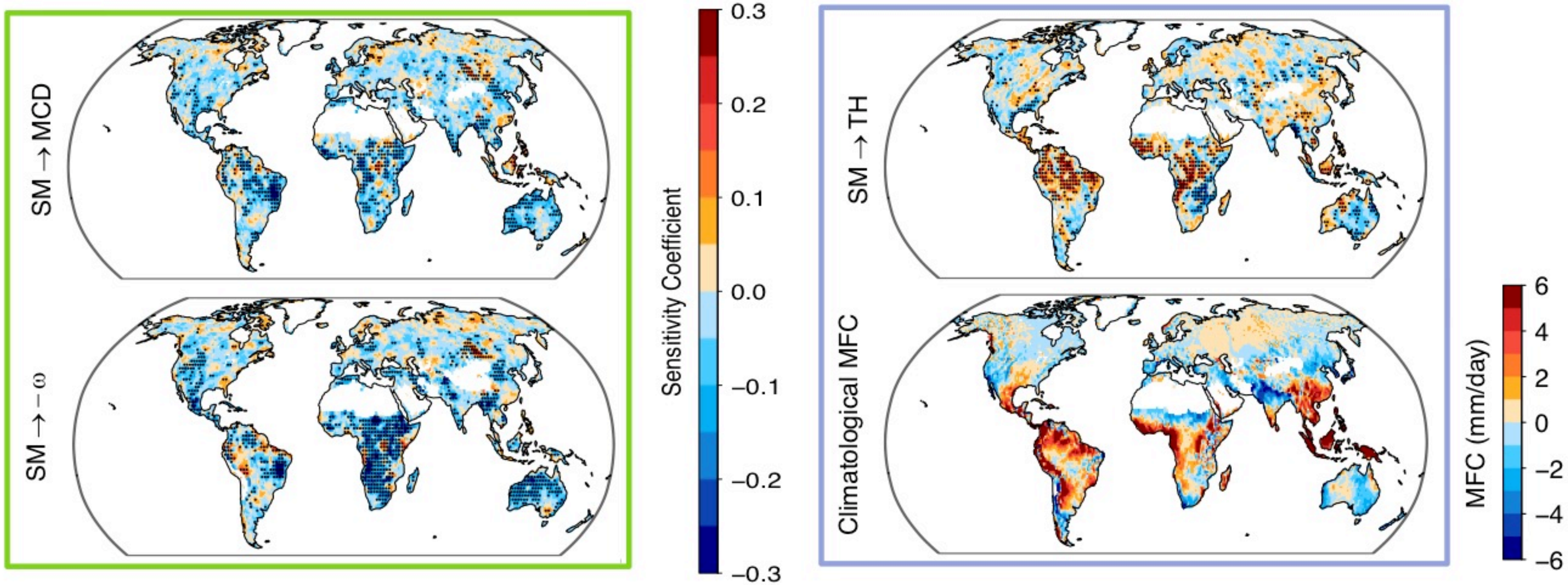
$$\Delta(P-E) \approx \Delta MC \approx -\frac{1}{\rho_w g}\nabla\cdot\int_0^{p_s}(\bar{q}_0\Delta\bar{\boldsymbol{u}} + \bar{\boldsymbol{u}}_0\Delta\bar{q})dp$$

$\boldsymbol{u}$: wind vector
q: specific humidity

Dynamic component

Thermodynamic component

Negative SM-(P-E) feedbacks dominated by SM regulation of atmospheric circulation



Summary

- The **negative SM feedback on P-E** will **offset ~60% of the decline in dryland P-E** otherwise expected in the absence of SM feedbacks.

- The negative feedback is not caused by atmospheric thermodynamic responses to declining SM, but rather **reduced SM regulates atmospheric circulation and vertical ascent** to enhance moisture transport into drylands.

Thank you!